SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS
INSTITUTE OF TRANSPORTATION STUDIES

TRANSITION COSTS FOR NEW TRANSPORTATION FUELS: A Comparison of Hydrogen Fuel Cell and Plug-in Hybrid Vehicles

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Analyze transition scenarios for FCVs and PHEVs

Estimate

- **greenhouse gas (GHG) emissions**
- **gasoline consumption**

Relative to a **REFERENCE** case where no advanced technologies are implemented

Examine **transition costs** to bring FCV or PHEV technology to cost competitiveness.

Add PHEV case to NRC Scenarios

1) **H2 SUCCESS** H2 & fuel cells play a major role beyond 2025

2) **EFFICIENCY** Currently feasible improvements in gasoline internal combustion engine technology are introduced

3) **BIOFUELS** Large scale use of biofuels, including ethanol and biodiesel.

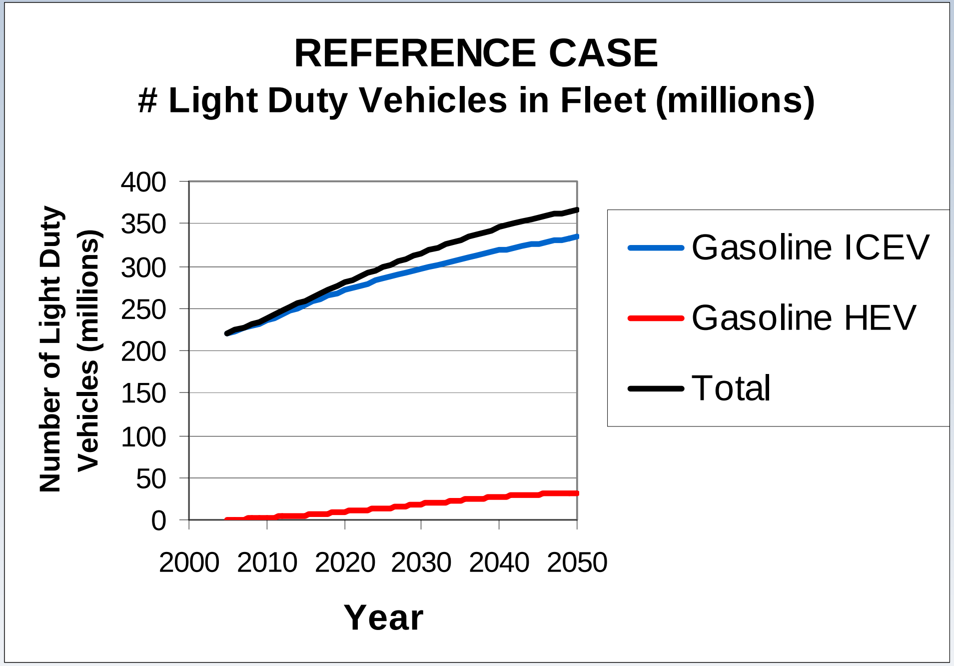
4) **ALL OF THE ABOVE** More efficient ICEVs, biofuels and FCVs vehicles are implemented.

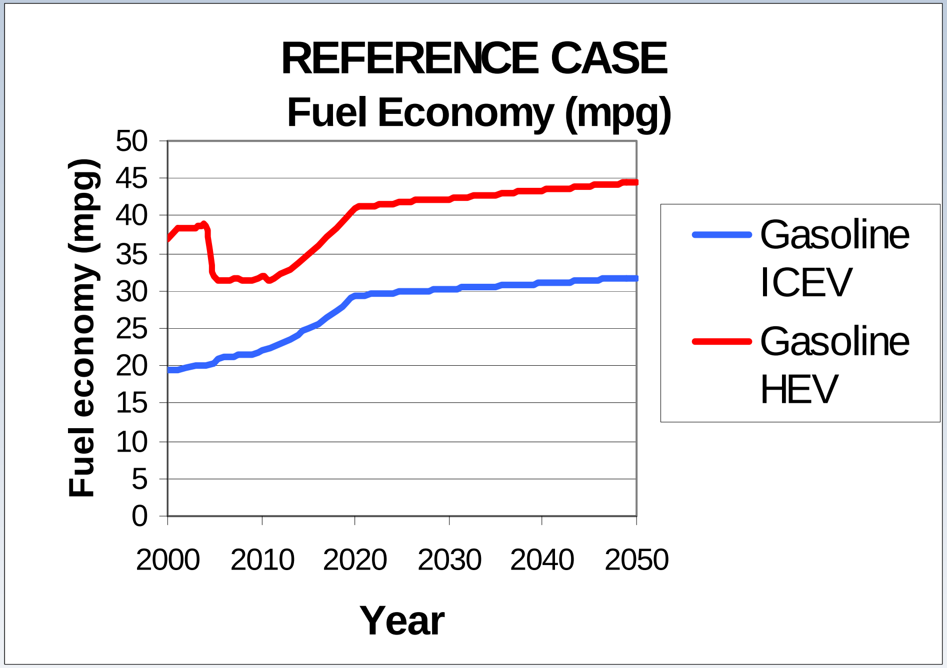
5) PLUG-IN HYBRID SUCCESS PHEVs play a major role beyond 2025

Modeling Assumptions

- Only US light duty vehicles considered.
- Analysis time frame: 2005-2050
- Costs in 2005 constant dollars.
- Ref case, energy prices from EIA AEO 2008 High Price Case
- Cost, performance of alt fueled and evolving gasoline vehicles from recent studies (NRC, MIT, DOE, EPRI).
- Total # vehicles and VMT same for all scenarios.
- Input market penetration rate for alt fueled vehicles.
- Track vehicle stock and vintages over time, => energy use, cost and GHG for each year.

Reference Case
(AEO 2008 High Price Case extended to 2050)





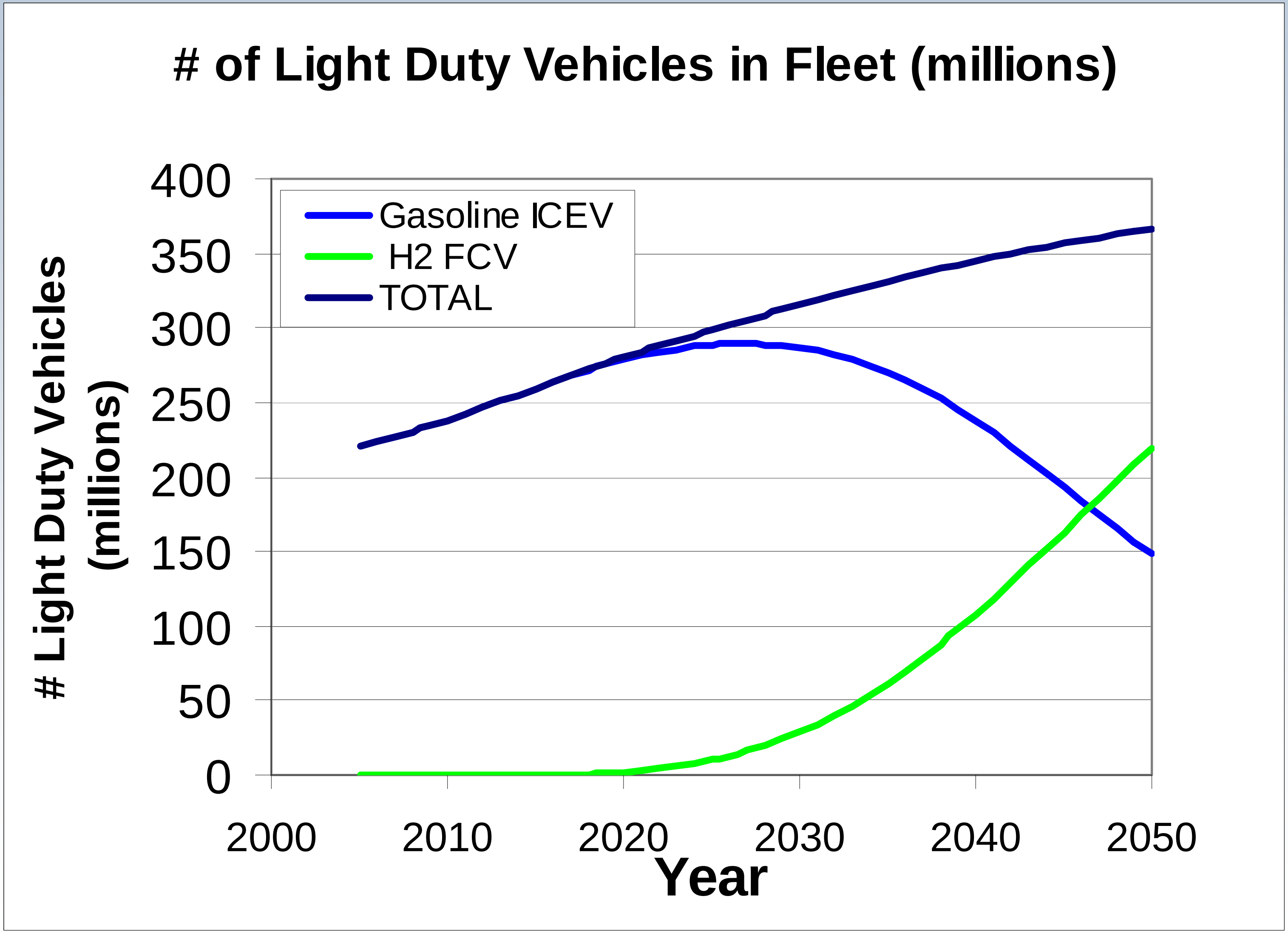
Improving gasoline ICEV fuel economy (new CAFÉ standards).
No H2 FCVs, other adv vehicle/fuels

Ethanol ~10% of gasoline by vol. ≥ 2030.

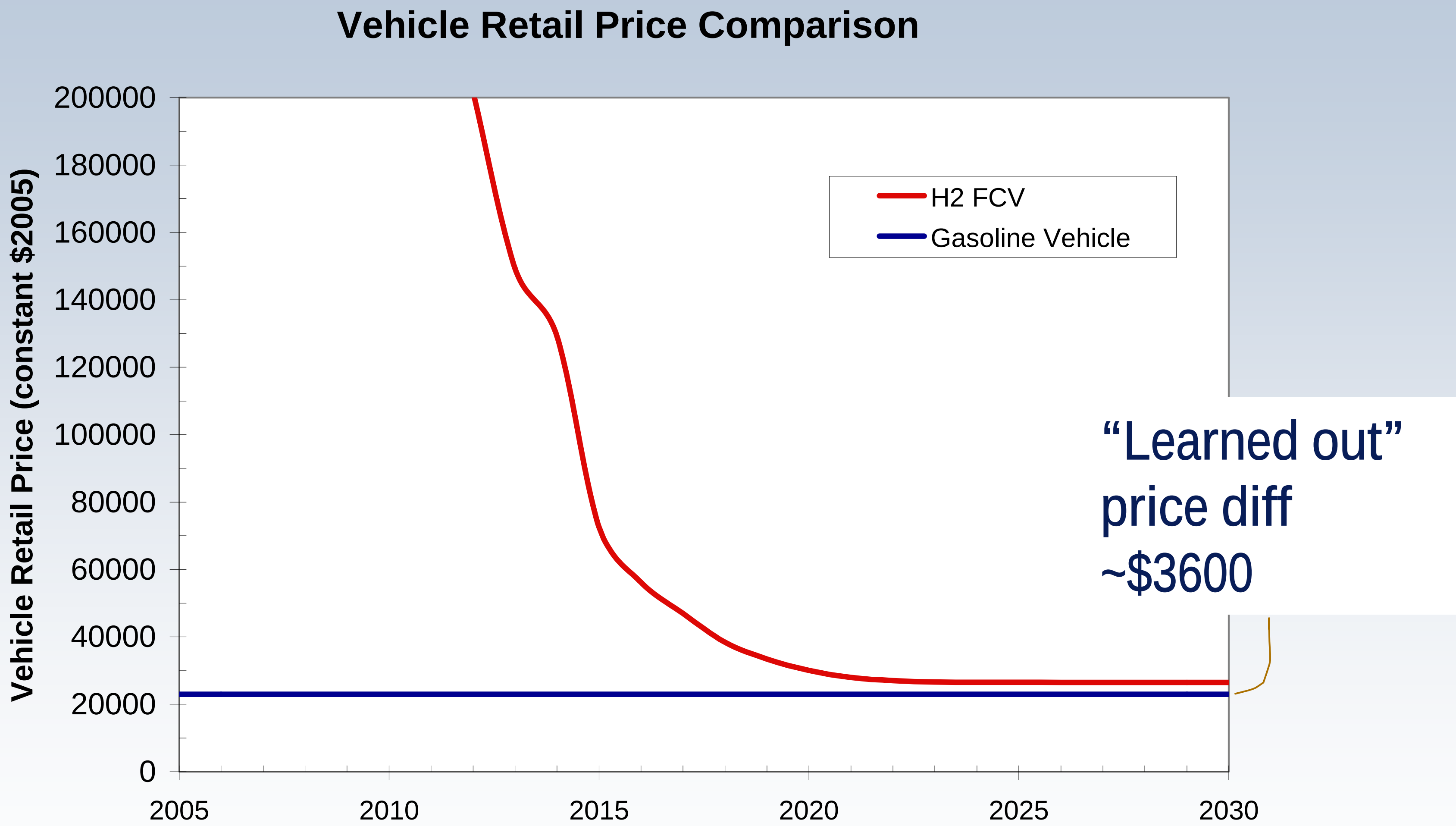
Oil price $80-120/bbl (2010-2030)

