The Transition to Sustainable Energy for Transportation

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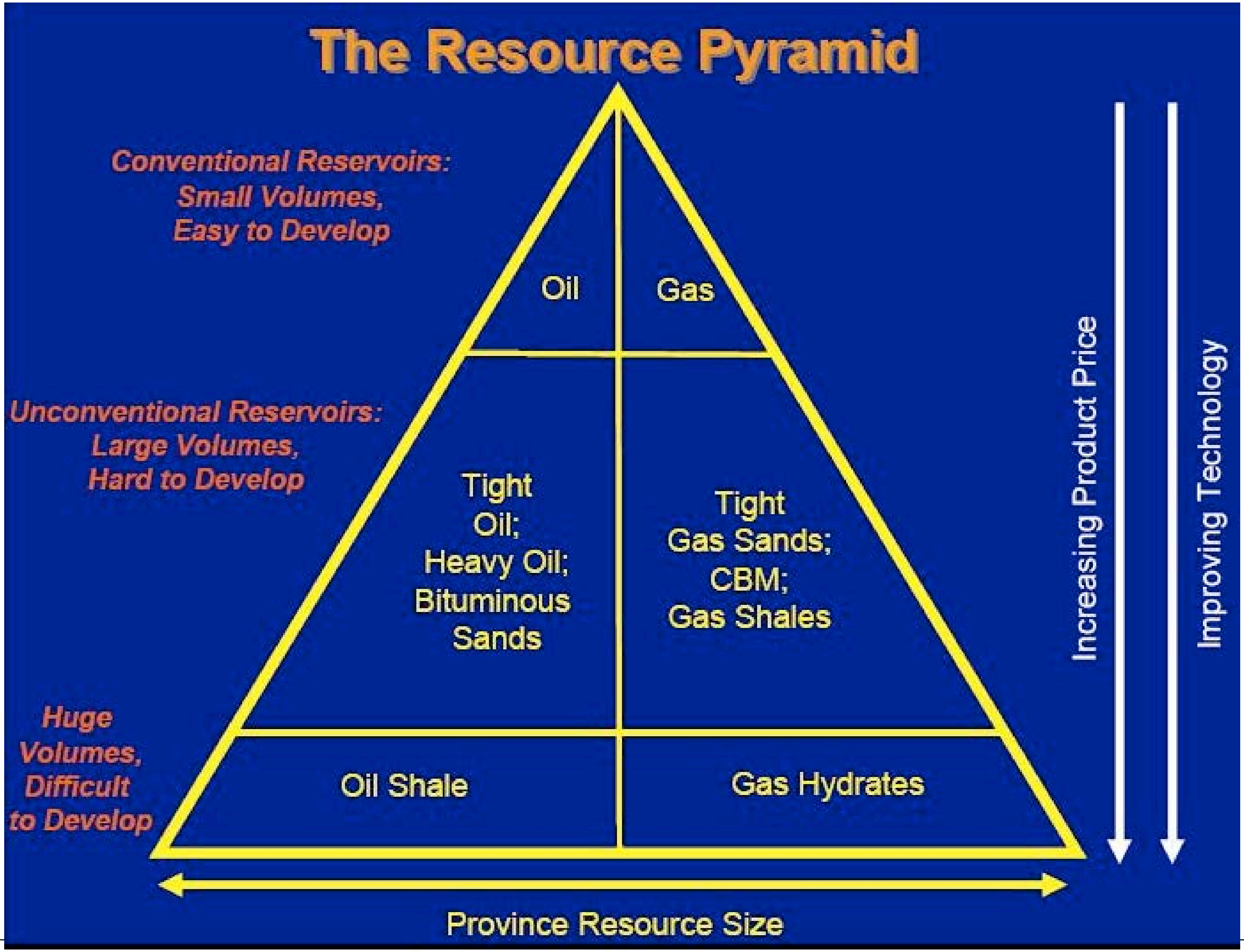
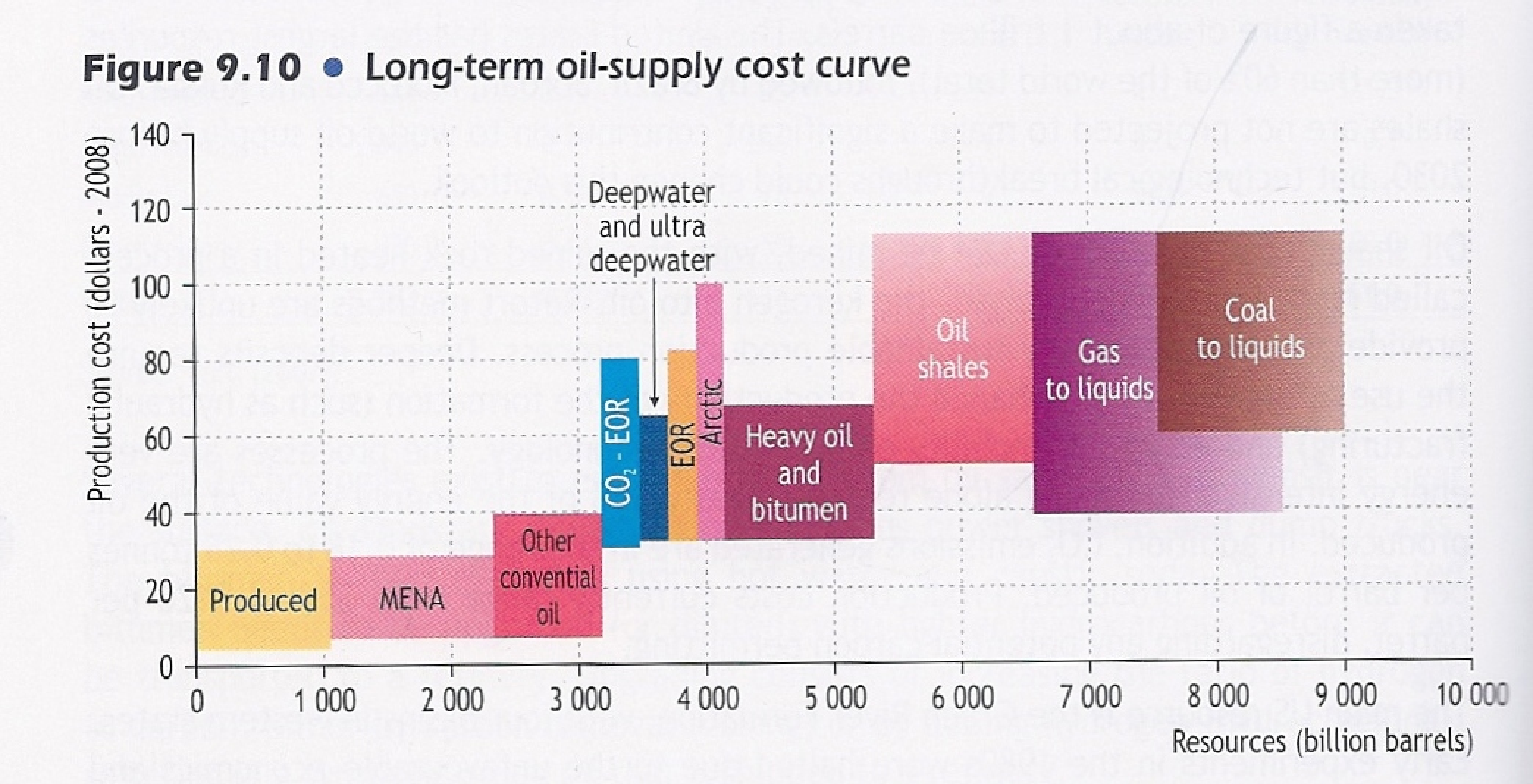
Global Energy Assessment (IIASA, 2012): Sustainable energy requires the following:

- *"Without question **a radical transformation of the present energy system** will be required over the coming decades." (p. xiii)*
- *"An effective transformation requires **immediate action**." (p. xv)*
- *"In all (sustainable, ed.) pathways **conventional oil is essentially phased out shortly after 2050**." (p. 51)*

Shale gas & oil: an unexpected revolution in global energy resources or technology and markets as usual?

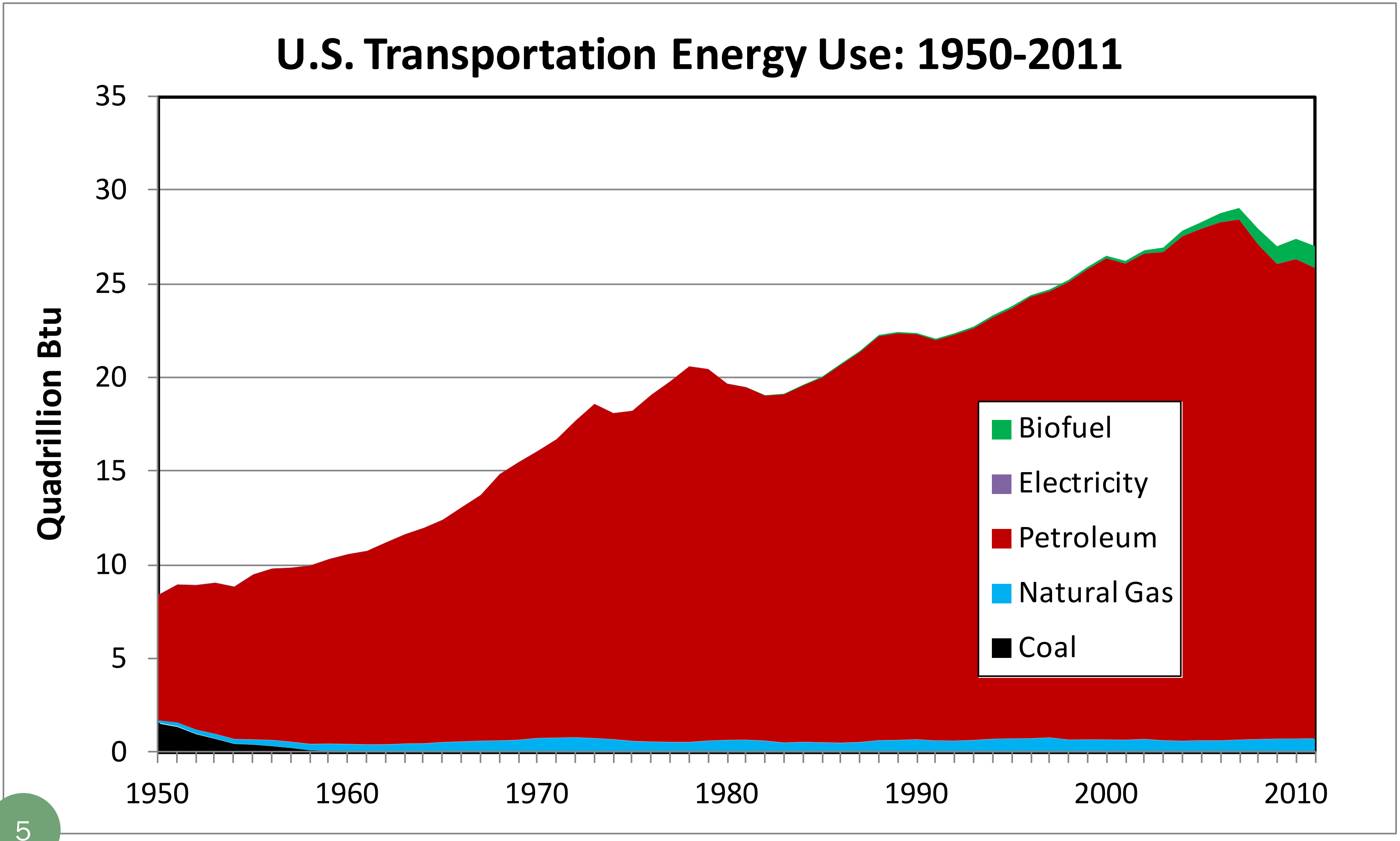


The IEA estimates that an order of magnitude more liquid fossil fuel can be produced at prices the world has already proven it is willing to pay.
But, that's the carbon we need to keep out of the atmosphere.



Source: International Energy Agency, World Energy Outlook 2008, OECD, Paris.

If energy transitions were easy… **To avoid the “Planning Fallacy” consider empirical evidence from similar situations.**



Energy Information Administration, Annual Energy Review 2011, table 2.1e.

We need to listen to McNutt and Rodgers.

