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

Prof. Joan Ogden
University of California, Davis
jmogden@ucdavis.edu

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Hartford, CT
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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.
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)

# of Light Duty Vehicles in Fleet (millions)

- Gasoline ICEV
- H2 FCV
- TOTAL

Year:
- 2000
- 2010
- 2020
- 2030
- 2040
- 2050

# Light Duty Vehicles (millions):
- 0
- 50
- 100
- 150
- 200
- 250
- 300
- 350
- 400

“Learned out”
price diff
~$3600
**Case 1: Phased Introduction of H2 FCVs in “Lighthouse” Cities (USDOE 2007)**

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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)

Hydrogen Cost in Selected Cities

Levelized Cost of H2 ($/kWh, $2005)

Los Angeles, California
Miami, Florida
Denver, Colorado
Washington DC
Albuquerque, New Mexico
New York, New York
Dallas, Texas
Atlanta Georgia

Levelized Cost of H2 (kg, $2005$/)

2 3 4 5 6 7 8
US Average Delivered H2 Cost and Gasoline price (NRC 2008)

($/gallon gasoline equivalent)

$ per gallon gasoline equivalent energy

2000 2010 2020 2030 2040 2050

Year

H2

Gasoline
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

- Diff Veh (Gas-FCV)
- Diff Fuel (Gas-FCV)
- TOTAL Diff Cash Flow
- Cum Cash Flow

Year:
- 2010
- 2015
- 2020
- 2025
- 2030
- 2035

$ Billion/y:
- 150
- 100
- 50
- 0
- -50
- -100
## H2 Transition Timing and Costs (NRC 2008)

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

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

OEM cost for Li-ion PHEV battery falls ~10-14% w/each doubling of production rate.
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%

Retail Price for PHEVs and Gasoline Reference Vehicles

Year

$/Vehicle

2010 2015 2020 2025 2030 2035

$1000/kWh, PR=0.9
$1000/kWh, PR=0.85
$700/kWh, PR=0.9
$700/kWh, PR=0.85
Gasoline Ref
Vehicle Buydown for FCVs and PHEVs ($/veh)

PHEV enters market sooner, and at lower price, but learned-out price could be less for FCV.
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)

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<th>Table 6-1. Infrastructure costs for Level 1 residential charging.</th>
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<tr>
<td><strong>Level 1 Residential</strong></td>
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<td>EVSE (charge cord)</td>
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<tr>
<td>Residential circuit installation (20A branch circuit, 120 VAC/1-Phase)</td>
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<tr>
<td>Administration costs</td>
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<tr>
<td><strong>Total Level 1 Cost</strong></td>
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<th>Table 6-2. Infrastructure costs for Level 2 residential charging.</th>
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<td><strong>Level 2 Residential</strong></td>
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<td>EVSE (32 A wall box)</td>
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<td>EVSE (charge cord)</td>
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<tr>
<td>Residential circuit installation (40A branch circuit, 240 VAC/1-Phase)</td>
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<td>Administration costs</td>
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<td><strong>Total Level 2 Cost</strong></td>
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<th>Table 6-3. Infrastructure costs for Level 1 apartment complex charging.</th>
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<td><strong>Level 1 Apartment</strong></td>
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<td>EVSE (five charge cords)</td>
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<tr>
<td>Apartment complex circuit installation (five, 20A branch circuits, 120 VAC/1-Phase with separate meter and breaker panel)</td>
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<tr>
<td>Administration costs</td>
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<tr>
<td><strong>Total Level 1 Cost</strong></td>
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<td><strong>Total per Charger Cost</strong></td>
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<th>Table 6-4. Infrastructure costs for Level 2 apartment complex charging.</th>
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<td><strong>Level 2 Apartment</strong></td>
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<td>EVSE (five 32A wall boxes)</td>
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<td>EVSE (five charge cords)</td>
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<tr>
<td>Apartment complex circuit installation (five, 40A branch circuits, 240 VAC/1-Phase with separate breaker panel)</td>
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<td>Administration costs</td>
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<td><strong>Total Level 2 Cost</strong></td>
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<td><strong>Total per Charger Cost</strong></td>
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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 with 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

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

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

![Graph showing GHG emissions for different vehicles.](image)

- **PHEV-60**: 31.0 (Petroleum) + 58.8 (Electricity) = 90.8
- **PHEV-30**: 43.8 (Petroleum) + 42.4 (Electricity) = 86.2
- **PHEV-10**: 65.4 (Petroleum) + 18.9 (Electricity) = 84.3
- **HEV**: 87.3 (Petroleum)

NG ——— Coal
GHG emissions Intensity for Future Low-C Grid

(\text{gCO}_2\text{eq/kWh}) \quad (\text{EPRI/NRDC})

~2/3 GHG Reduction 2010\to 2050

FUTURE GRID: Coal IGCC w/CCS, New Biomass, New Nuclear, Adv. Renewables
### Key parameters of the High, Medium, and Low CO₂ Intensity electric scenarios.

<table>
<thead>
<tr>
<th>Scenario Definition</th>
<th>High CO₂ Intensity</th>
<th>Medium CO₂ Intensity</th>
<th>Low CO₂ Intensity</th>
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<tbody>
<tr>
<td>Price of Greenhouse Gas Emission Allowances</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
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<tr>
<td>Power Plant Retirements</td>
<td>Slower</td>
<td>Normal</td>
<td>Faster</td>
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<tr>
<td>Annual Electricity Demand Growth</td>
<td>1.56% per year on average</td>
<td>1.56% per year on average</td>
<td>2010-2025: 0.45% 2025-2050: None</td>
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PC – Pulverized Coal  
SCPC – Supercritical Pulverized Coal  
CCNG – Combined Cycle Natural Gas  
GT – Gas Turbine (Natural Gas)  
CCS – Carbon Capture and Storage
NRC $\text{H}_2$ Scenario: GHG Emissions Intensity

$\text{gCO}_2$/MJ $\text{H}_2$ (NRC 2008)

Hydrogen: GHG emissions per MJ of H2
(g CO2 equivalent per MJ)

EARLY H2
SUPPLY: NG

FUTURE H2
SUPPLY: NG, Coal
w/CCS, Biomass,

~2/3 GHG Reduction 2010-> 2050
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)
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 ≤ 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 (≥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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Plug-in Hybrid Electric Vehicle Charging Infrastructure Review

Final Report
Battelle Energy Alliance
Contract No. 58517

Kevin Morrow
Donald Karner
James Francfort

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Environmental Assessment of Plug-In Hybrid Electric Vehicles

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

Matthew A. Kromer and John B. Heywood

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

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By
Fritz R. Kalhammer
Bruce M. Kopf
David H. Swan
Vernon P. Roan
Michael P. Walsh, Chairman

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