Gasoline GHG Emissions (well to tank) = 90 gCO2 eq/MJ fuel

Case 1: H2 Success (NRC 2008)



H_2 FCV Vehicle Price vs. time (NRC 2008)



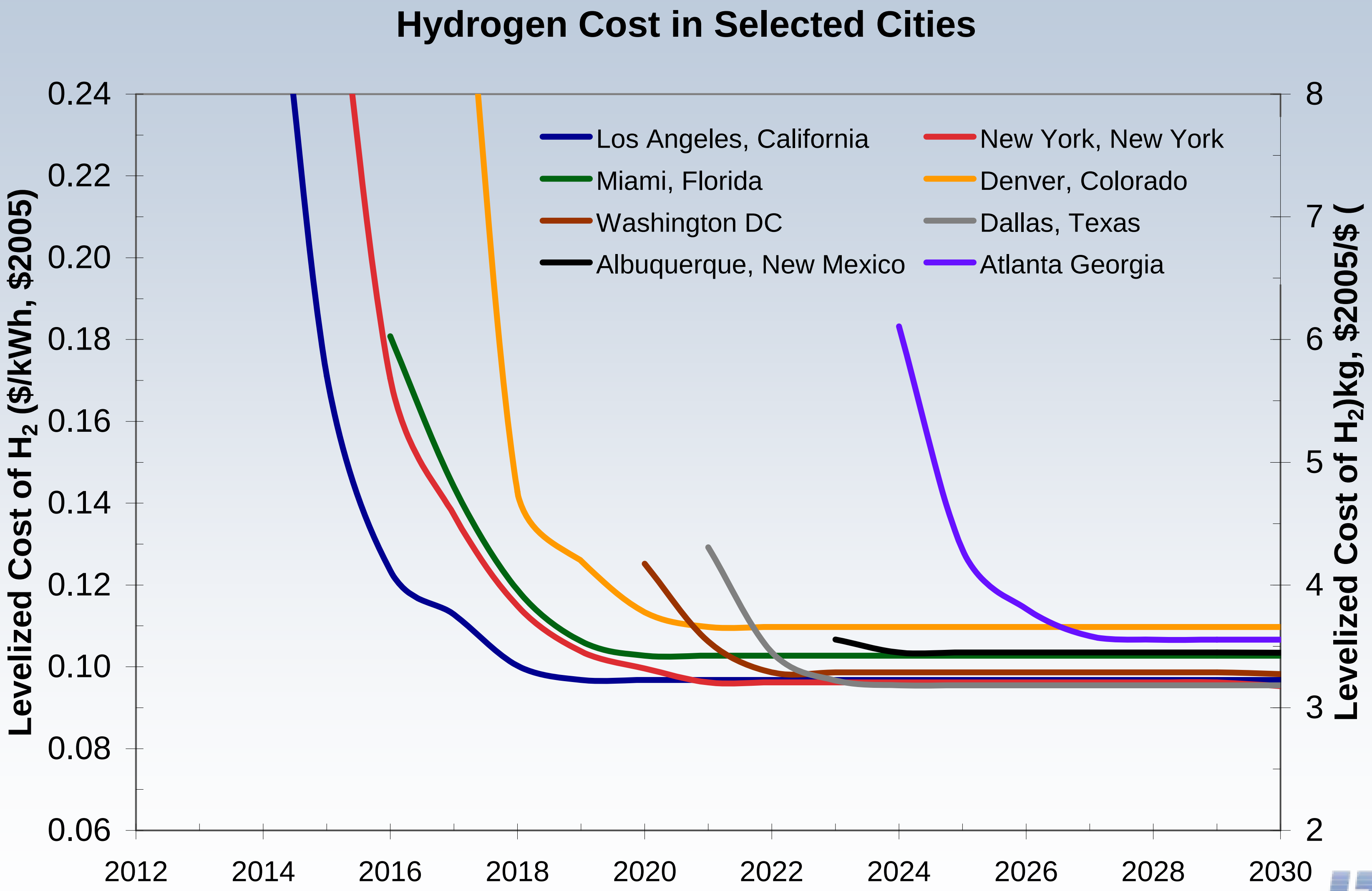
H2 FCV Vehicle Price curve based on model by Greene, Leiby and Bowman (2007). Price falls due to R&D improvements, cumulative experience and manufacturing scale-up.

Case 1: Phased Introduction of H2 FCVs in "Lighthouse" Cities (USDOE 2007)

	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

5% initial station coverage in each city to assure fuel availability for consumers ("chicken and egg" problem)

Infrastructure Model Finds Lowest Cost H2 Supply in each of 73 US Cities (NRC 2008)



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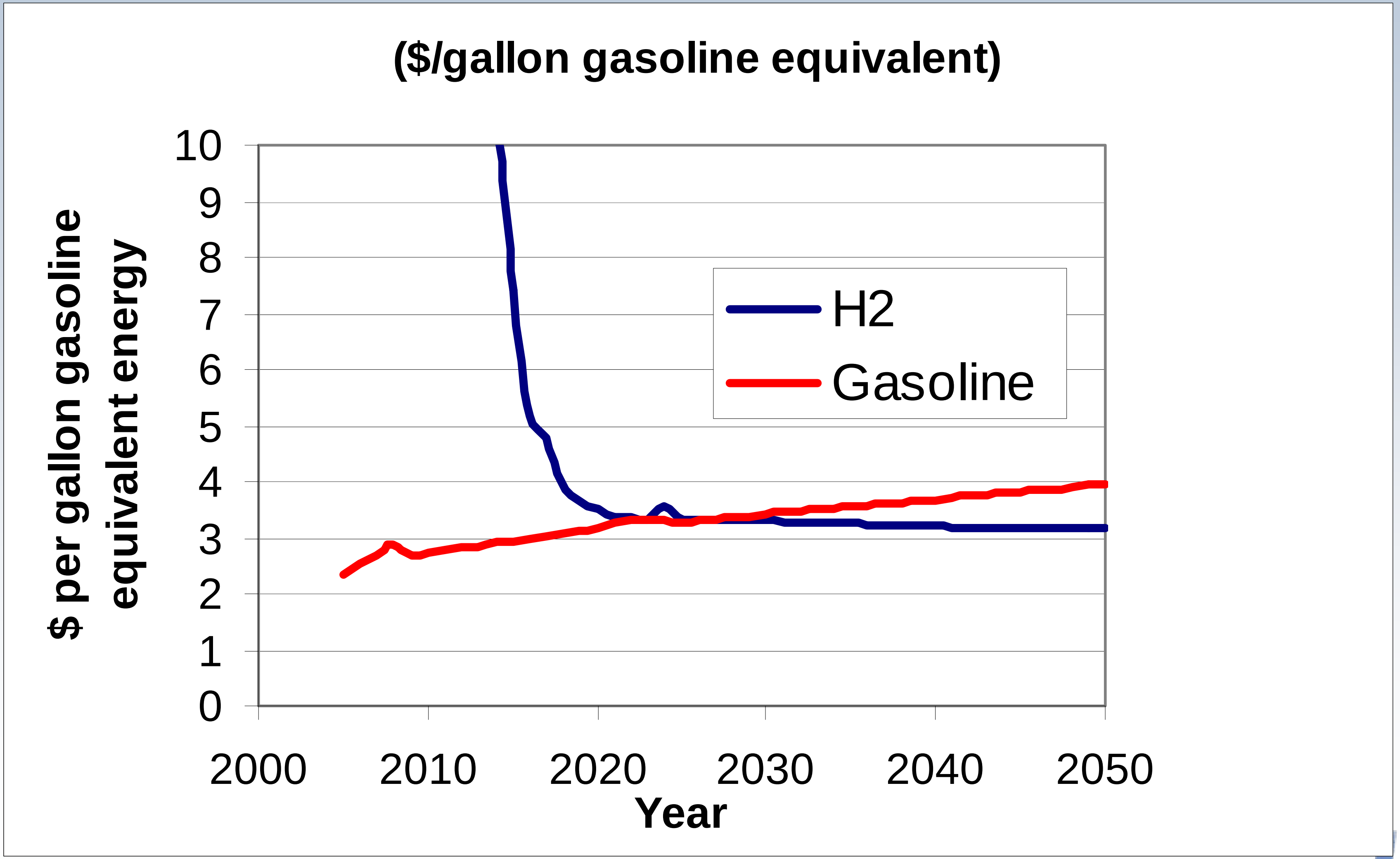
US Average Delivered H2 Cost and Gasoline price (NRC 2008)



Hydrogen Transition Modeling

- **What are investment costs for H2 fuel cell vehicles to reach cost competitiveness with reference gasoline vehicle?**