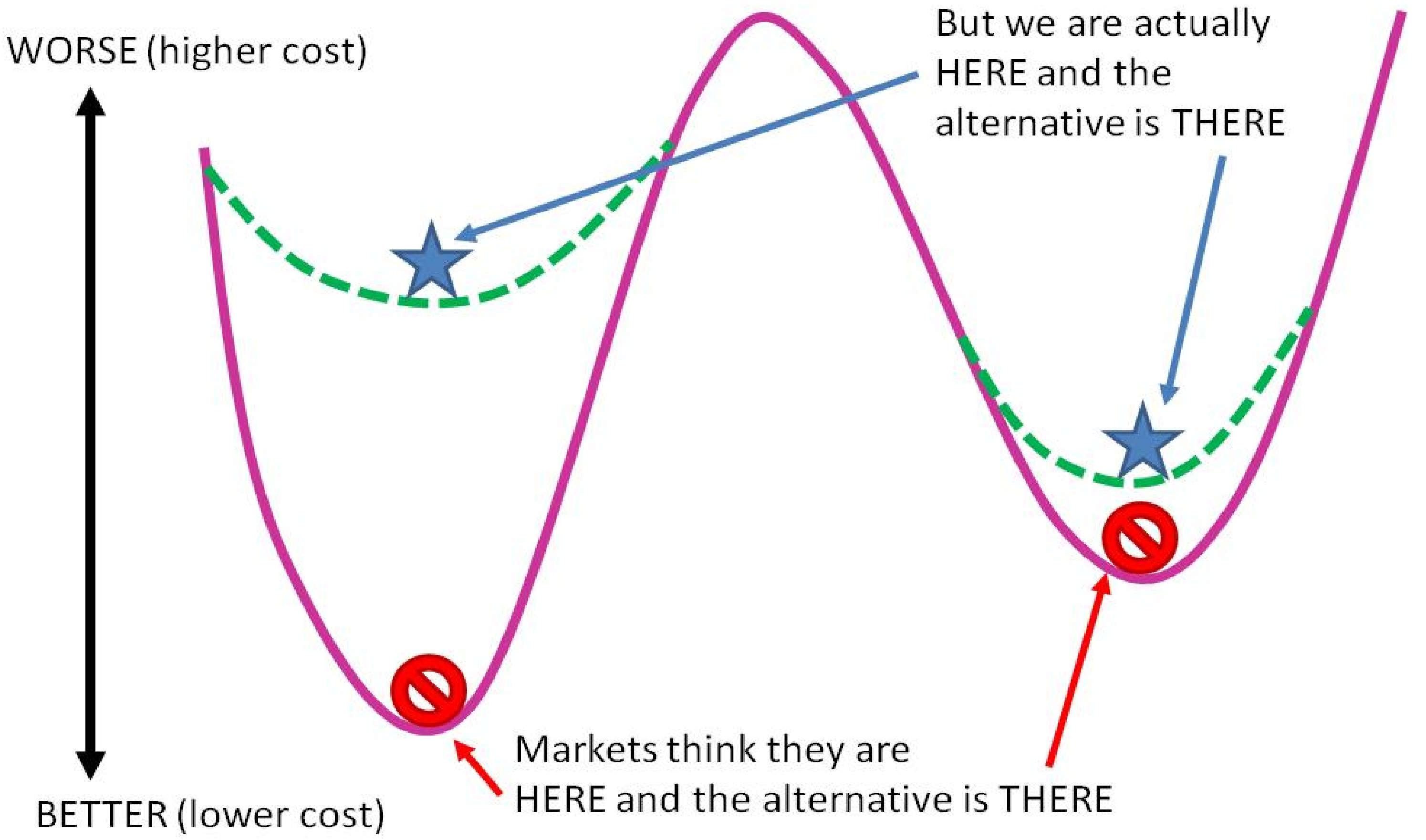
"Lessons learned from 15 years of alternative fuels experience – 1988 to 2003", McNutt and Rodgers in Sperling and Cannon, eds., *The Hydrogen Transition*, 2004 (Asilomar 2003).

- "…new technologies have to be better…and must keep ahead of conventional technology improvements that will inevitably occur."
- "Unregulated and unsubsidized private sector investment in refueling infrastructure has proven to be very limited."
- Building infrastructure in anticipation of market development has rarely happened, and when it has, the investors have usually been disappointed, especially with high cost refueling stations…."
- "Social attributes of the new alternative fuels are not valued by mainstream consumers."
- "Given consumer reticence, the political system has not yet shown a willingness to impose significant visible costs on private players…."

Why is a large-scale energy transition for the public good a different kind of problem?

- It takes decades. The difference between social and private discount rates becomes critical.
- Technological progress is inherently uncertain, as are economic conditions.
- Externalities are involved but not all the social costs are externalities (e.g., monopoly power in world oil market).
- There are other important market shortcomings (e.g., energy paradox).
- The transition creates external benefits (network & other) which are difficult for private agents to capture.
  - Value of fuel availability to car buyers
  - Learning-by-doing spillovers
  - Scale economies (pecuniary)
  - Reduction of risk-aversion of majority
  - Value of choice diversity (versus scale economies)
- **"Deep Uncertainty"**

"Not 1970's environmental economics." Markets may see no net present value to the transition, even if externalities are internalized.



Assume we want to maximize the net present value (NPV) of the transition wrt policy actions. The NPV in every year is dependent on previous years.

$$NPV = \sum_{t=0}^{T} \frac{1}{(1+r)^t} [B_{Pt}(\mathbf{X}_t, \mathbf{b}_t) + B_{Ut}(\mathbf{X}_t, \mathbf{b}_t) - C_{FT}(\mathbf{X}_t, \mathbf{b}_t) - C_{Vt}(\mathbf{X}_t, \mathbf{b}_t)]$$

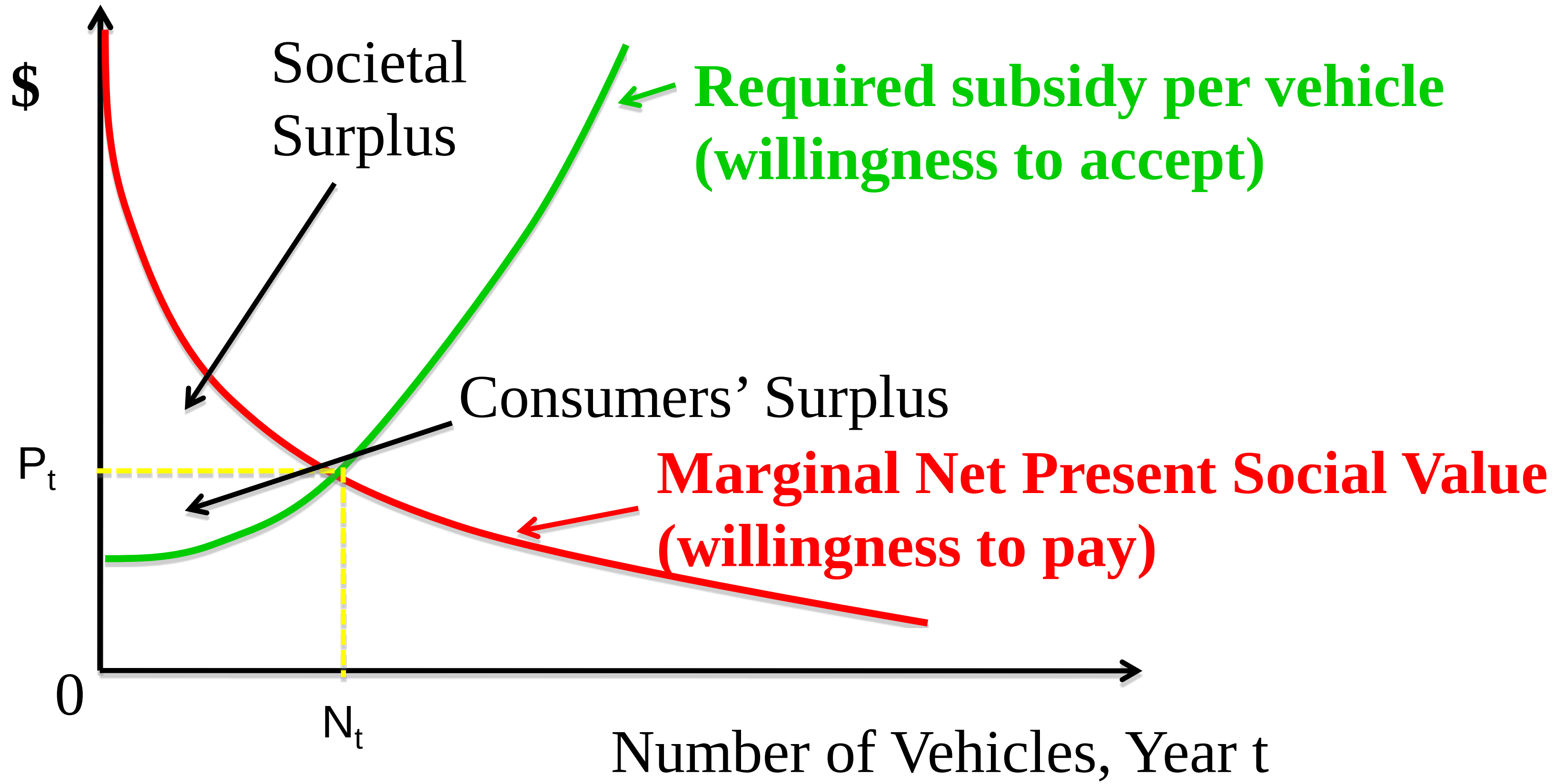
Where $\mathbf{X}_t$ is a matrix and $\mathbf{b}_t$ is a vector of parameters:

$$\mathbf{X}_t = \begin{bmatrix} x_{1t} & \cdots & x_{nt} \\ \vdots & \ddots & \vdots \\ x_{10} & \cdots & x_{n0} \end{bmatrix}$$

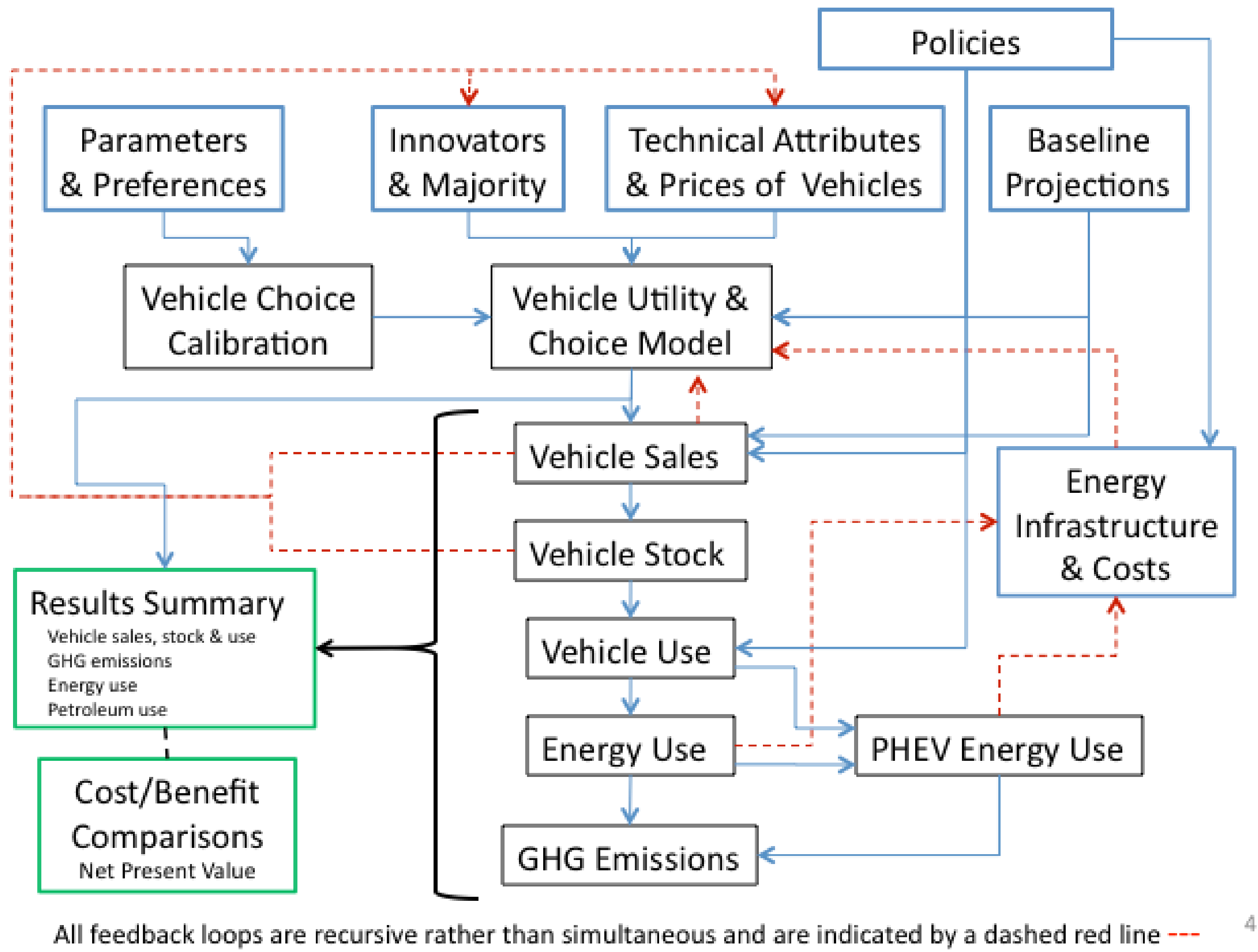
$$\mathbf{b}_t = [b_{1t}, b_{2t}, \ldots b_{mt}]$$

Is there such a thing as an economically efficient transition?