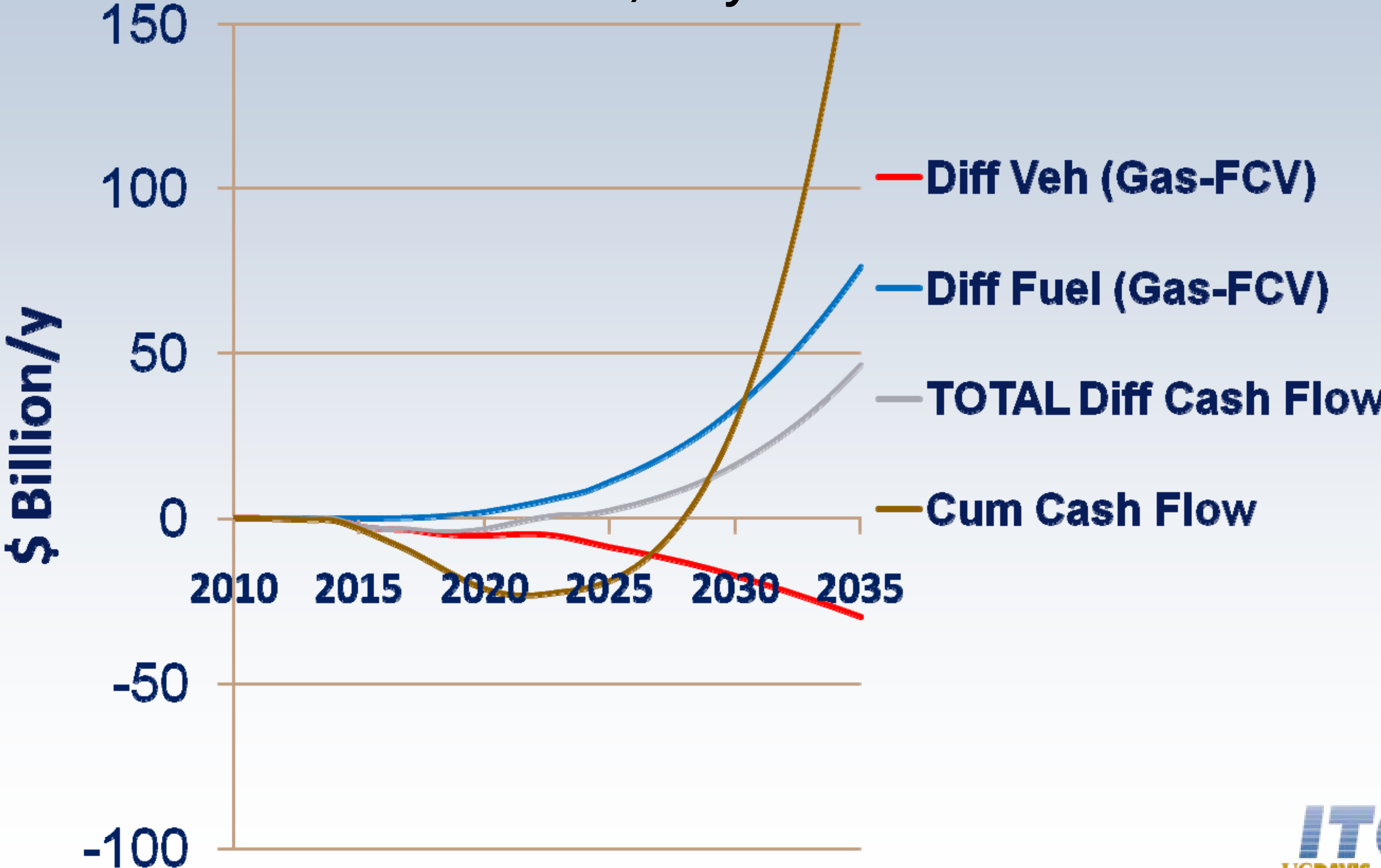
- **Conduct cash flow analysis to see when strategy of introducing H2 FCVs *breaks even* with BAU (staying with gasoline ref vehicle).**

- **Consider *cost differences* (gasoline-H2) $/y**
    - **first costs for vehicles**
    - **fuel costs**

H2 Transition Cash Flow Analysis

(H2 Success case NRC 2008)

Breakeven Year = 2023; Buydown Cost = $22 Billion



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H2 Transition Timing and Costs (NRC 2008)

Breakeven Year (Annual Cash flow = 0)	2023
Cumulative cash flow difference (H2 FCV - Gasoline ref Car) to breakeven year	$22 Billion
Cumulative vehicle first cost difference (H2 FCVs-Gasoline Ref Car) to breakeven year	$40 Billion
# H2 FCVs cars at breakeven year (millions)	5.6 (1.9% of fleet)
H2 cost at breakeven year	$3.3/kg
H2 demand, # H2 stations at breakeven year	4200 t/d 3600 stations
Total cost to build infrastructure for demand at breakeven year	$8 Billion

H2 FCVs break even within about 10 years. Vehicle costs dominate.

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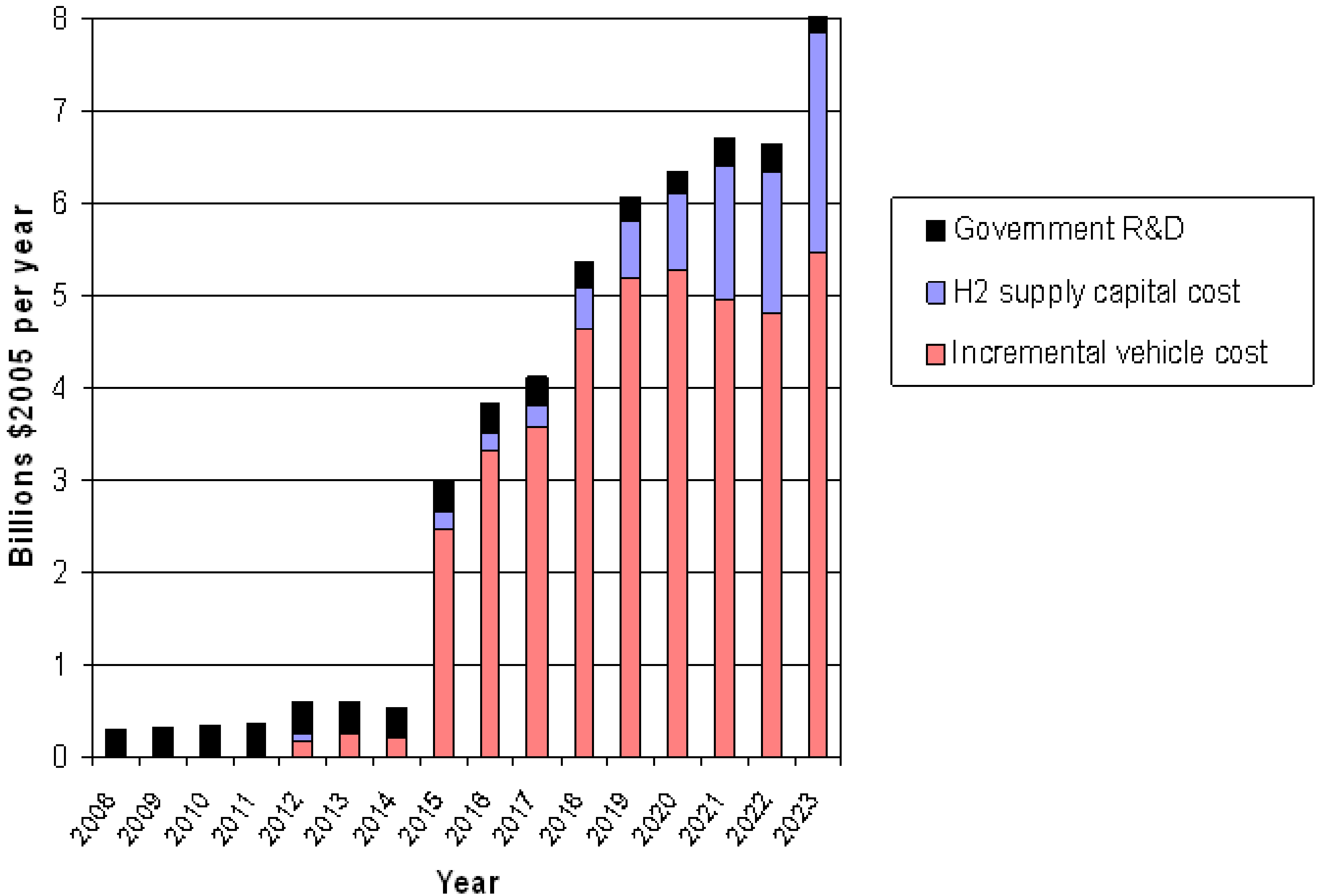
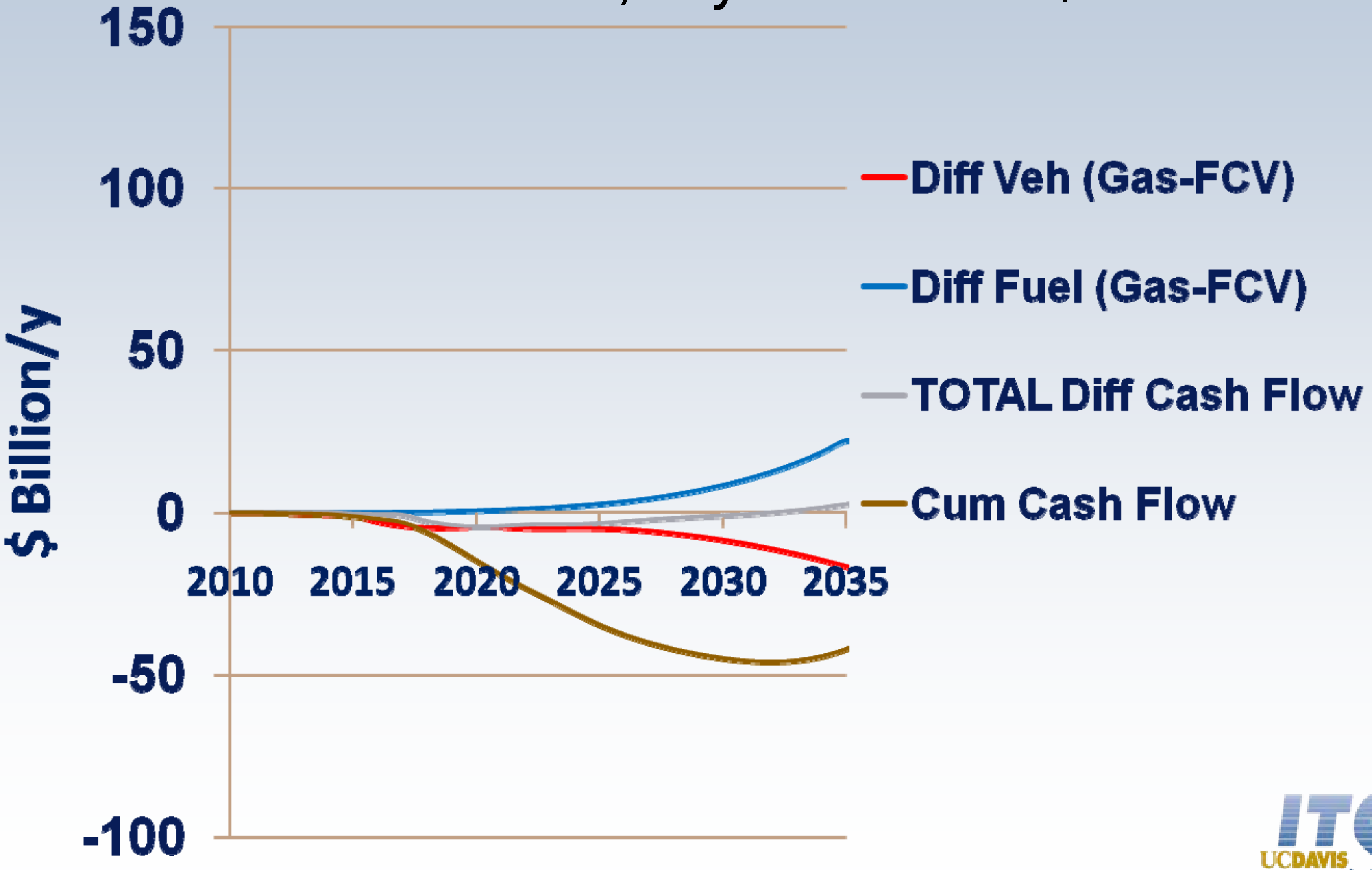
Expenditures to bring H2 FCVs to competitiveness ~$55B (NRC 2008)



H2 Transition Cash Flow Analysis (NRC 2008

H2 Partial Success:FCV introduced later, at slower rate, higher cost)

Breakeven Year = 2033; Buydown Cost = $46 Billion

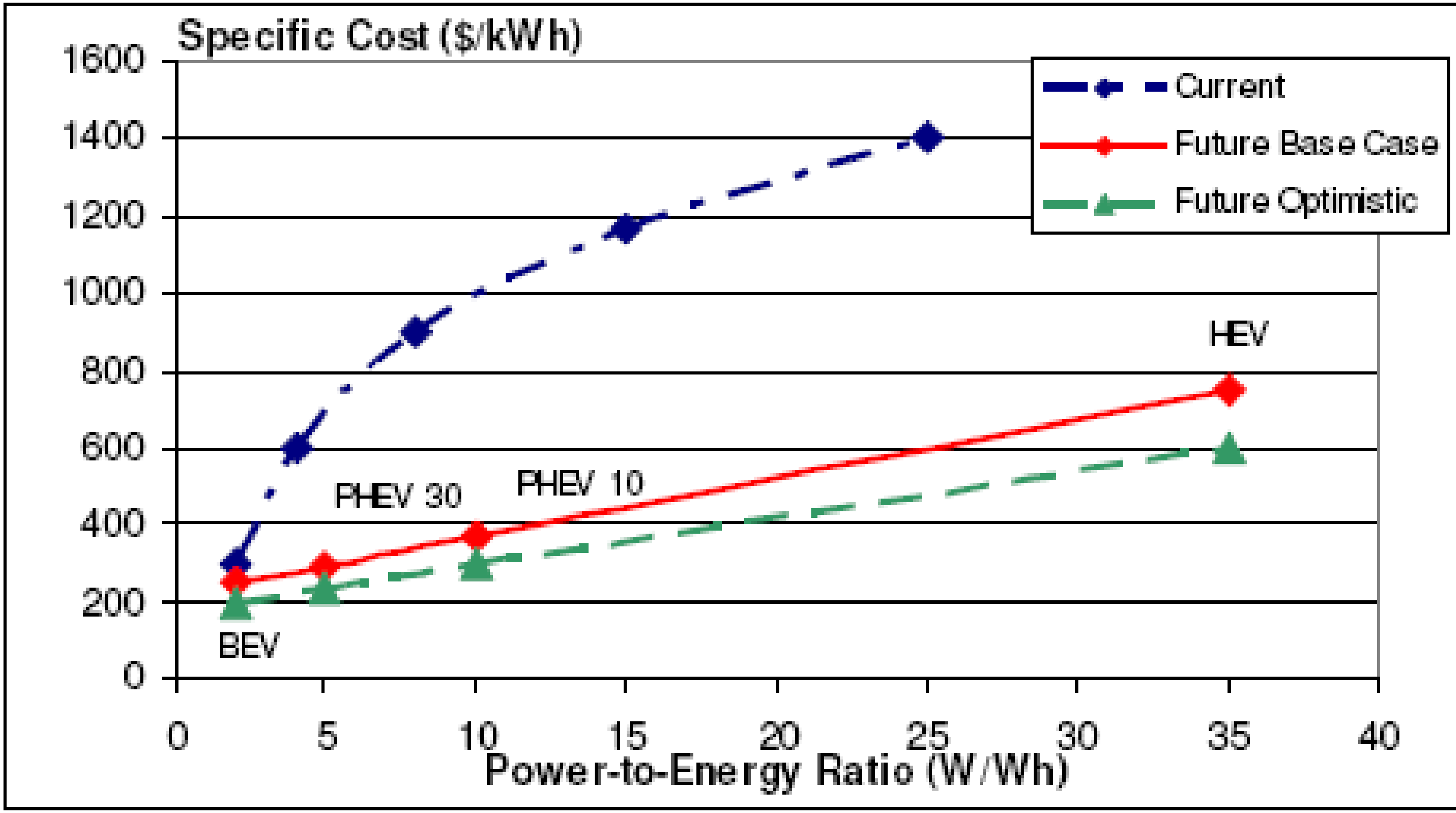


Case 5: PHEV Success

- Introduce PHEVs at the same rate as H2 FCVs, but start earlier (2010).
  - 1 million PHEVs on road by 2017
  - 220 million PHEVs (60% of fleet) in 2050
- Focus on PHEV-30 (30 mile "all electric range")
- Tech. optimism.* Use MIT's c. 2030 estimates of PHEV-30 battery and vehicle characteristics

* Kromer and Heywood, 2007. PHEV-30 has a 8.2 kWh battery and uses 71 Wh/km electricity + 2.43 liters gasoline per 100 km.

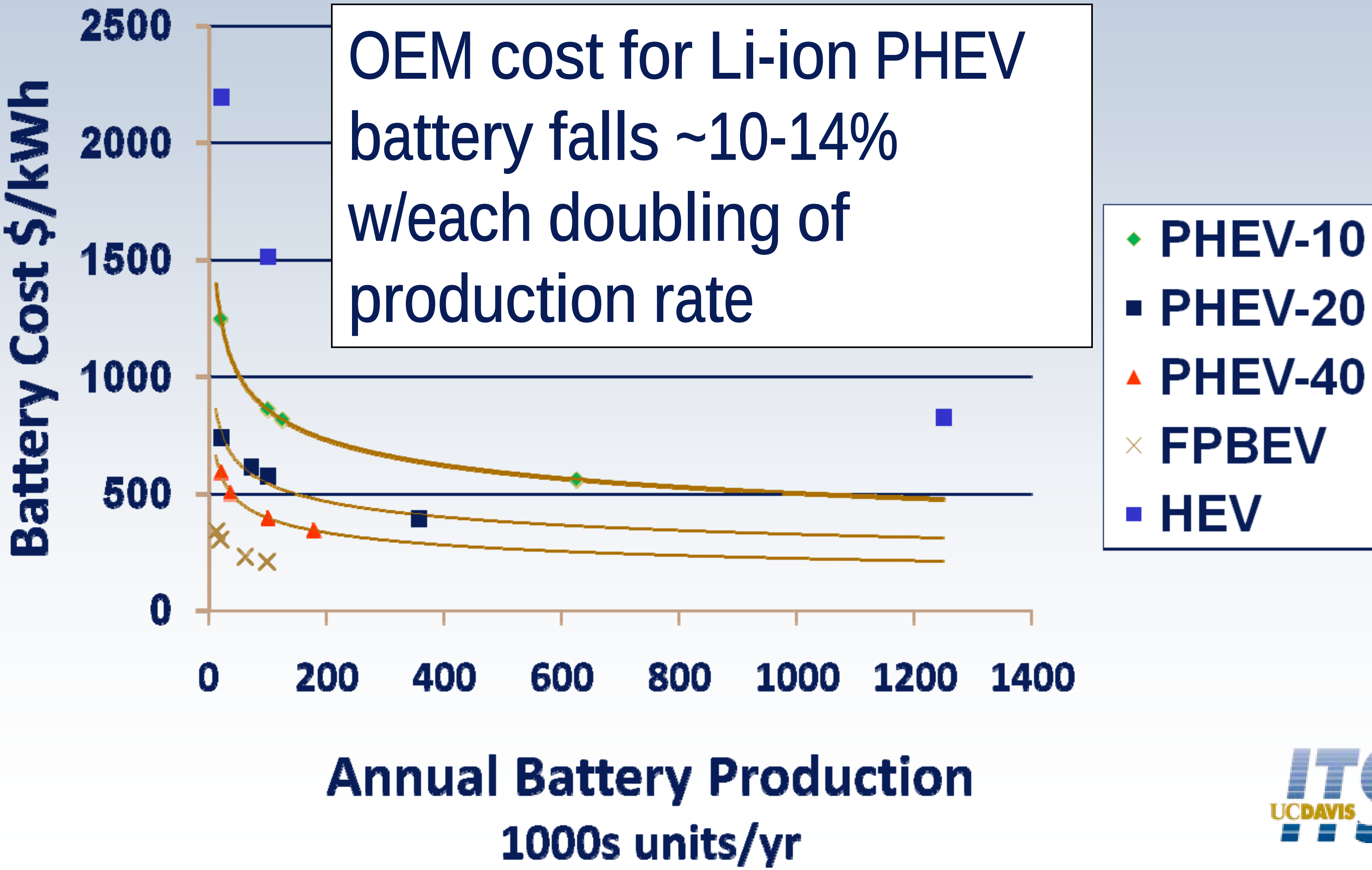
Current and Future Battery Costs (MIT)



Future PHEV Battery Cost might come down by a factor of ~3 from today's $700-1000/kWh

Li-Ion Battery OEM Cost $/kWh vs. Annual Production

(adapted from CARB ZEV Report 2007)