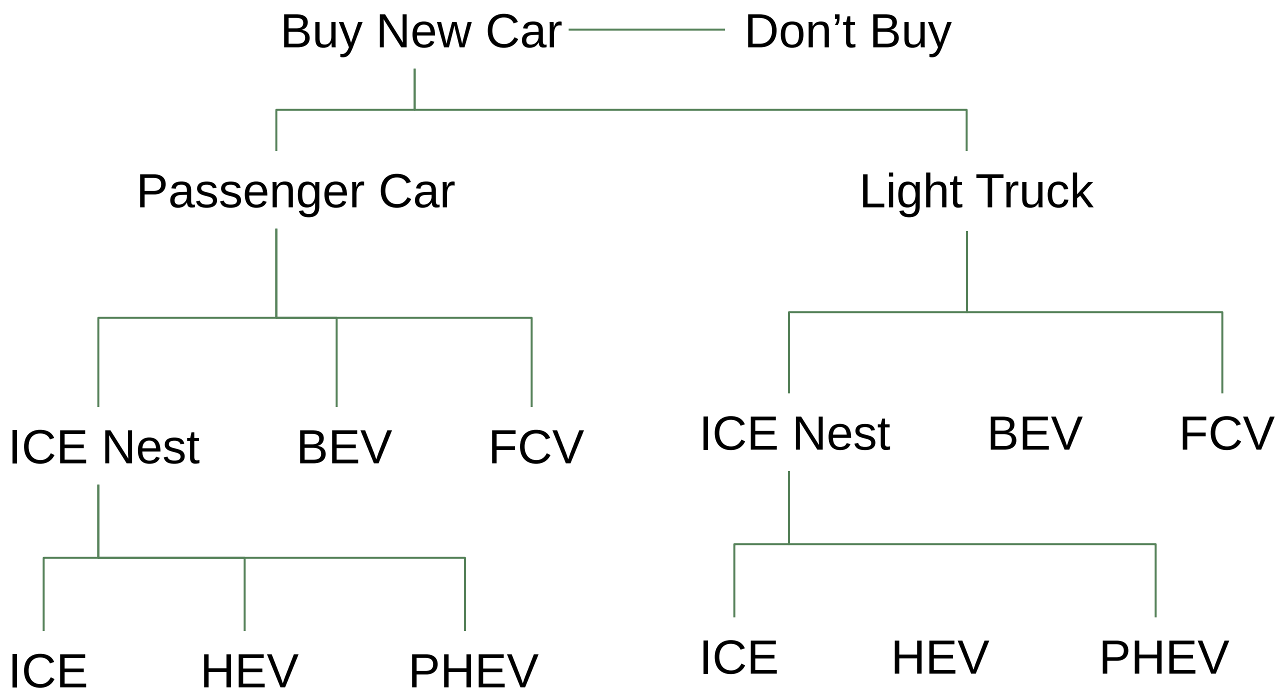
In year t, there is a social willingness to pay for having more vehicles and infrastructure in operation (dNPV/dN) and a market willingness to accept vehicle and provide infrastructure (dN/dP). There is an equilibrium providing "surplus" to both and resulting in sales of N_t vehicles at a subsidy of P_t. (**Oversimplification** due to tipping points, and uncertainty.)



The Light-duty Alternative Vehicle Energy Transition Model used in the NRC study *Transitions to Alternative Vehicles and Fuels* and ICCT study of *Transitions to Electric Drive in California*.



Keep it simple: Choice Model Structure

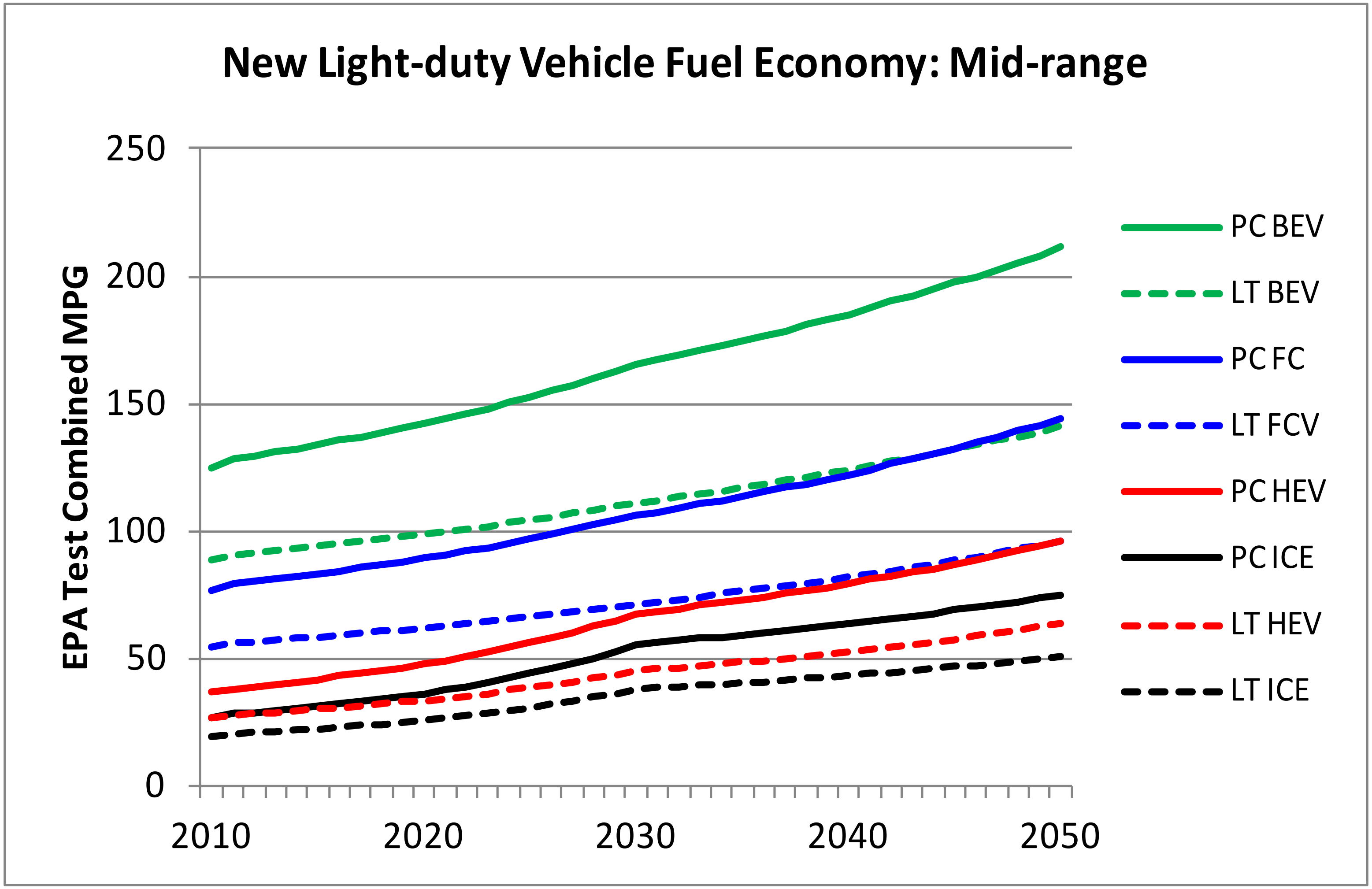


For each technology type, utility is measured as a function of vehicle attributes, fuel costs, fuel availability, risk aversion (majority), and diversity of choice (# of makes and models).

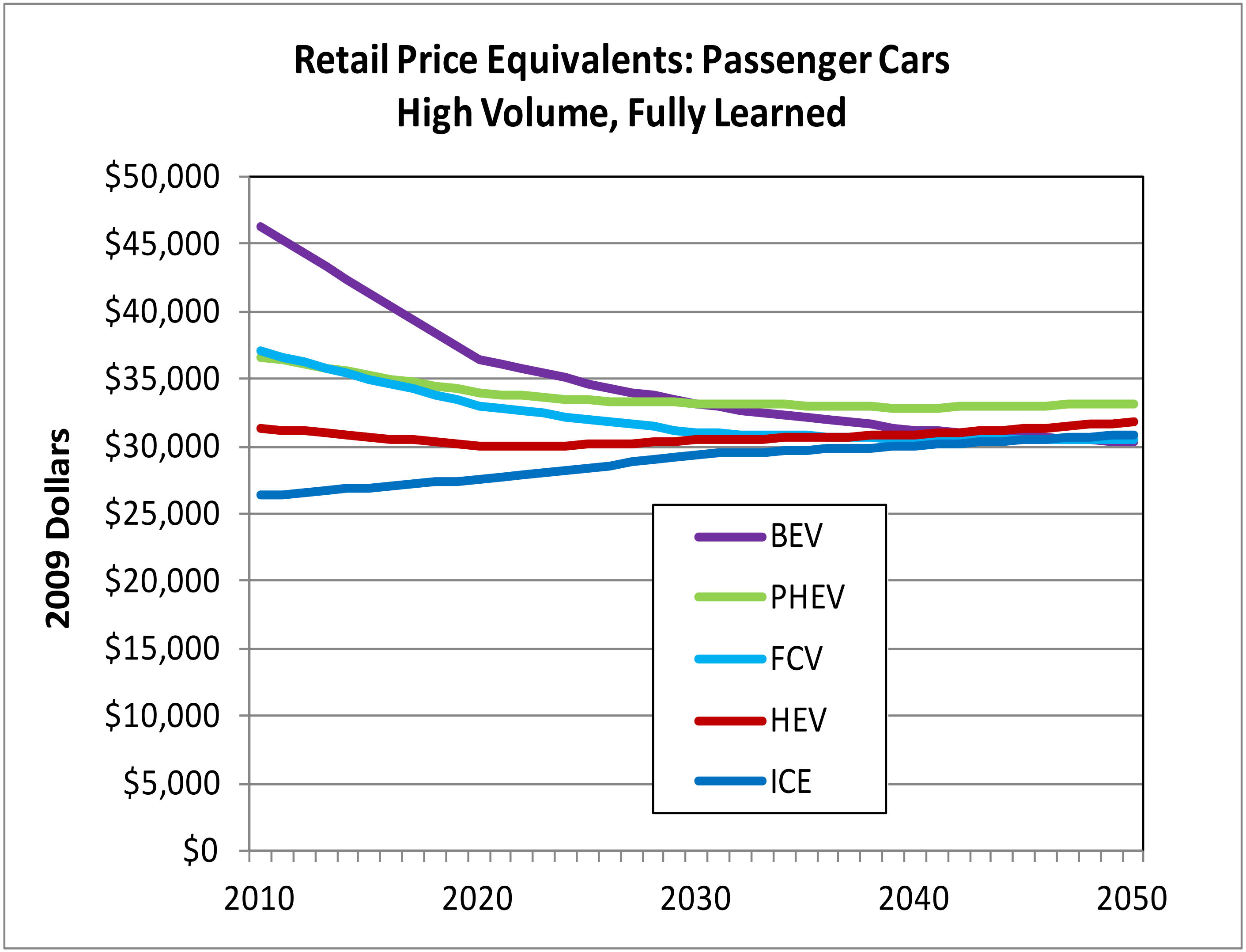
$$U_i = \sum_{j=1}^{n} \alpha_j X_{ij} + \beta P_i = \beta \left(\sum_{j=1}^{n} \frac{\alpha_j}{\beta} X_{ij} + P_i \right)$$

U_i = *average utility of vehicle technology type i*
X_{ij} = *jth attribute of vehicle technology type i*
P_i = *RPE of vehicle technology type i*
α_j = *average utils per unit of* X_{ij}
β = *average utils per dollar (of purchase price)*
α_j/β = *average $/unit of attribute j (dollar value)*

The NRC scenarios assume major efficiency gains.



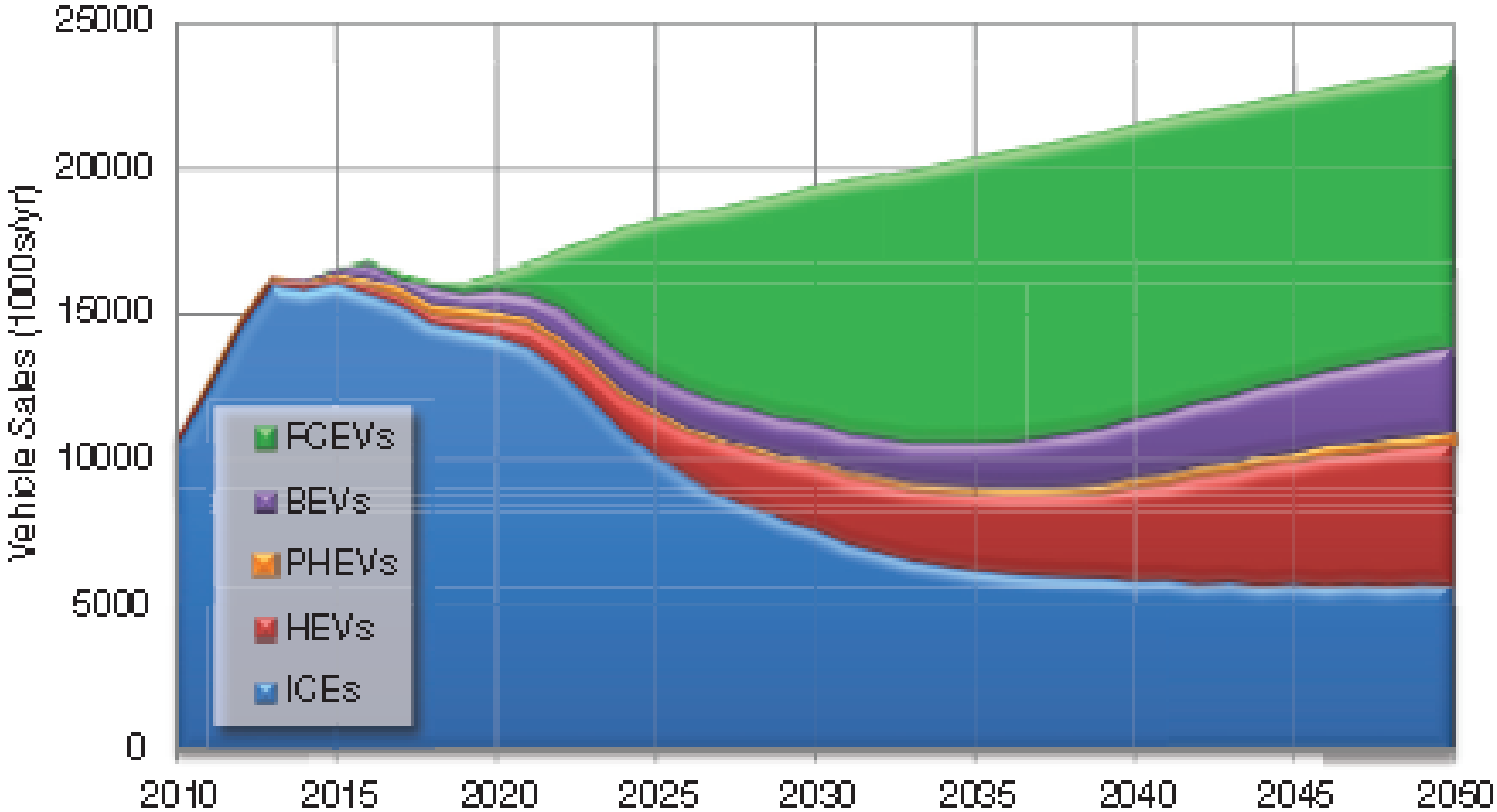
By reducing power requirements, the standards help make e-drive vehicles **cheaper** than ICEs.