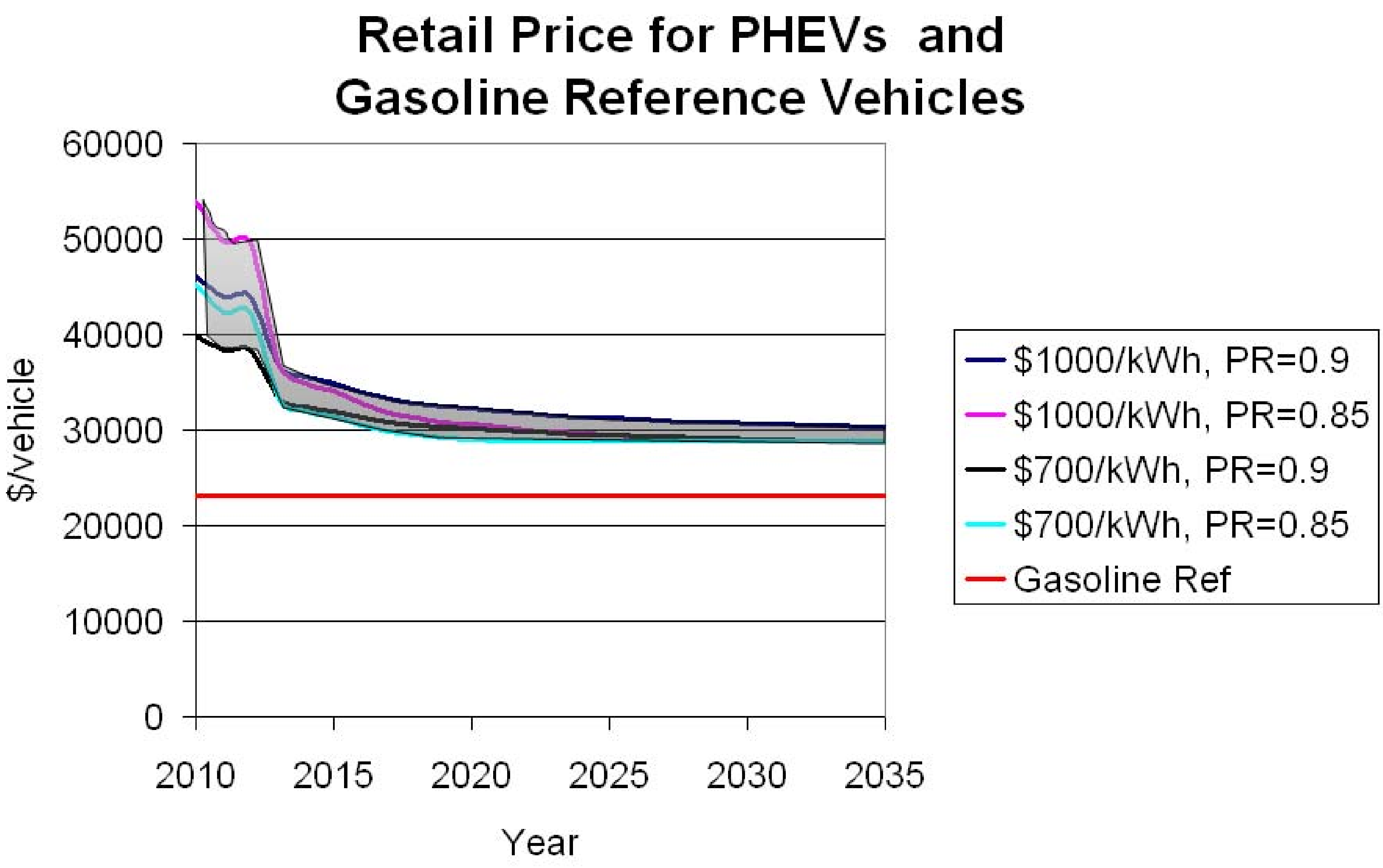


Cost assumptions for PHEVs

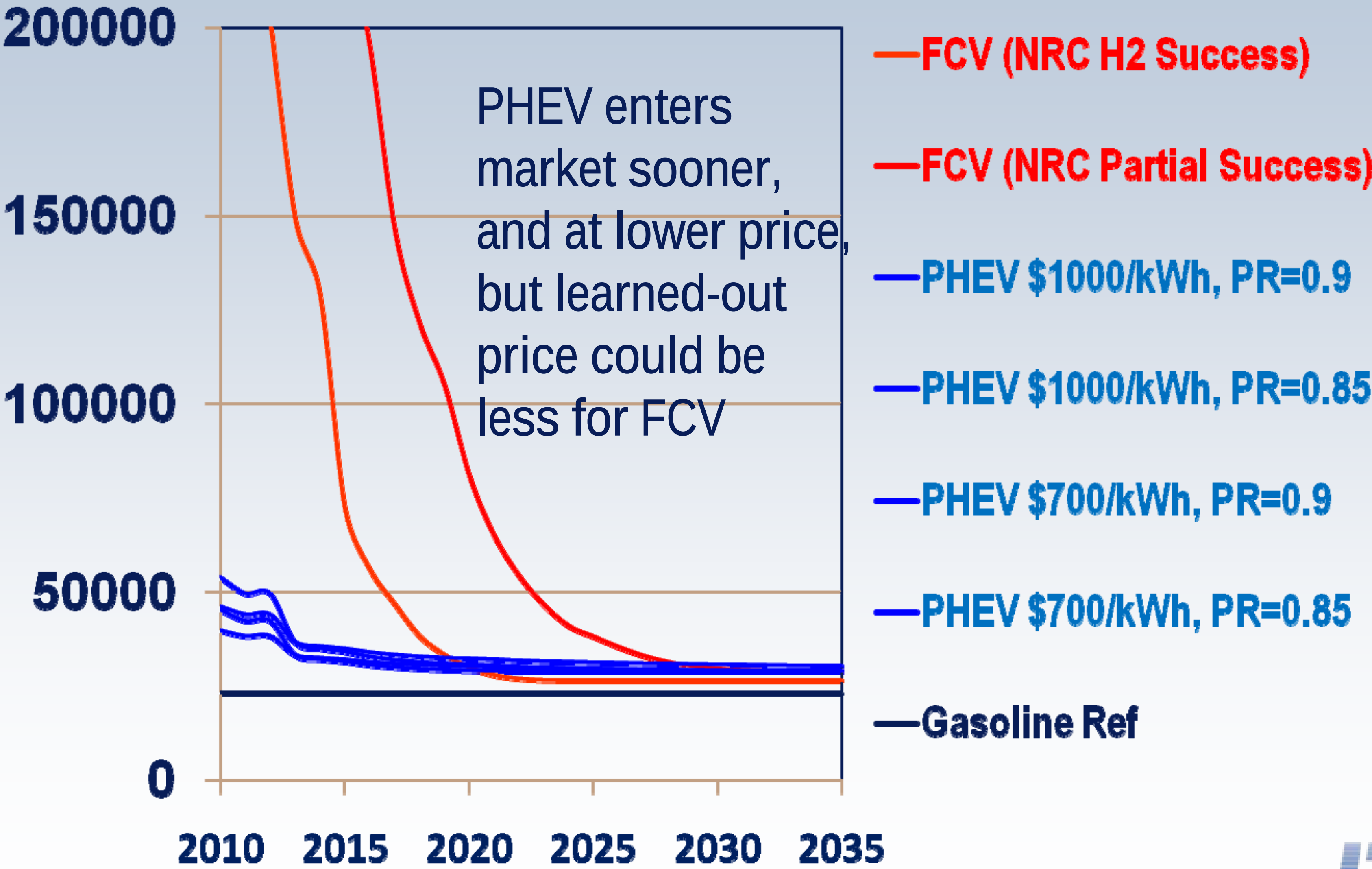
- Learned-out, mass-produced OEM battery cost \$320/kWh for PHEV-30 (8 kWh) battery
- PHEV-30 OEM battery cost \$700-1000/kWh, @50,000 units/yr
- Battery cost falls at rate of 10-15% for each doubling of production rate
- Estimate incremental vehicle cost for PHEV-30 vs. adv. gasoline ICEV, for evolving battery costs (use MIT veh modeling).
- Retail price = 1.4 x OEM manufacturing cost
- Electricity price for charging=6 cents/kWh (~\$2/gge)

PHEV-30 Retail Price vs. time

OEM Batt. Cost @50k units/y = $700-1000/kWh, progress ratio = 85-90%



Vehicle Buydown for FCVs and PHEVs ($/veh)



PHEV Infrastructure Cost (DOE 2008)

IN-HOME CHARGING COSTS (NOT = ZERO)

- EV charging cord
- Residential Circuit upgrades
- Installation, Labor, Permits, administrative costs

Level 1: $800-900/car

Level 2: $1500-2100/car

SYSTEM COSTS ARE NOT INCLUDED IN OUR ESTIMATE

- Elec. Transmission and Distribution system upgrades
- Generation additions
- (Credits for system benefits with PHEVs?)

In-home Infrastructure costs are not zero for PHEVs, esp. for large battery PHEVs, fast charge

Level 1: $800-900/car
Level 2: $1500-2100/car

(DOE, 2008)

Table 6-1. Infrastructure costs for Level 1 residential charging.

Level 1 Residential	Labor	Material	Permits	Total
EVSE (charge cord)	- -	$250	- -	$250
Residential circuit installation (20A branch circuit, 120 VAC/1-Phase)	$300	$131	$85	$516
Administration costs	$60	$43	$9	$112
Total Level 1 Cost	$360	$4 24	$94	$878

Table 6-2. Infrastructure costs for Level 2 residential charging.

Level 2 Residential	Labor	Material	Permits	Total
EVSE (32 A wall box)	- -	$650	- -	$650
EVSE (charge cord)	- -	$200	- -	$200
Residential circuit installation(40A branch circuit, 240 VAC/1-Phase)	$455	$470	$155	$1,080
Administration costs	$91	$94	$31	$216
Total Level 2 Cost	$546	$1,414	$186	$2,146

Table 6-3. Infrastructure costs for Level 1 apartment complex charging.

Level 1 Apartment	Labor	Material	Permits	Signage	Total
EVSE (five charge cords)	- -	$1,250	- -	- -	$1,250
Apartment complex circuit installation (five, 20A branch circuits, 120 VAC/1-Phase with separate meter and breaker panel)	$1,200	$516	$155	$350	$2,221
Administration costs	$240	$353	$31	$70	$694
Total Level 1 Cost	$1,440	$2,119	$186	$420	$4,165
Total per Charger Cost	$288	$424	$37	$84	$833

Table 6-4. Infrastructure costs for Level 2 apartment complex charging.

Level 2 Apartment	Labor	Material	Permits	Signage	Total
EVSE (five 32A wall boxes)	- -	$3,250	- -	- -	$3,250
EVSE (five charge cords)	- -	$1,000	- -	- -	$1,000
Apartment complex circuit installation (five, 40A branch circuits, 240 VAC/1-Phase with separate breaker panel)	$1,400	$696	$165	$350	$2,611
Administration costs	$280	$353	$33	$70	$736
Total Level 2 Cost	$1,680	$5,299	$198	$420	$7,597
Total per Charger Cost	$336	$1,060	$40	$84	$1,520

PHEV Transition Modeling

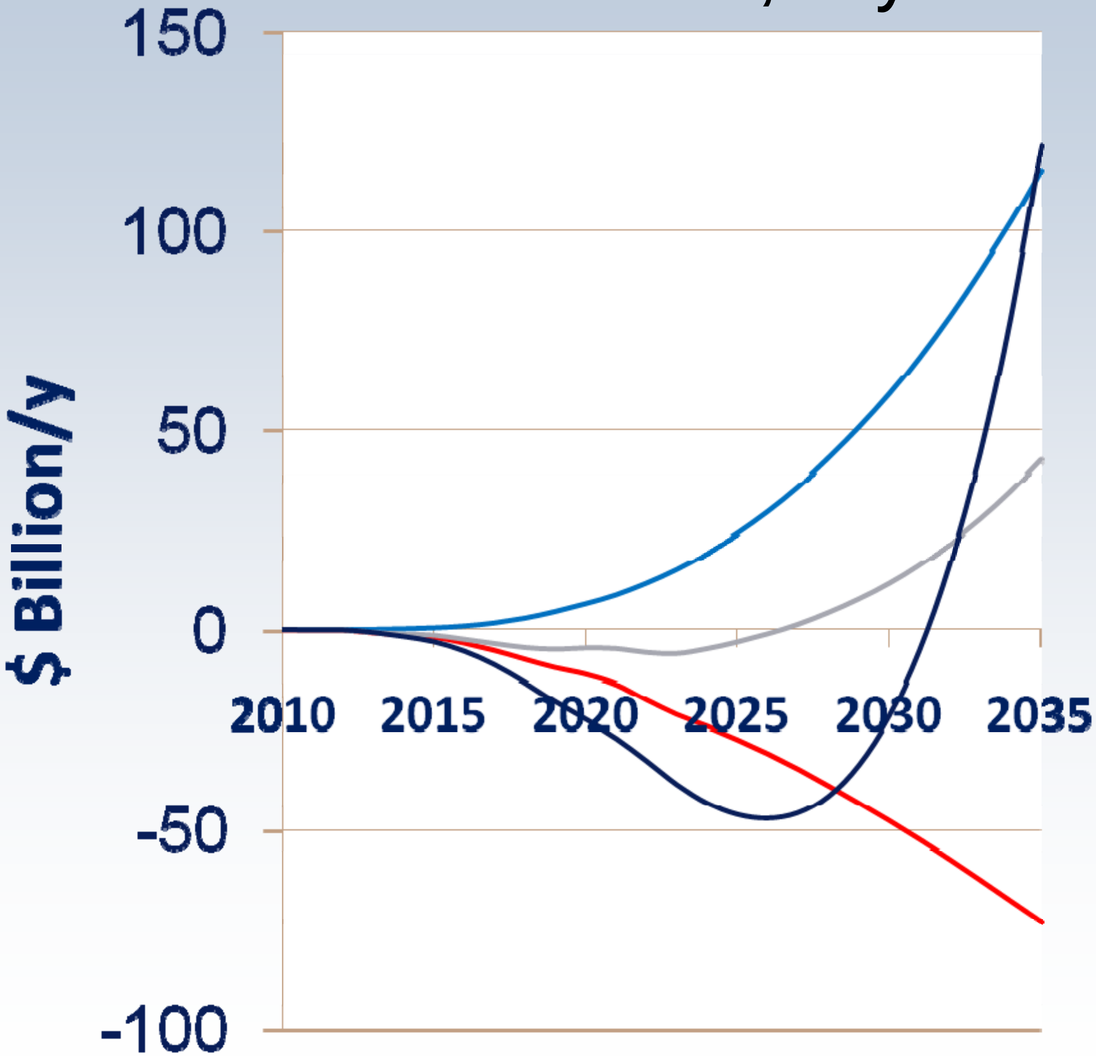
- **What are investment costs for PHEV vehicles to reach cost competitiveness with reference gasoline vehicle?**

- **Conduct cash flow analysis to see when strategy of introducing PHEV *breaks even* with BAU (staying with gasoline ref vehicle).**

- **Consider *cost differences* (gasoline-PHEV) $/y**
    - **first costs for vehicles**
    - **fuel costs**

PHEV Transition Cash Flow Analysis

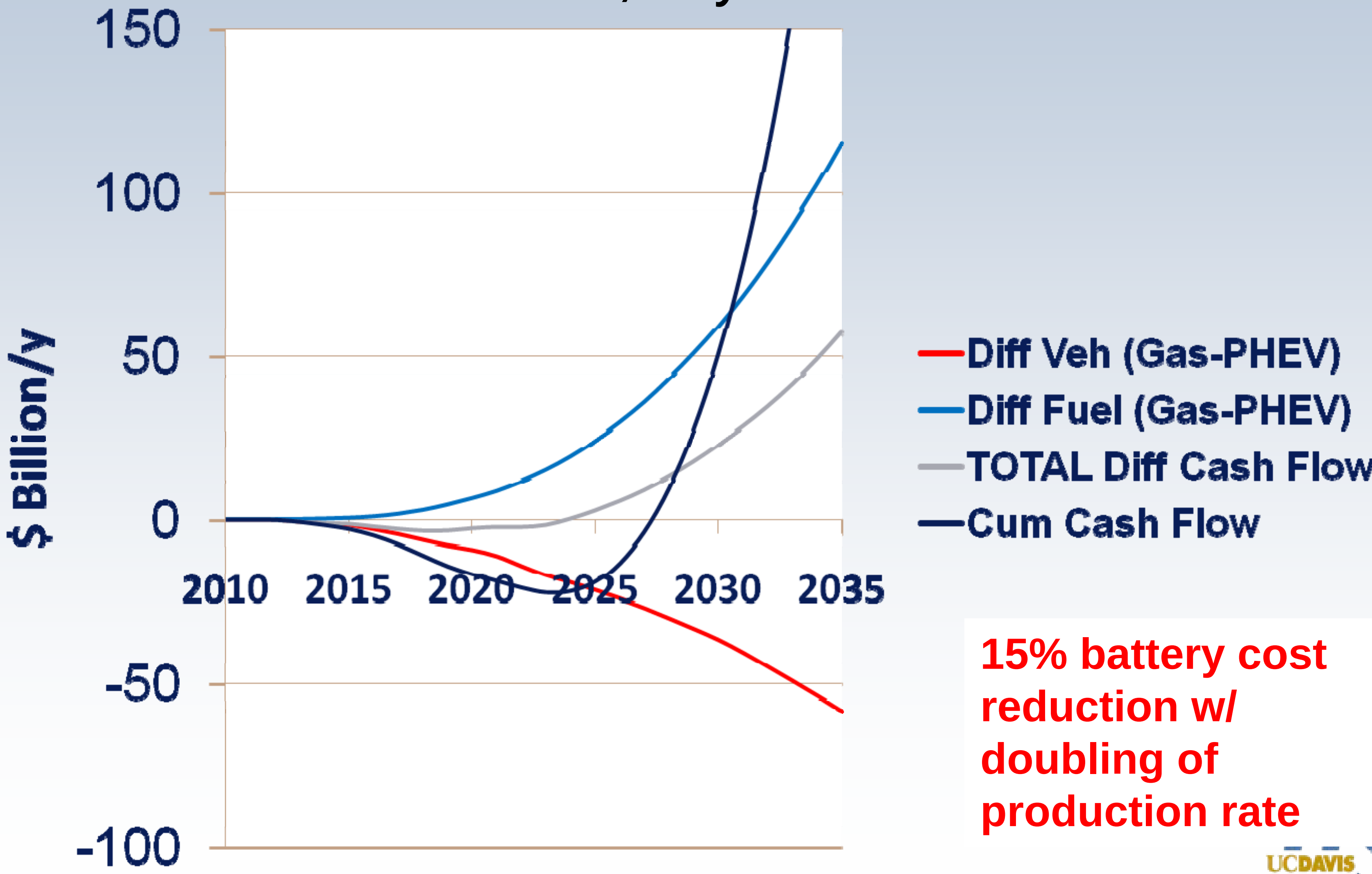
Breakeven Year = 2026; Buydown Cost = $47 Billion



10% battery cost reduction w/ doubling of production rate

PHEV Transition Cash Flow Analysis

Breakeven Year = 2023; Buydown Cost = $22 Billion



15% battery cost reduction w/ doubling of production rate

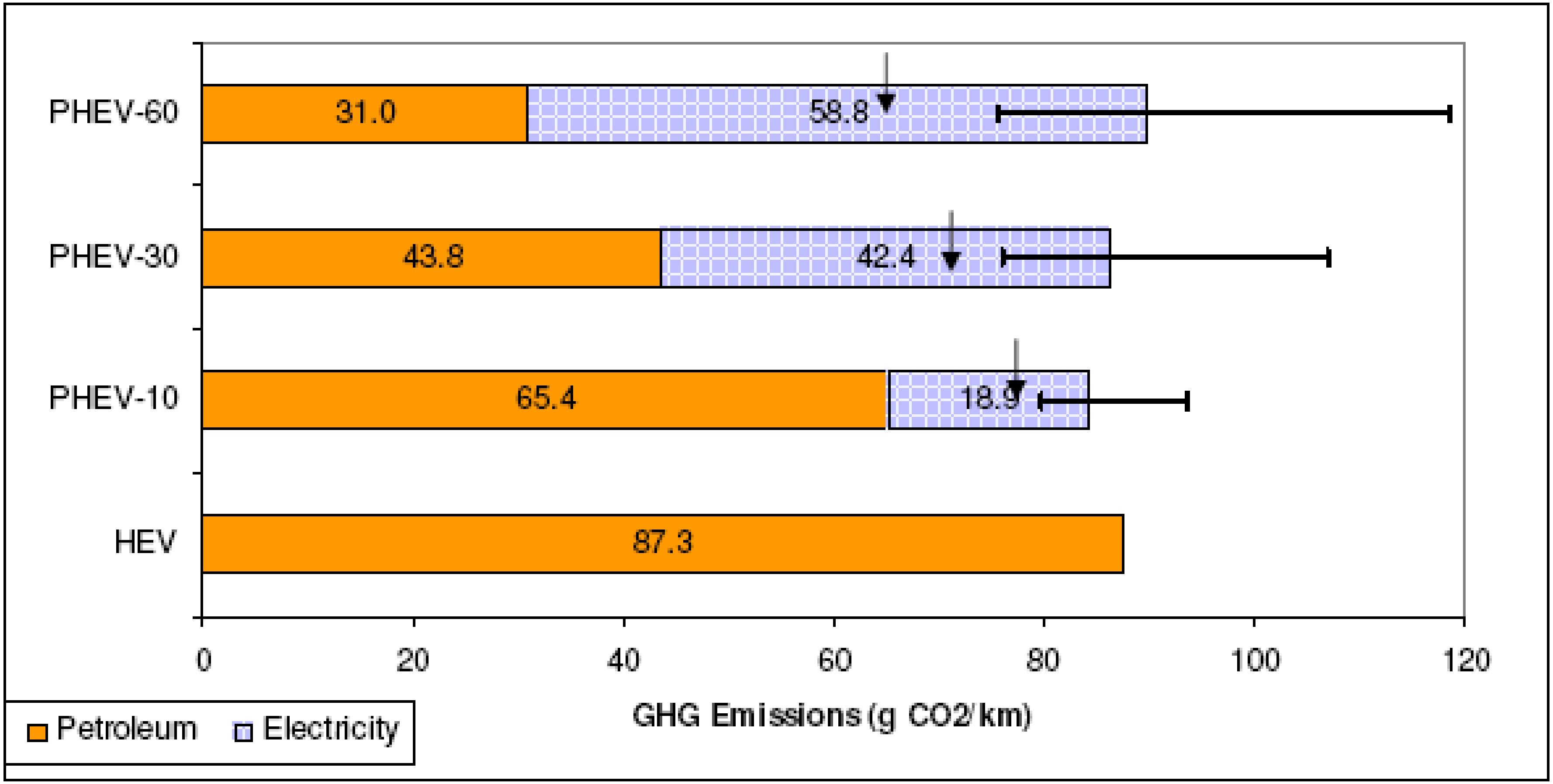
Sensitivity Study: PHEV Transition Timing & Costs

Battery OEM cost @50K unit/y; progress ratio	$1000/kWh PR=0.85	$1000/kWh PR=0.9	$700/kWh PR=0.85	$700/kWh PR=0.9
Breakeven Year (Annual Cash flow = 0)	2023	2026	2020	2023
Cumulative cash flow difference (PHEV-Gasoline ref Car) to breakeven year	$22 Billion	$47 Billion	$9 Billion	$17 Billion
Cumulative vehicle retail price difference (PHEVs-Gasoline Ref Car) to breakeven year	$75 Billion	$174 Billion	$26 Billion	$70 Billion
# PHEV cars at breakeven year (millions)	10 (4% of fleet)	20	4	10
Total cost in-home charging infrastructure for demand at breakeven yr	$8-20 Billion ($800-2000/car)	$16-40 Billion	$3-8 Billion	$8-20 Billion

Transition Timing & Cost Range: FCVs and PHEVs

	PHEV OEM Battery Cost $700-1000/kWh @ 50k/yr, PR=85-90% Fast ramp up 1(10) million PHEVs in 2017 (2023)	**FCV** NRC 2008) (FC sys=$50-75/kW; H2 storage = $10-15/kWh fast vs. slow ramp-up 2-10 million FCVs in 2025
Breakeven Year (Annual Cash flow = 0)	2020-2026	2023-2032
Cum cash flow difference (AFV- Gasoline ref Car) to breakeven year	$9-47 Billion	$22-47 Billion
Cumulative vehicle retail price difference (AFVs-Gasoline Ref Car) to breakeven year	$26-174 Billion $7000-9000/car	$40-91 Billion $7000-9000/car
# cars at breakeven yr (millions)	4-20	5.6-10
Total ***capital cost of infrastructure*** for demand at breakeven yr	$3-40 Billion ($800-2000/car for residential charging)	$8-19 Billion ($1400-2000/car for full infrastructure)

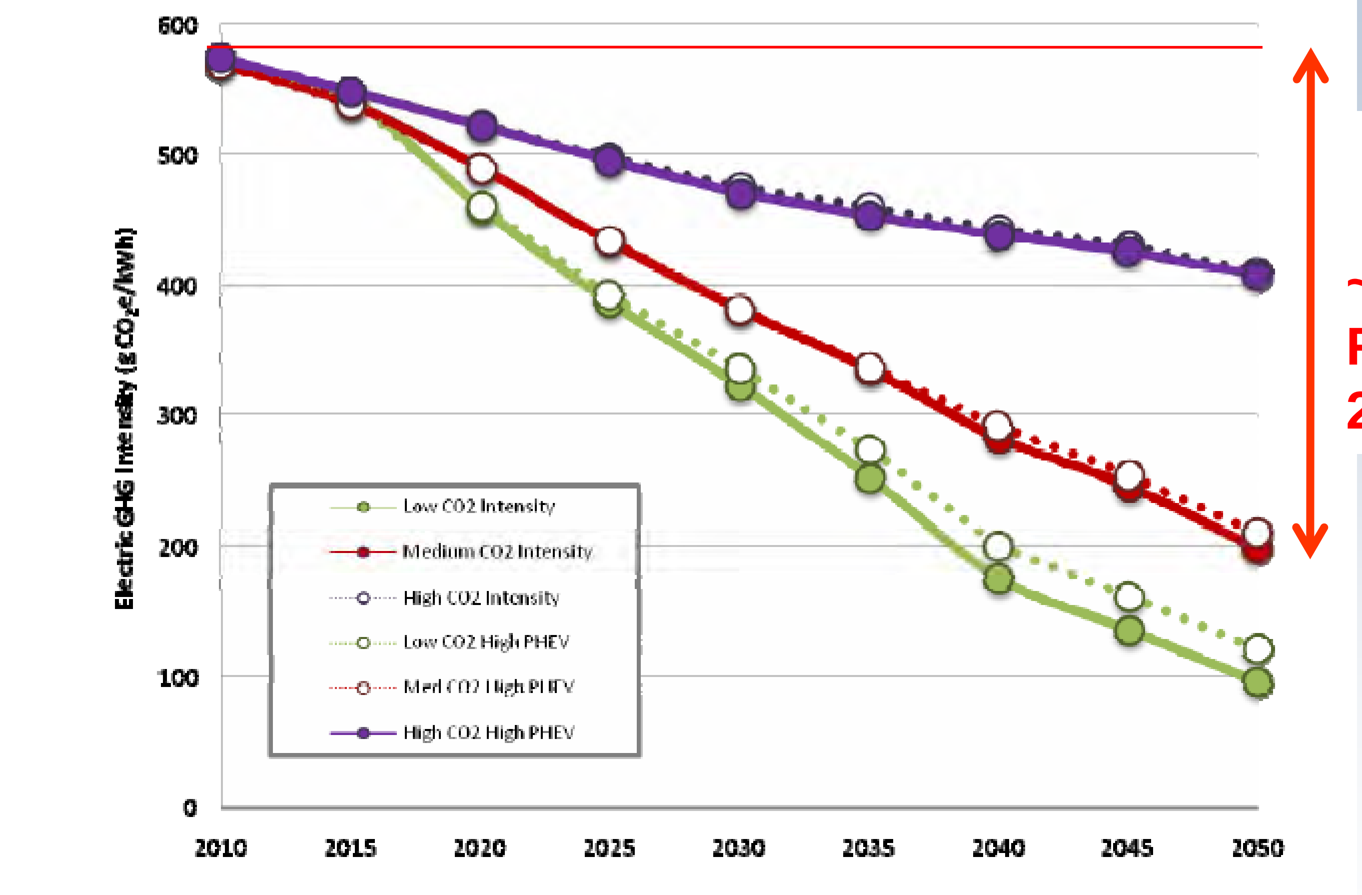
GHG benefits of PHEVs depend on grid mix
(PHEVs~ HEVs for current US grid) (MIT).