Several important policies are assumed:

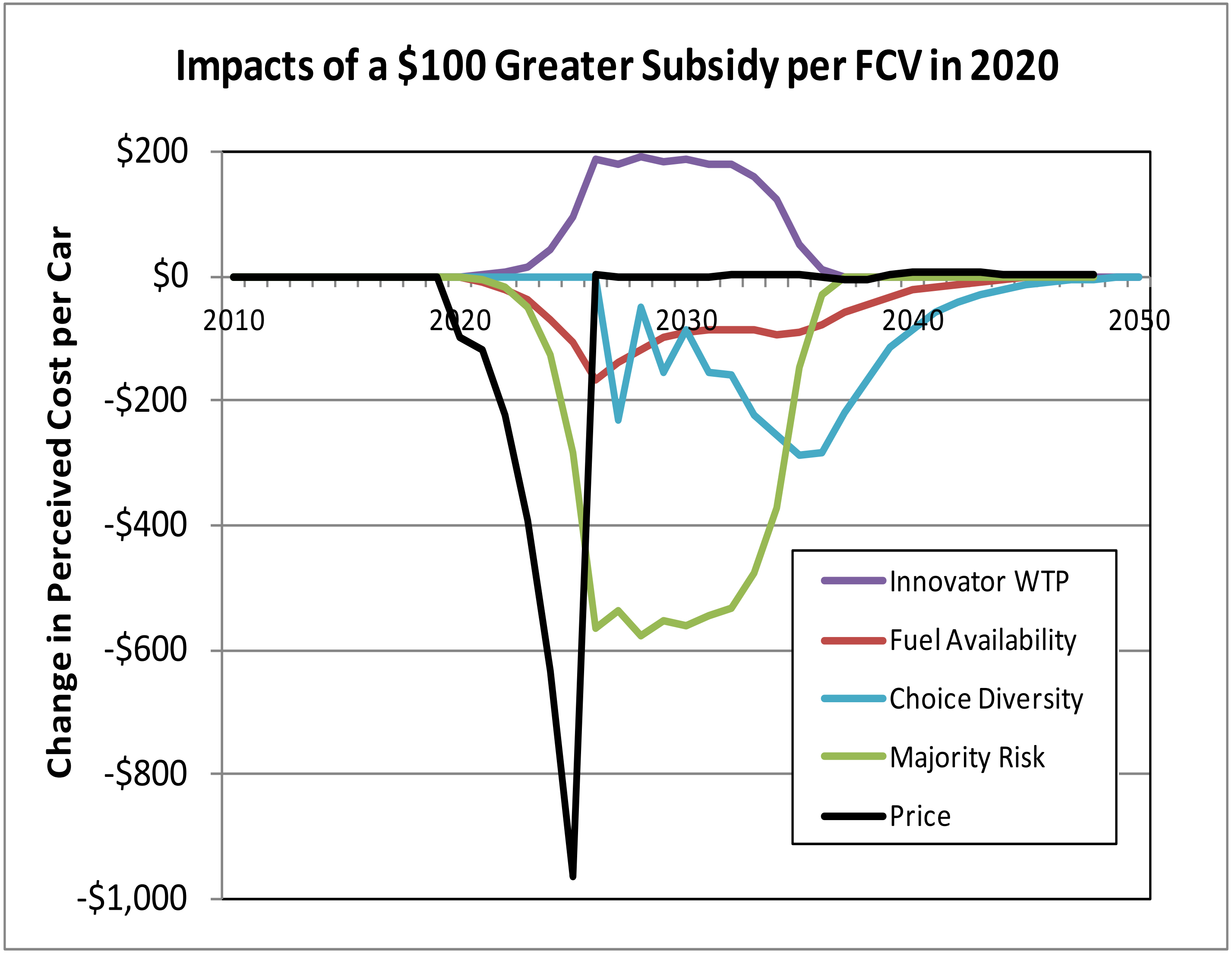
- Increasingly strict fuel economy/emissions standards.
- Policies to insure low carbon fuels.
- Existing vehicle subsidies end after 2015, but…
- Fuel economy/emissions standards induce vehicle pricing that reflects the social costs of oil and GHGs (like feebates).
- Highway user fee on energy indexed to average energy efficiency of all vehicles in use.
- **A scenario consists of additional vehicle and infrastructure subsidies or mandates after 2015.**
- **Please remember, the following analysis is not definitive, but it *is* based on the NRC study premises.**

A strategy promoting both FCVs and PEVs led to an 88% reduction in GHG emissions and a 100% reduction in petroleum use by 2050.

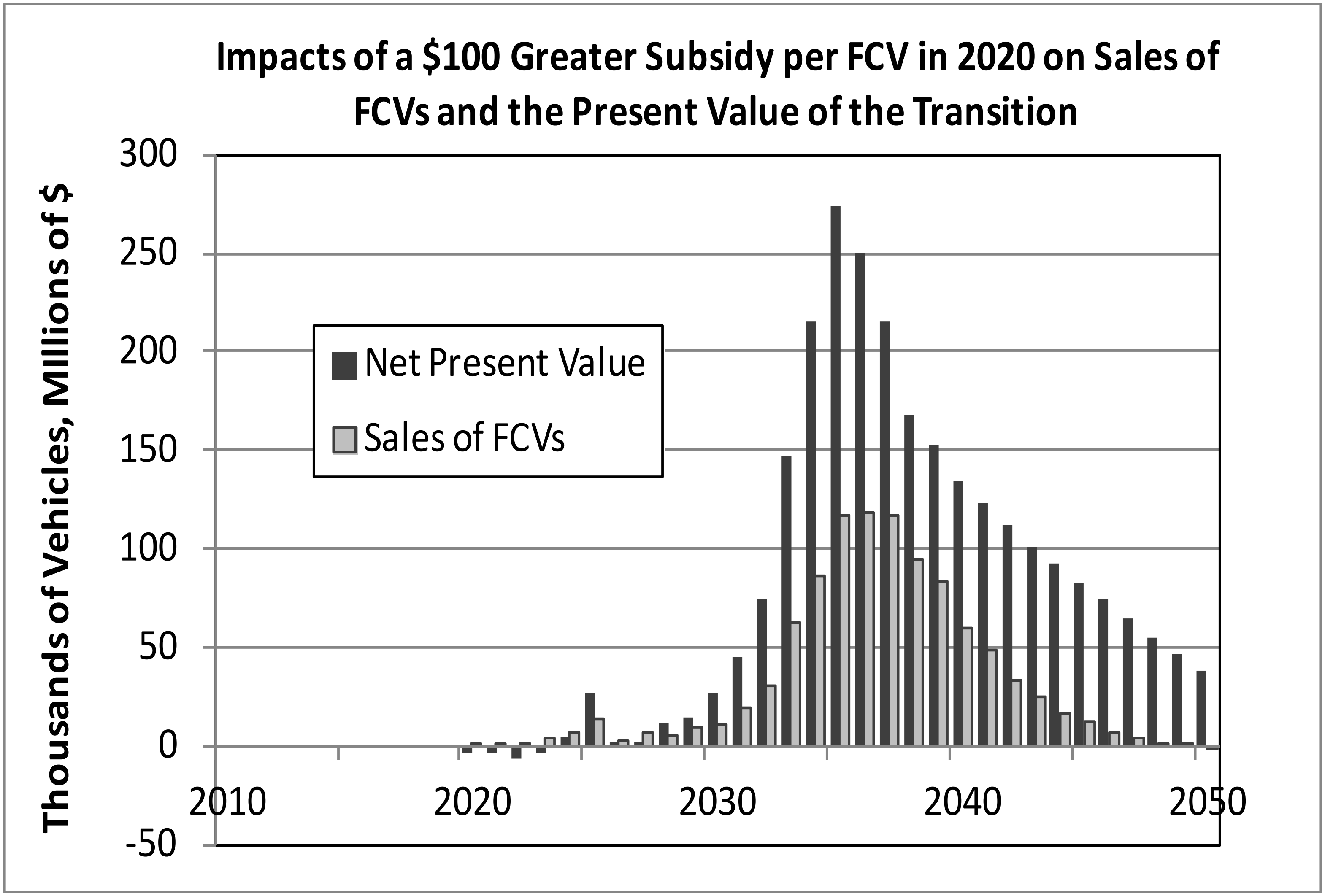


Feedback effects can be surprisingly large.

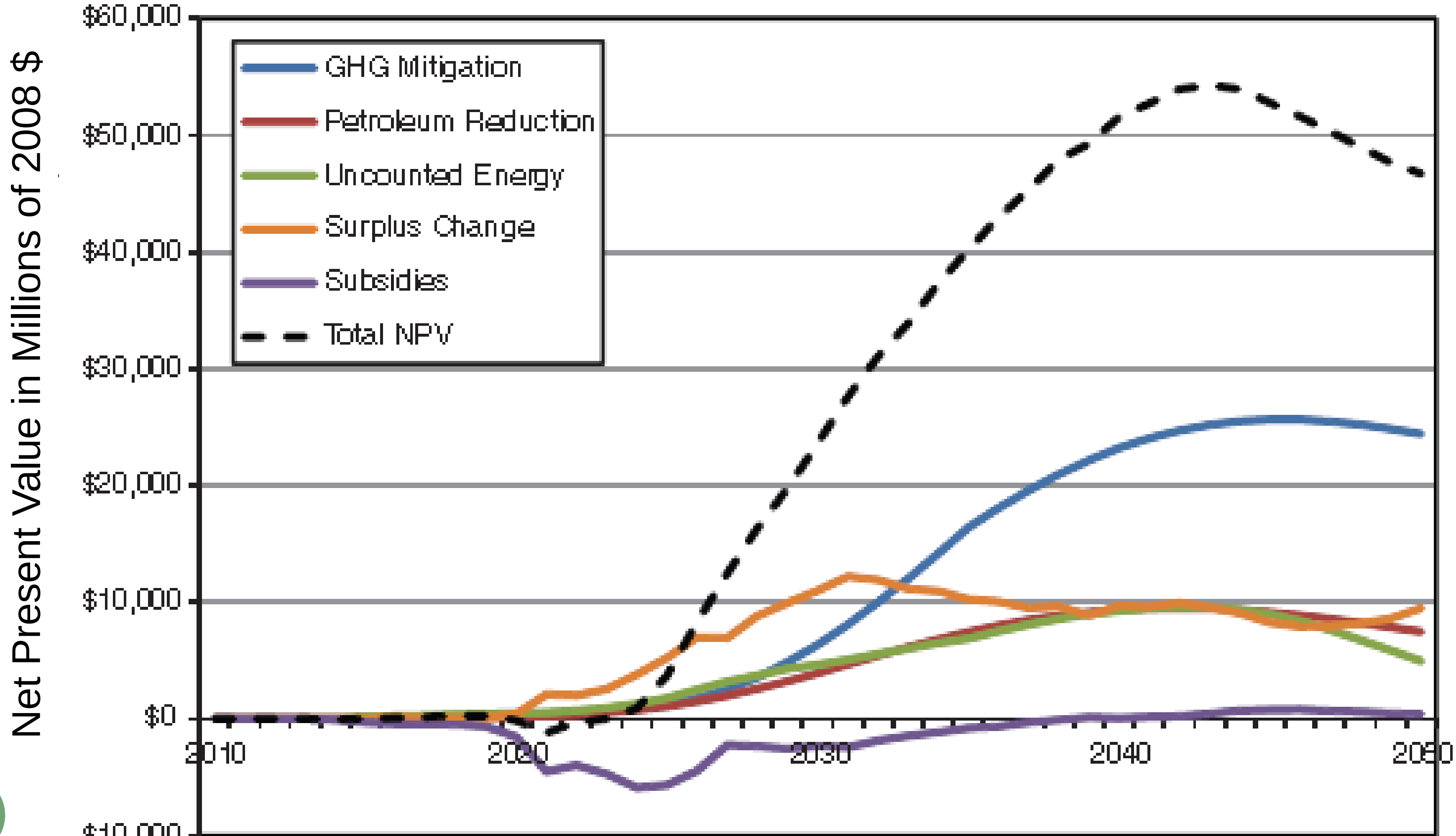
Effects of a $100 subsidy for fuel cell vehicles in California and the Section 177 (ZEV) states. Rest-of-U.S. policy lags 5 years.