NG ├──┤ **Coal**

GHG emissions Intensity for Future Low-C Grid

(gCO_2eq/kWh) (EPRI/NRDC)



~2/3 GHG Reduction 2010-> 2050

FUTURE GRID: Coal IGCC w/CCS, New Biomass, New Nuclear, Adv. Renewables

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EPRI/NRDC PHEV Study Scenarios for Future Low-C Grid

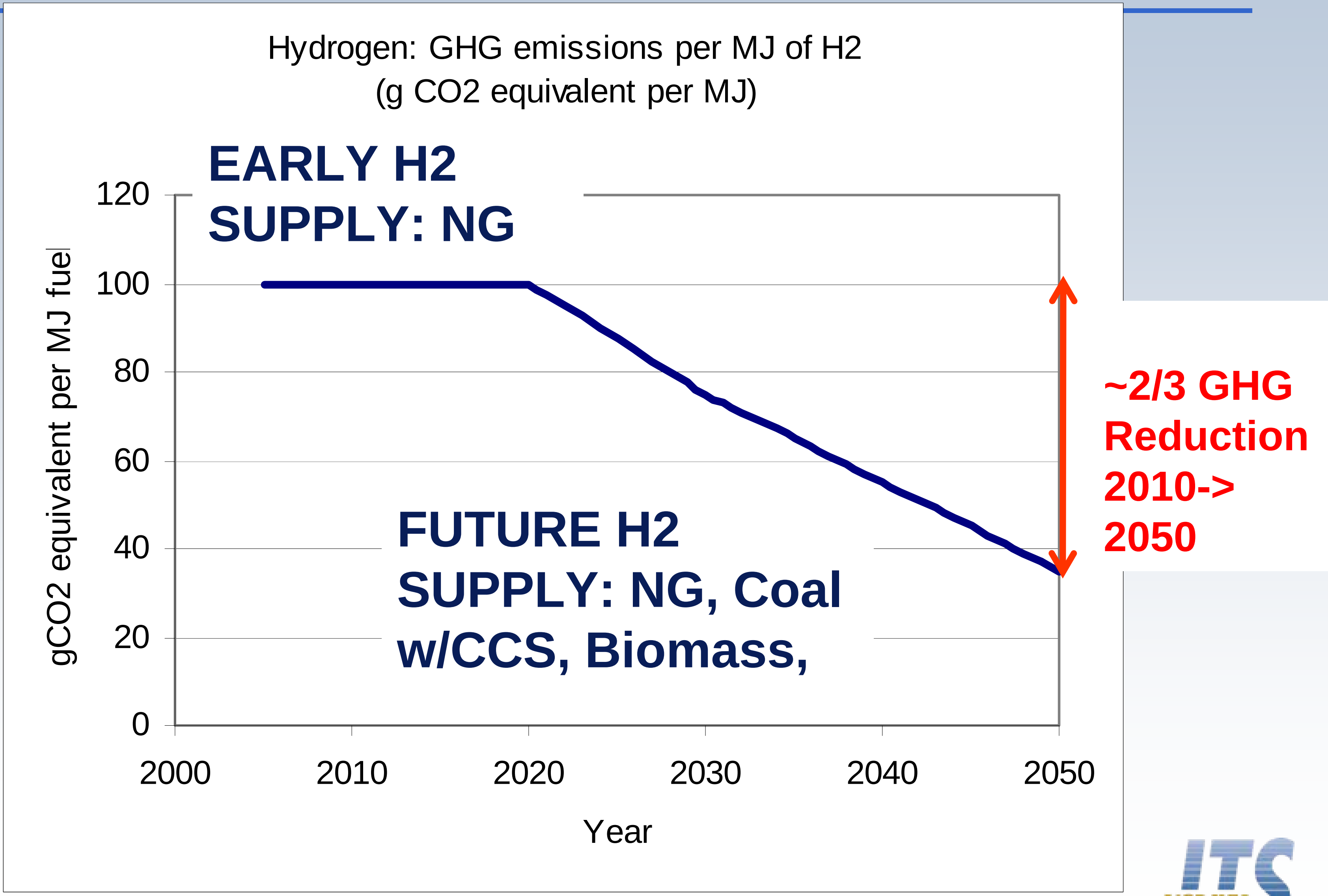
Key parameters of the High, Medium, and Low CO_2 Intensity electric scenarios.

Scenario Definition	High CO_2 Intensity	Medium CO_2 Intensity	Low CO_2 Intensity
Price of Greenhouse Gas Emission Allowances	Low	Moderate	High
Power Plant Retirements	Slower	Normal	Faster
New Generation Technologies	Unavailable: Coal with CCS New Nuclear New Biomass	Available: IGCC Coal with CCS New Nuclear New Biomass Advanced Renewables	Available: Retrofit of CCS to Existing IGCC and PC Plants
	Lower Performance: SCPC, CCNG, GT, Wind, and Solar	Nominal EPRI Performance Assumptions	Higher Performance: Wind and Solar
Annual Electricity Demand Growth	1.56% per year on average	1.56% per year on average	2010-2025: 0.45% 2025-2050: None

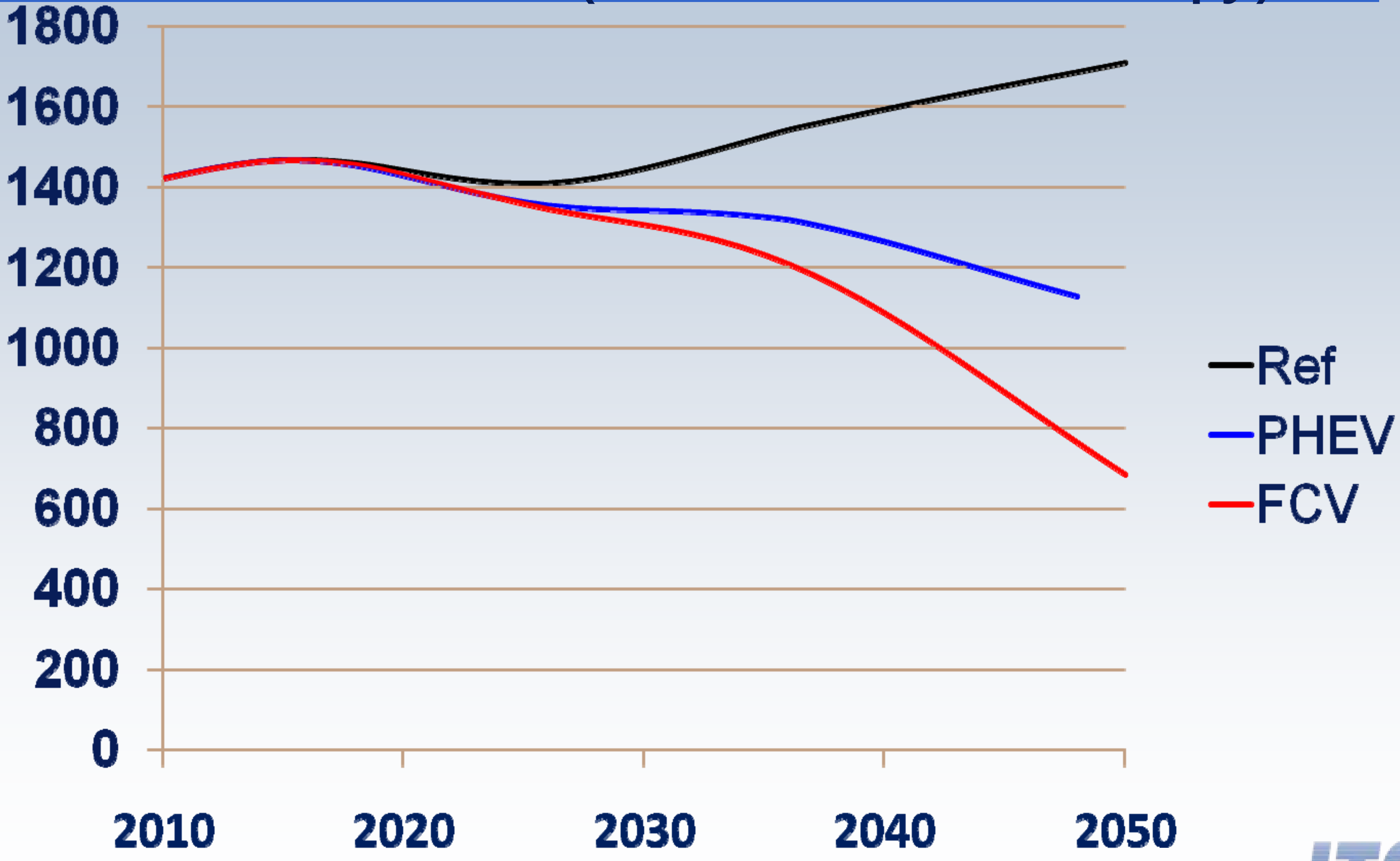
PC – Pulverized Coal
SCPC – Supercritical Pulverized Coal
CCNG – Combined Cycle Natural Gas
GT – Gas Turbine (Natural Gas)
CCS – Carbon Capture and Storage

NRC H_2 Scenario: GHG Emissions Intensity

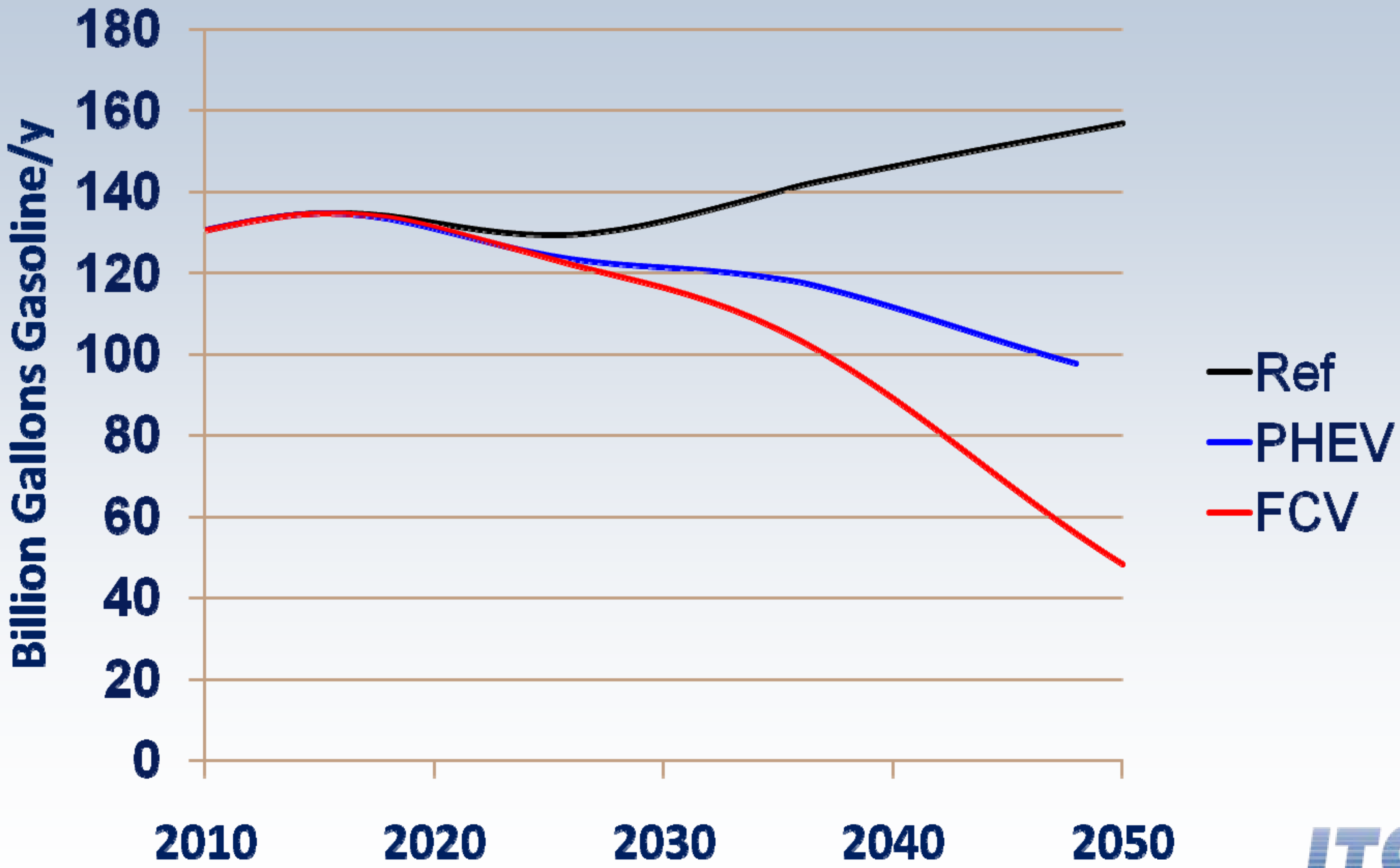
gCO_2/MJ H_2 (NRC 2008)



COMPARISON OF PHEV and FCV SCENARIOS: GHG Emissions(Million tonne CO2eq/y)

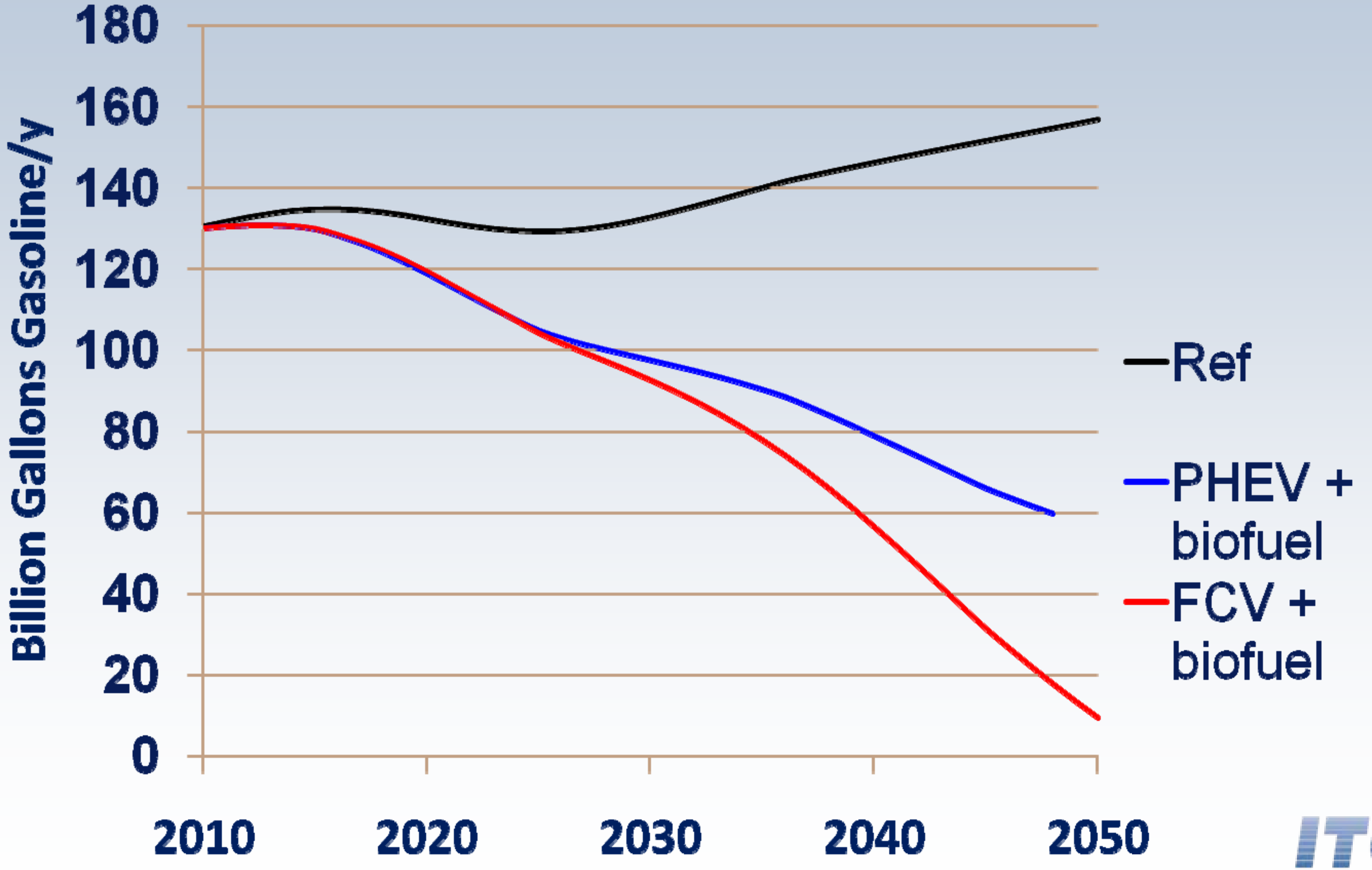


COMPARISON OF PHEV and FCV SCENARIOS: Oil Use (Billion gal/y)



What if we replace gasoline w/ low-C biofuels?

~35 B gal/yr by 2022; ~75 B gal/y by 2050 (NRC Case 3)



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Societal Benefits PHEVs and FCV

- PHEV GHG benefit depends on grid mix.
  - Ave. PHEV benefit small vs. HEV for marginal US grid
- H2 FCV GHG benefit depends on H2 supply mix
  - wtw GHG emissions for H2 FCVs $\leq$ HEVs (H2 from NG)
- GHG and oil reductions for PHEVs and FCVs small before 2025 because of time needed for vehicles to penetrate market.
- Long term GHG and oil use reductions are significantly greater with FCVs than PHEVs for similar level of energy supply de-carbonization

Conclusions (1)

- Transition costs, timing to “breakeven year” are similar for FCVs and PHEVs (10s of Billions of dollars total, spent over 10-15 period)
  - This is less than current corn ethanol subsidy of ~$10 B/yr.
- Majority of transition cost is for vehicle buydown ($\geq$80%).
  - Ave. price subsidy needed for FCVs and PHEVs over 10-15 transition period is similar ~$7000-9000/car.
- Critical vehicle technologies w.r.t. transition cost:
  - FCV: FC, H2 storage
  - PHEV: Adv. Battery

Conclusions (2)

- Infrastructure costs are not zero for PHEVs ($800-2000/car for residential charging)
- Total infrastructure capital costs to "breakeven" year are same order of magnitude for PHEVs and FCVs, although early infrastructure logistics are less much complex with PHEVs.
- Long term societal benefits greater with FCVs vs. PHEVs, **for a given level of decarbonized energy supply**.
- Both could be part of a portfolio of approaches leading toward electric drive light duty sector.

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- For useful conversations and feedback
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  - Dr. Tom Turrentine, UC Davis
  - Dr. David Greene, ORNL

extras

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U.S. Department of Energy Vehicle Technologies Program – Advanced Vehicle Testing Activity

Plug-in Hybrid Electric Vehicle Charging Infrastructure Review

Final Report
Battelle Energy Alliance
Contract No. 58517

Kevin Morrow
Donald Karner
James Francfort

November 2008

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EPRI/NRDC 2007

ELECTRIC POWER RESEARCH INSTITUTE

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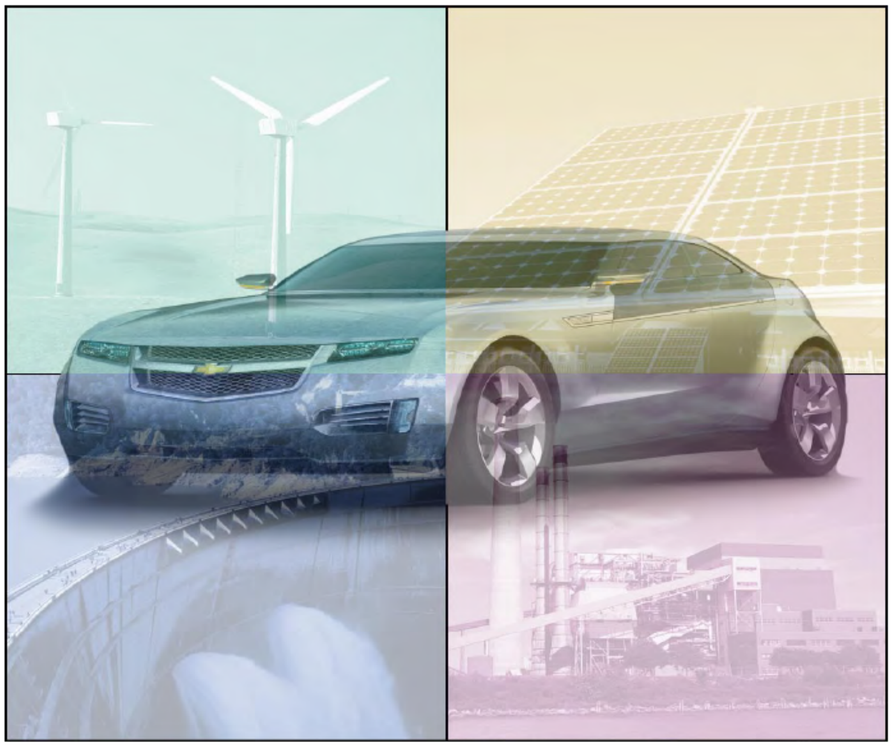
THE EARTH'S BEST DEFENSE

Environmental Assessment of Plug-In Hybrid Electric Vehicles

Volume 1: Nationwide Greenhouse Gas Emissions



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MIT 2007

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Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet

Matthew A. Kromer and John B. Heywood

May 2007
LFEE 2007-02 RP

Sloan Automotive Laboratory
Laboratory for Energy and the Environment
Massachusetts Institute of Technology
77 Massachusetts Avenue,
Cambridge, MA 02139

Publication No. LFEE 2007-02 RP

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CARB/ZEV Panel Report 2007

Status and Prospects for Zero Emissions Vehicle Technology

Report of the ARB Independent Expert Panel 2007

Prepared for
State of California Air Resources Board
Sacramento, California

By

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Bruce M. Kopf
David H. Swan
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April 13, 2007