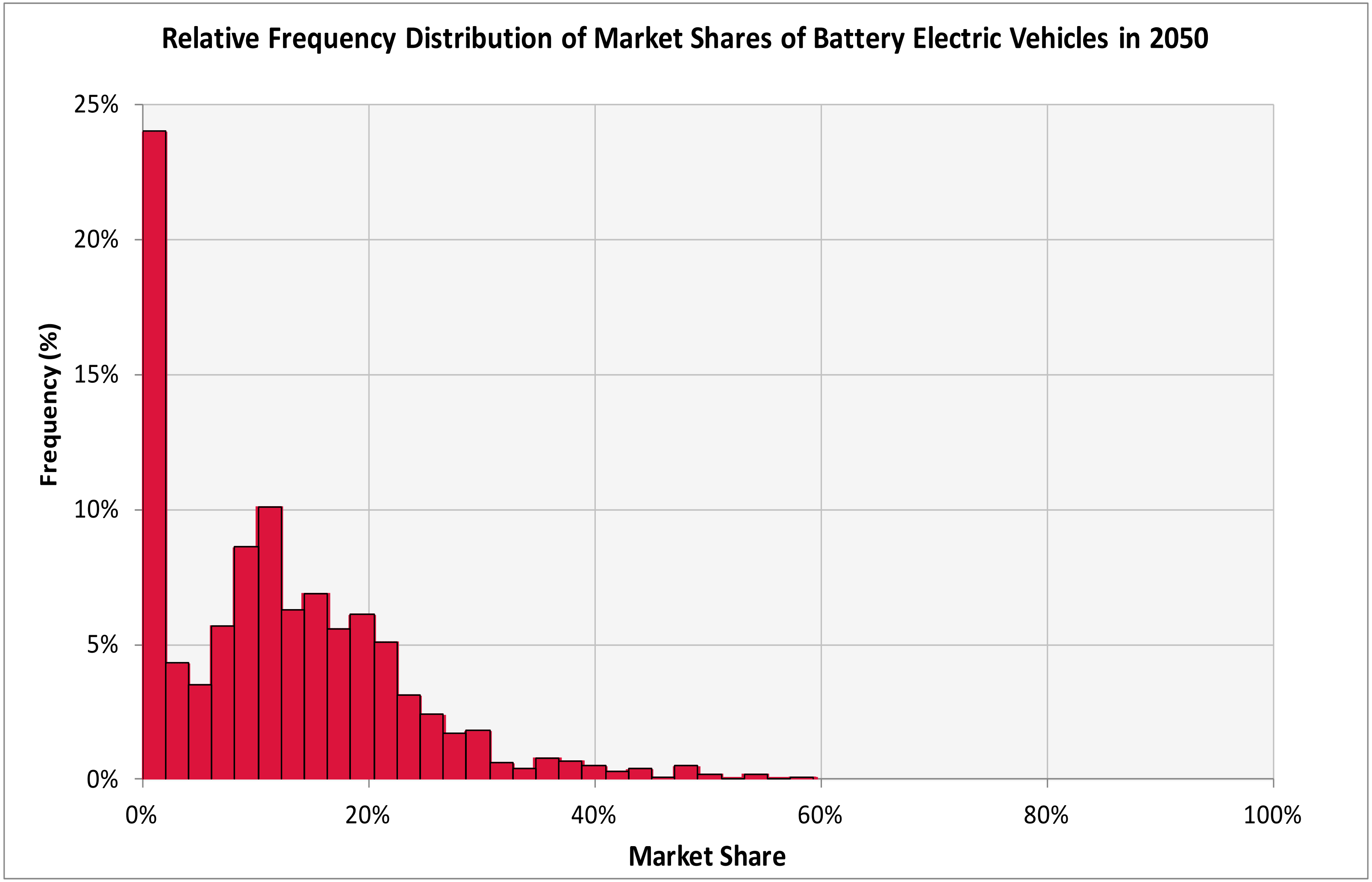
If the NRC technology scenario is realized, small initial costs yield large future gains.



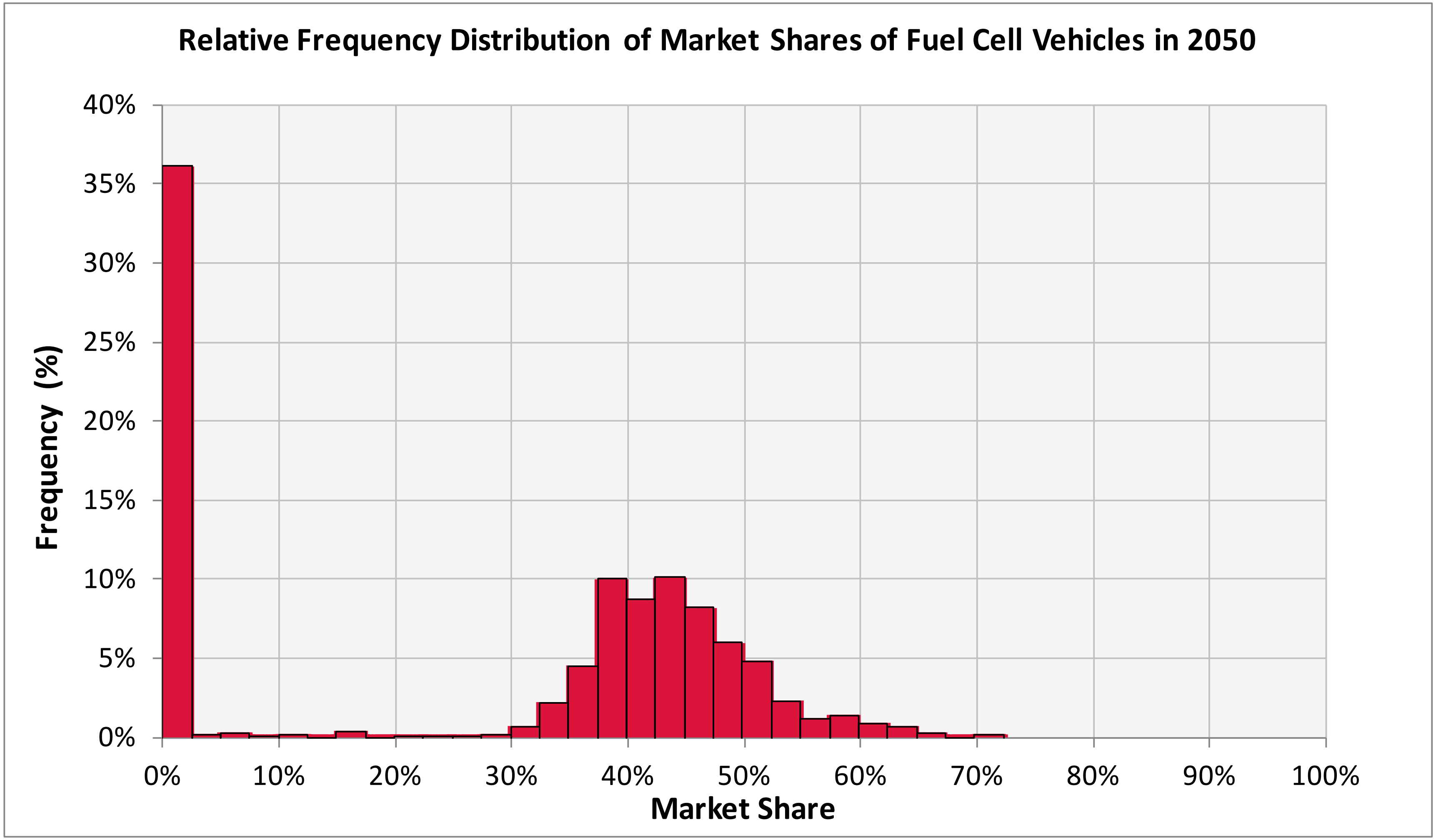
This graph from the NRC (2013) *Transitions to Alternative Vehicles and Fuels* study suggests that NPV benefits are roughly an order of magnitude greater than excess costs. Note: Energy Savings > Excess Cost.



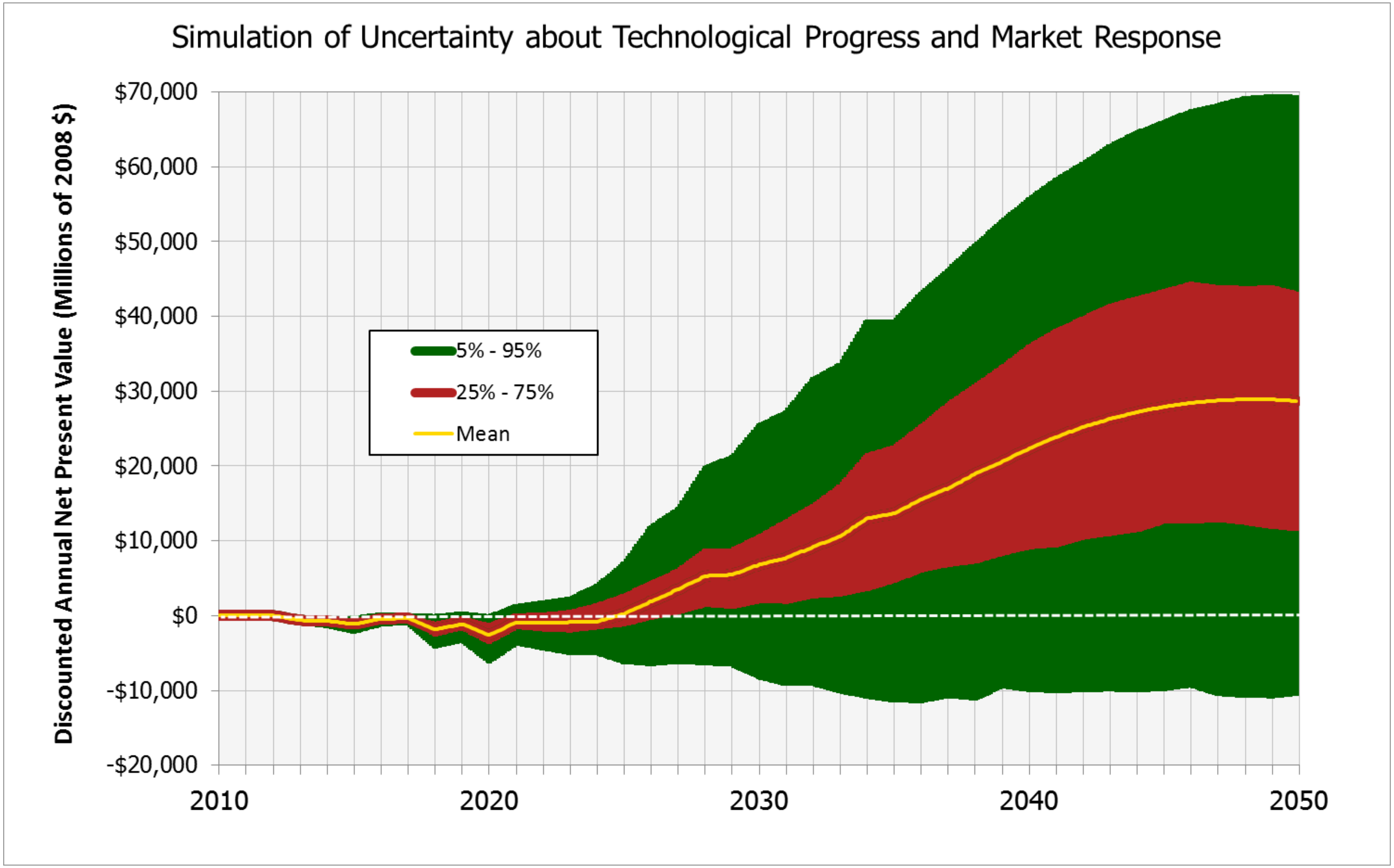
Sensitivity analysis illustrates tipping points & uncertainty (policies constant, market uncertain).



Tipping points appear more extreme for FCVs due to network externalities (chicken or egg) and their larger potential market share.



How large is the valley? How certain the reward? (adjusting policies to achieve fixed market shares while including uncertainty in technological progress).



The modeling results suggest some potentially important inferences.

- Net benefits of transition appear to exceed excess costs by approximately an order of magnitude, but
  - NPV < 0 for about a decade.
  - Subsidies may be needed for an extended period (to 2025 or 2030).
  - Temporarily, must do more than "internalize the external costs".
- There are important "tipping points".
- "Network external benefits" create large positive feedbacks.
- Mandates (ZEV) and/or subsidies seem to be essential.
- Early hydrogen infrastructure is critical for FCEVs.
- FCEV market potential appears to be > BEV > PHEV.
- What happens elsewhere strongly affects CA & US.

What do we need to know that we don't?

1. Innovators/majority: How many? $How much? How long?
2. How important is fuel availability?
3. How important is limited range/long recharging time?
4. How valuable are workplace & public recharging?
5. How valuable is diversity of choice?
6. How important is coordination with the rest of the world?
7. How sensitive are consumers' to vehicle and fuel prices?
8. What are viable financing policies & business models for early recharging and refueling infrastructure?
9. Which policies are most cost-effective and acceptable?
10. The value of research: save money, sustain public support.

How can we mitigate the "planning fallacy"? Reread McNutt and Rodgers, Asilomar 2003).

THANK YOU.

Baker Center Report: *Analyzing the Transition to Electric Drive in California*
http://bakercenter.utk.edu/wp-content/uploads/2013/06/Transition-to-Electric-Drive-2013-report.FINAL_.pdf

NRC Report: *Transitions to Alternative Vehicles and Fuels*
http://www.nap.edu/catalog.php?record_id=18264

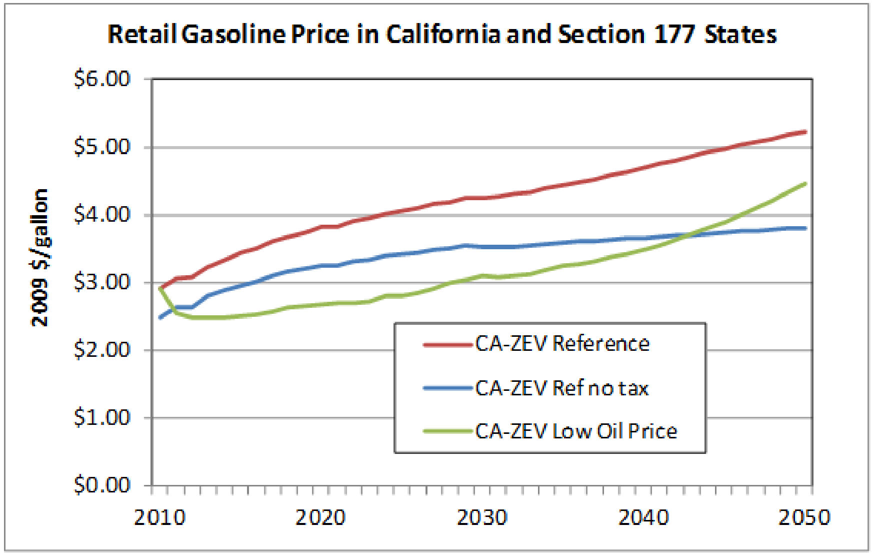
"Transition from Petro-Mobility to Electro-Mobility", in Stolten and Scherer, eds., *Transition to Renewable Energy Systems*, Wiley-VCH, Weinheim, Germany.

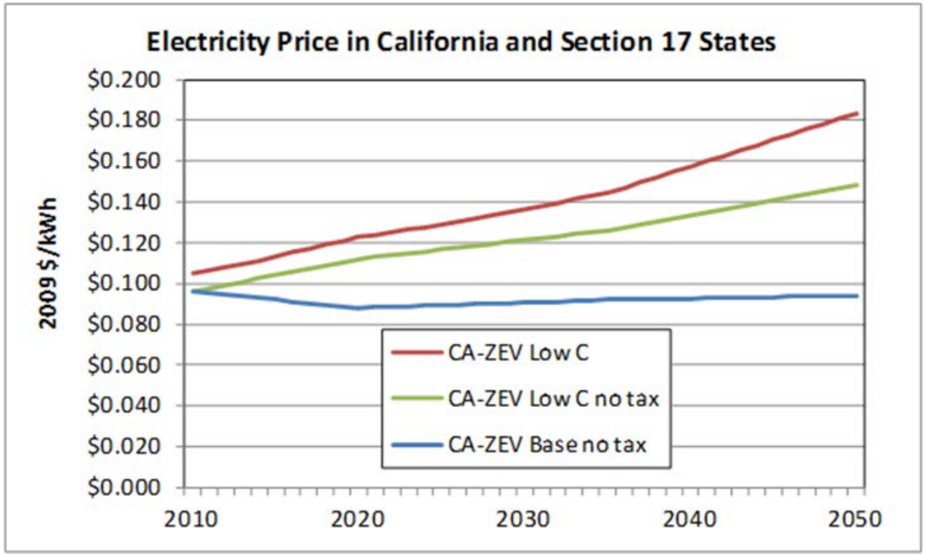
Analyzing the Transition to Electric Drive Vehicles in the U.S., D.L. Greene, C. Liu and S. Park, forthcoming, *Futures*.

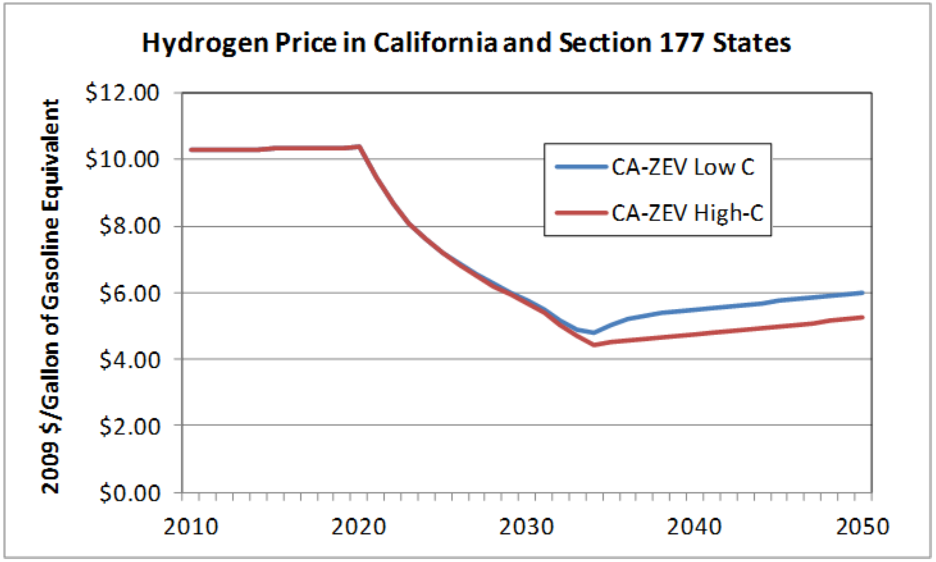
The LAVE model is highly generalized.

- 2 regions rather than geographically detailed.
- 2 market segments: innovators/early adopters v. majority.
- 2 types of vehicles: passenger cars and light trucks.
- Knowledge of market response is limited.
  - Innovators, early adopters, majority
  - Cost of limited fuel availability
  - Cost of short range/long recharge
  - Scale economies, learning-by-doing, risk aversion…
- The model provides a structured framework for integrating knowledge and assumptions rather than an accurate prediction of the future.

Like the NRC study, we took energy prices from the 2011 Annual Energy Outlook, and changed the motor fuel tax to an Indexed Highway User Fee on Energy.

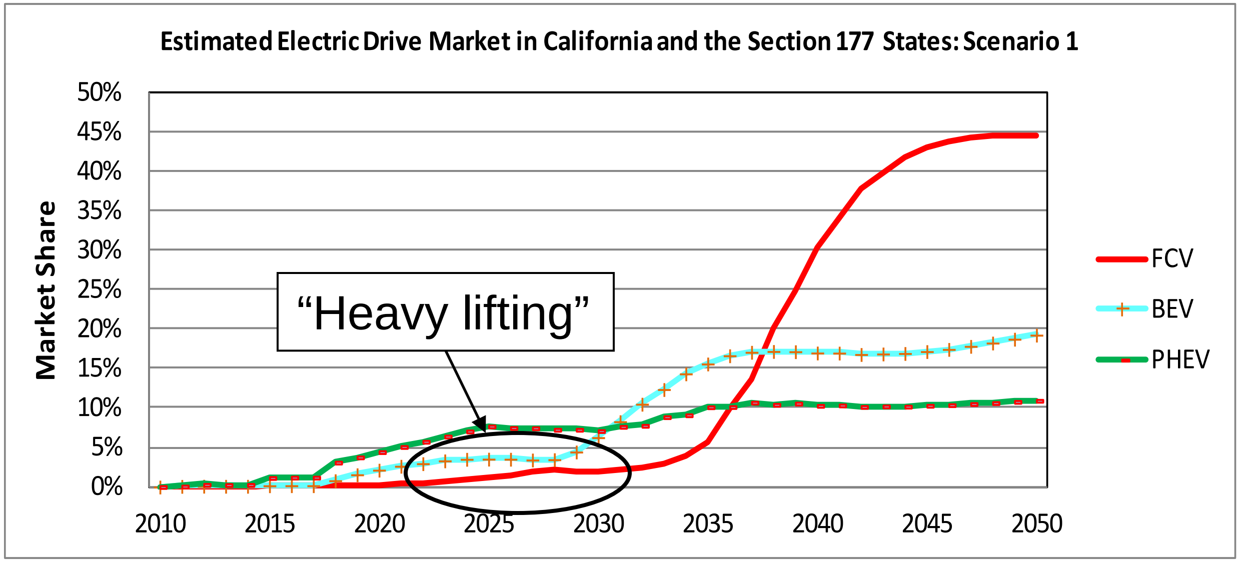


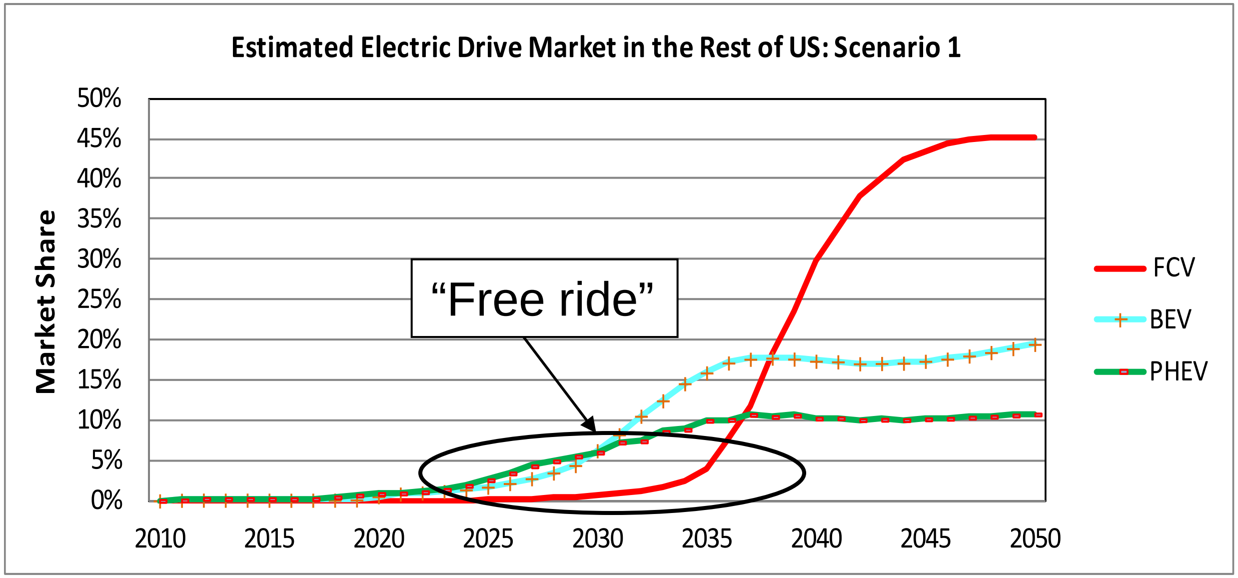




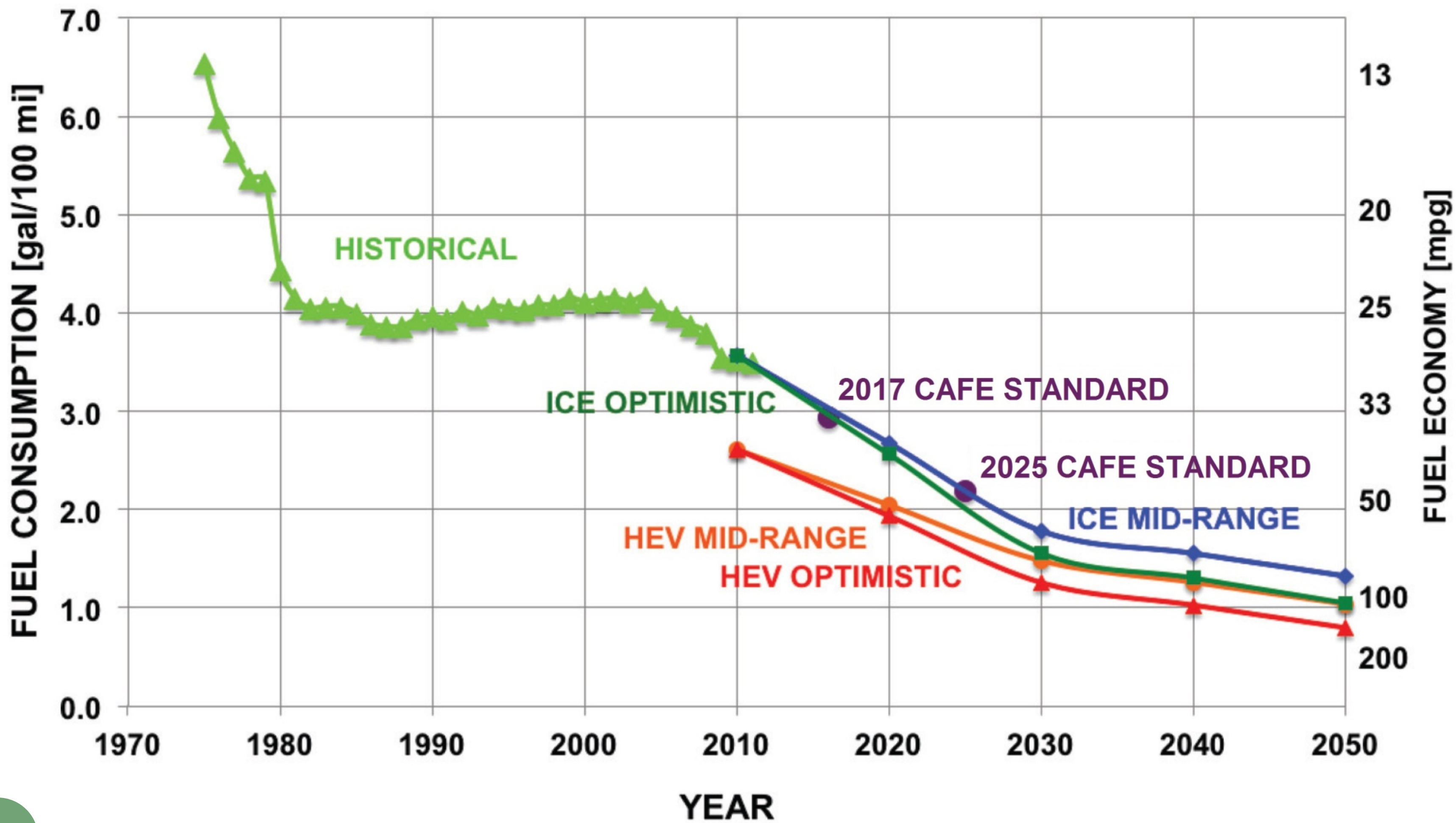
One tipping point is hydrogen infrastructure.

If the rest of US installs early H_2 infrastructure FCVs thrive.





A key premise of the NRC study was that fuel economy & GHG emissions standards would be tightened through 2050.



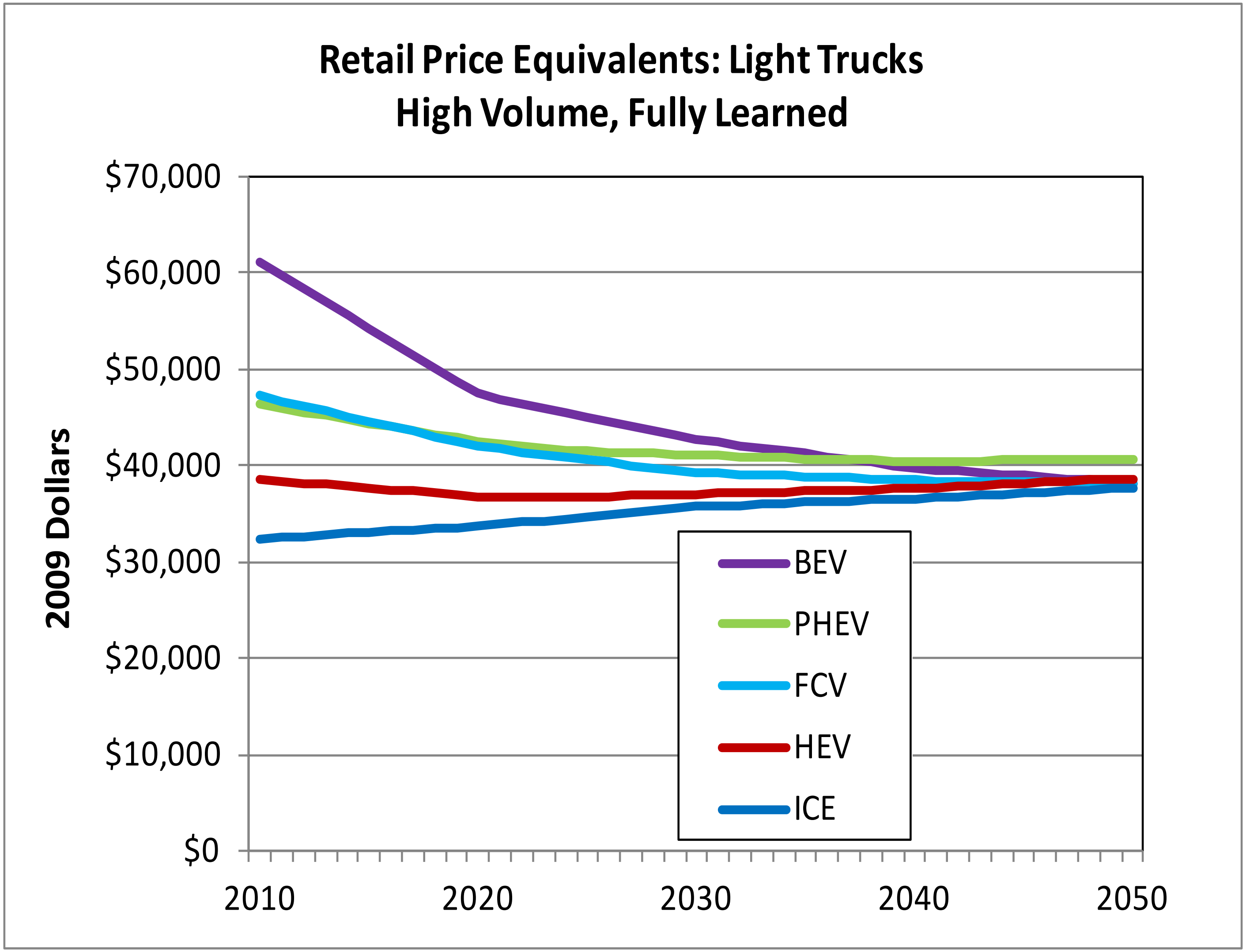
How are these fuel economies achieved? Reduced load + improved drivetrain efficiency.

TABLE 2.9 Details of the Potential Evolution of a Midsize Car, 2007-2050

Conventional Drivetrain	Baseline	2030 Midrange	2030 Optimistic	2050 Midrange	2050 Optimistic
Engine type	Baseline	EGR DI turbo	EGR DI turbo	EGR DI turbo	EGR DI turbo
Engine power, kW	118	90	84	78	68
Transmission type	6-sp auto	8-sp auto	8-sp auto	8-sp auto	8-sp auto
Drivetrain improvements					
Brake energy recovered through alternator, %	—[a]	14.1	14.1	14.1	14.1
Reduction in transmission losses, %	n/a	26	30	37	43
Transmission efficiency, %	87.6	91	91	92	93
Reduction in torque converter losses, %	n/a	69	75	63	88
Torque converter efficiency, %	93.2	98	99	99	99
Reduction in pumping losses, %	n/a	74	76	80	83
Reduction in friction losses, %	n/a	39	44	53	60
Reduction in accessory losses, %	n/a	21	25	30	36
% increase in indicated efficiency	n/a	5.6	6.5	10.6	15.6
Indicated efficiency, %	36.3	38.4	38.7	40.2	42
Brake thermal efficiency, %	20.9	29.6	30.3	32.5	34.9
Load changes					
% reduction in CdA	n/a	15	24	29	37
CdA (m^2)	7.43	6.31	5.64	5.29	4.68
% reduction in Crr	n/a	23	31	37	43
Crr	0.0082	0.0063	0.0057	0.0052	0.0047
% reduction in curb weight	n/a	20	25	30	40
Curb weight, lb	3325	2660	2494	2328	1995
Fuel economy, test mpg	32.1	65.6[b]	74.9	88.5	111.6

NOTE: All conventional drivetrains have stop-start systems and advanced alternators that can capture energy to drive accessories.
[a]Ricardo assumed stop start and smart alternator, with 14.1 percent of braking energy recovered, resulting in fuel economy = 34.9 mpg.
[b]Fuel economy with drivetrain changes only = 30.5 mpg.

The retail price projections for light trucks are similar but ICEs remain the least expensive.



The NRC study assumed the cost of producing "drop-in" bio-fuel via pyrolysis and refining would decrease over time to $3-$4 per gallon.

TABLE 3.5 Estimates of Future Biofuel Availability

	Annual Plant Investment Rate (billion dollars per year)			
	1	4	7.2	10.4
Biofuel production (billion gge per year) by				
2022	0.9	3.7	6.7	9.7
2030	1.8	7.4	13.3	19.2
2050	4.3	17.3	31.2	45.0
Biomass required in 2050 (million dry tons per year)	68	270	488	703
Estimated land-use change (million acres)	5.5	22.2	40.1	57.8
Total investment to 2050 (billion dollars)	38	152	275	396
Average number of biorefineries built per year	2.7	10.8	19.5	28.2

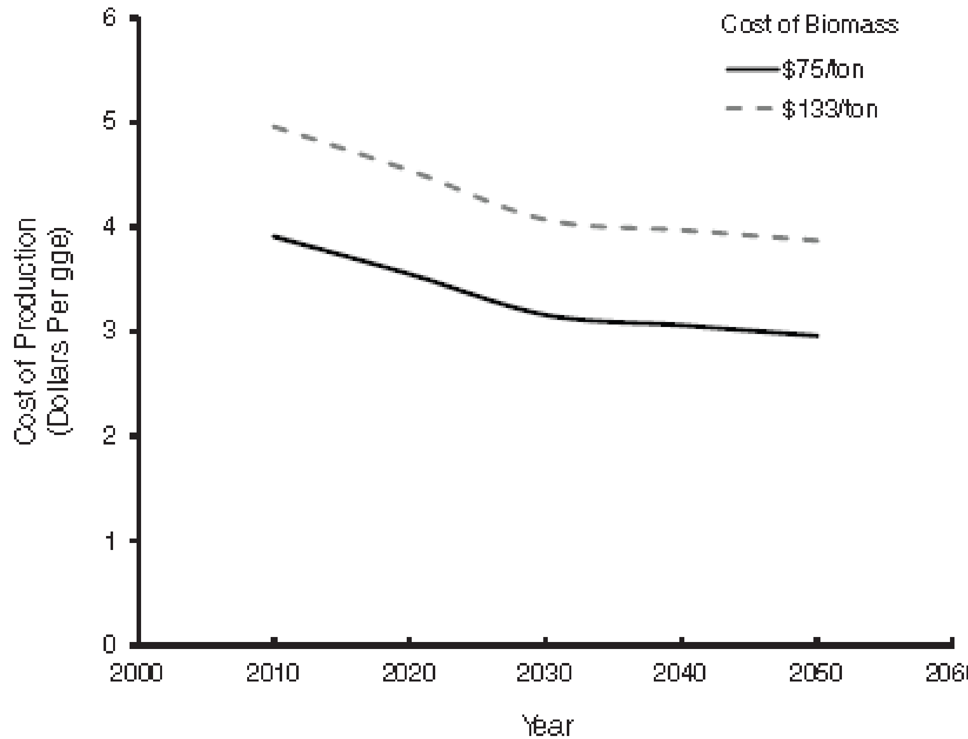
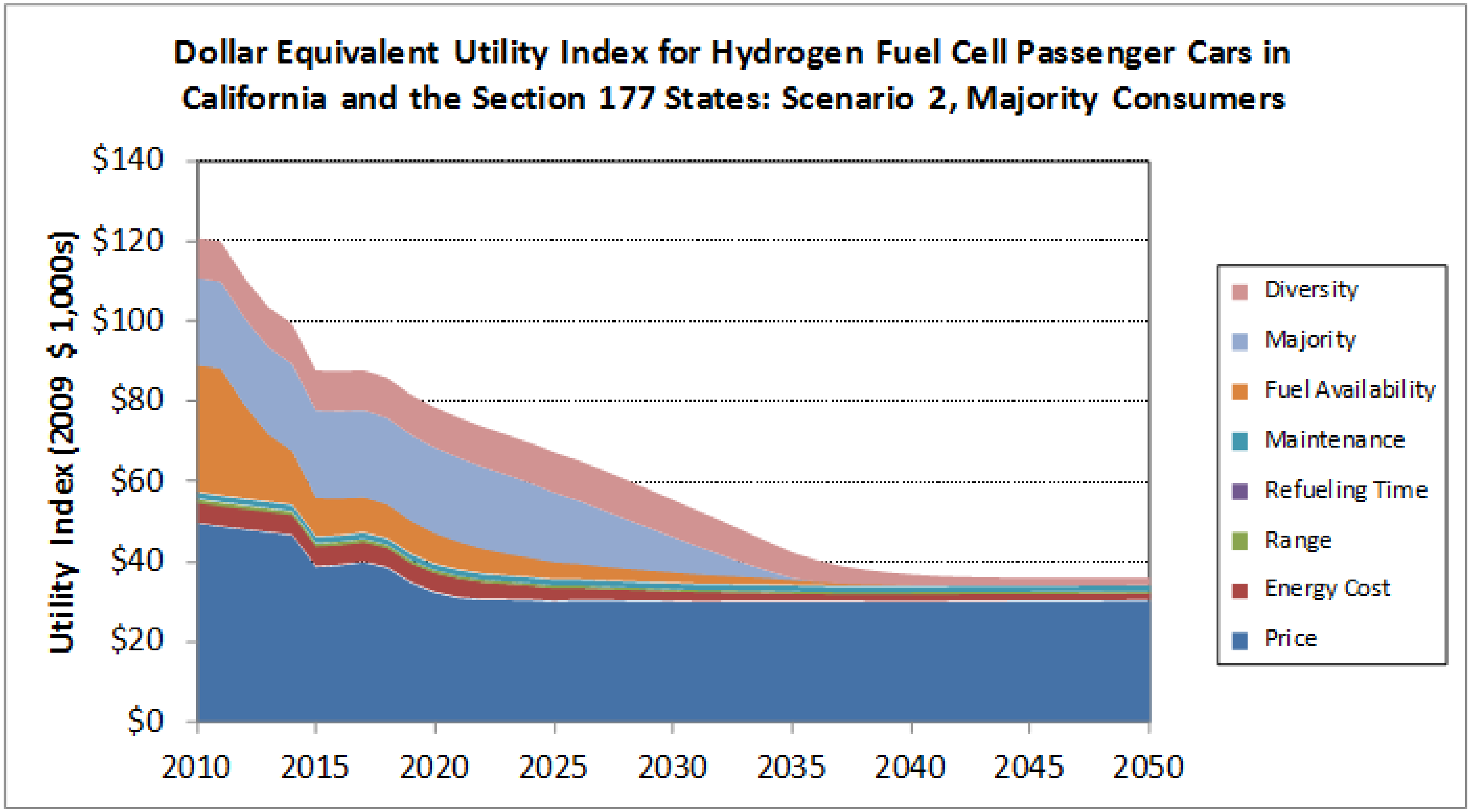
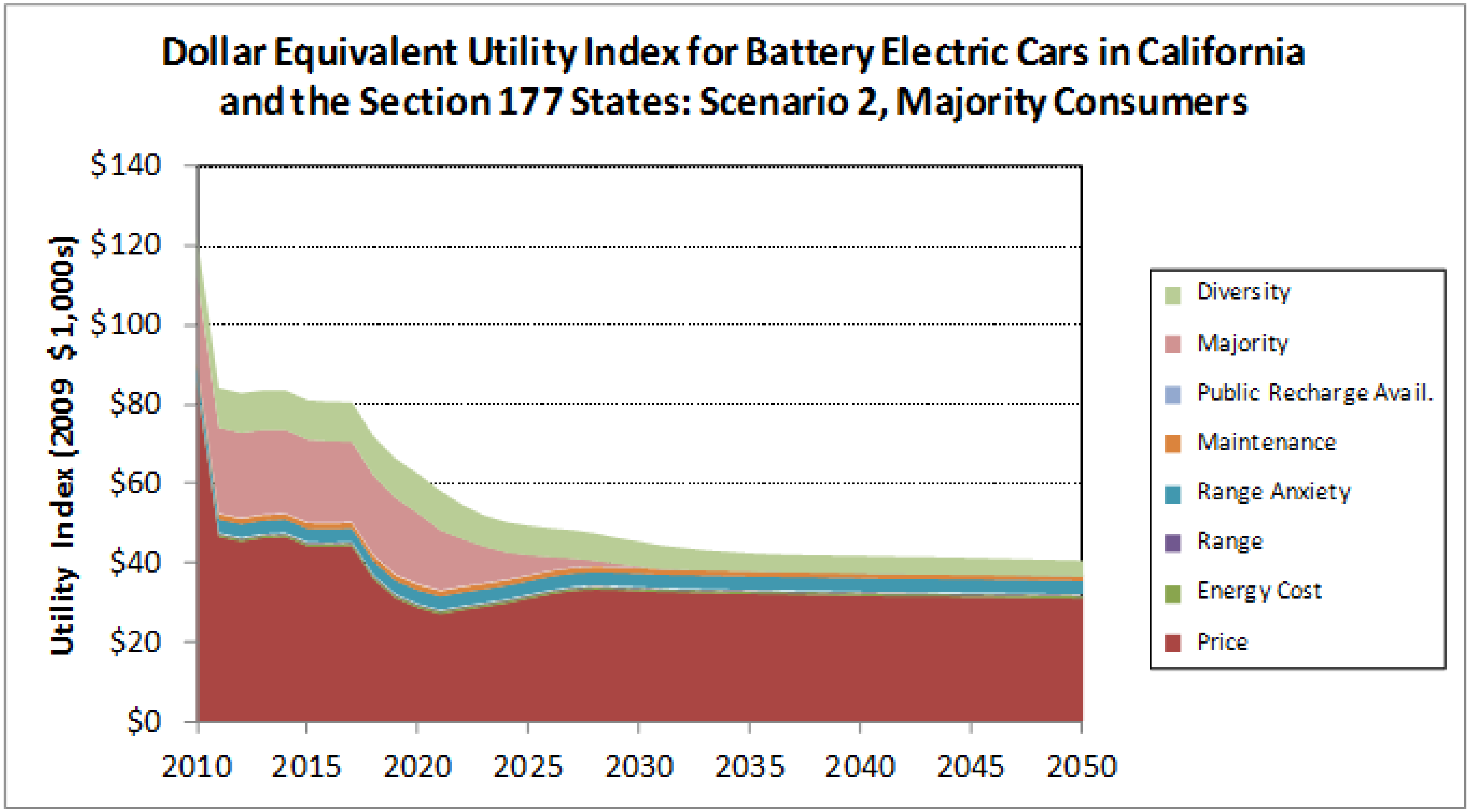


FIGURE 3.2 Sensitivity of biofuel cost to biomass cost.

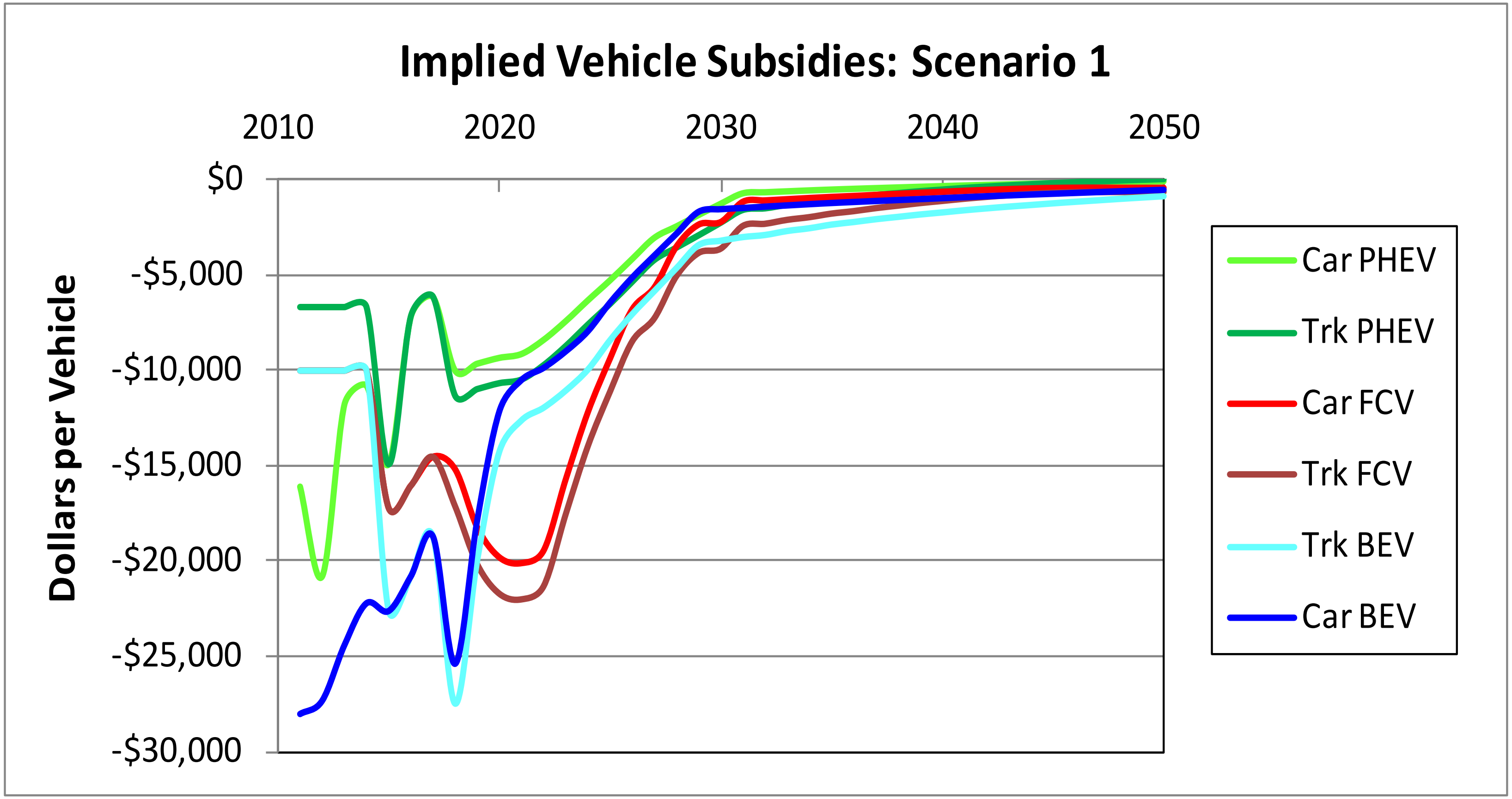
Quantification of the transition costs (market barriers) allows one to see how network external benefits enable the transition.
(Note: "Price" includes any subsidies)



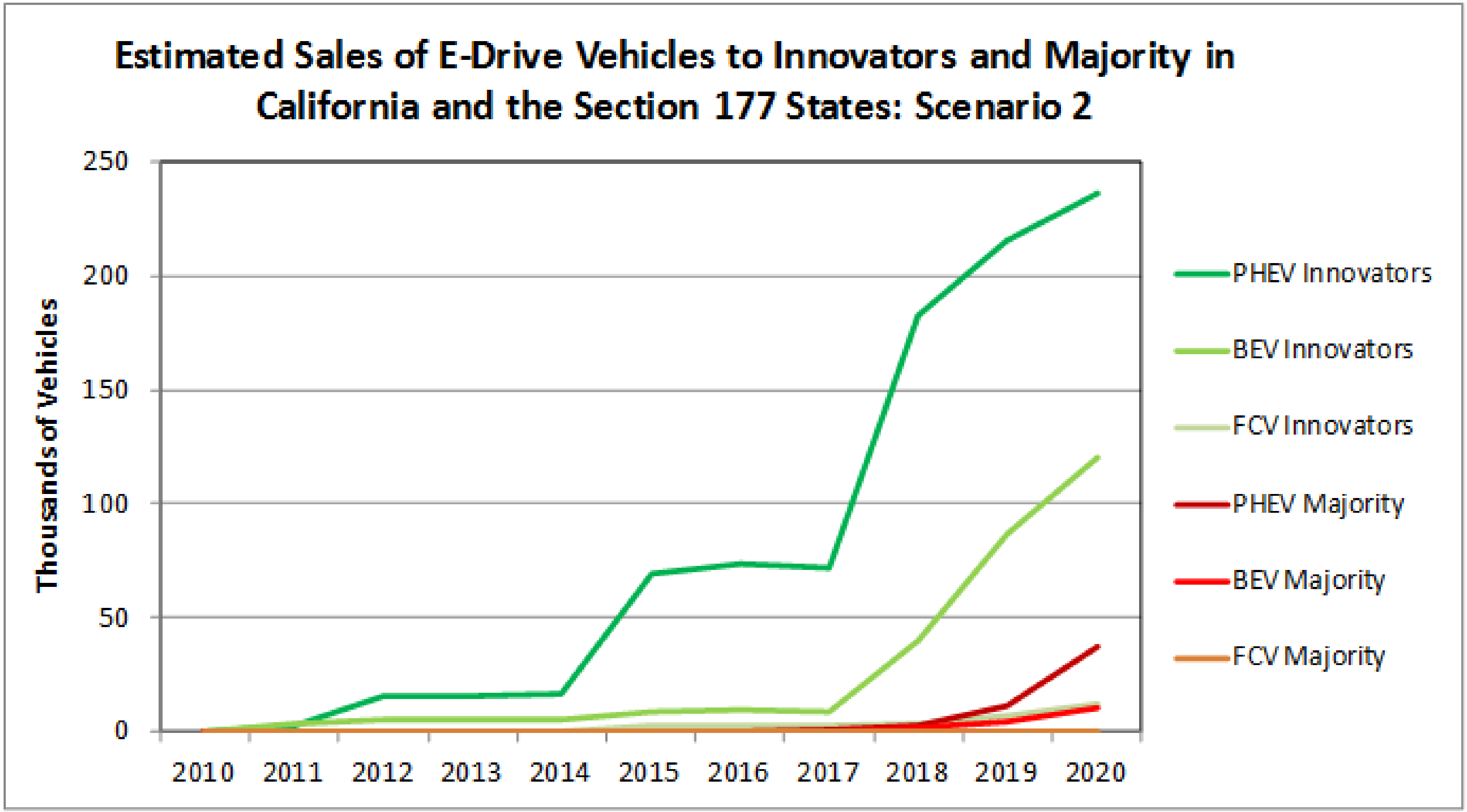
For BEVs, availability of recharging is much less of a hindrance but range/recharge time remains a significant cost. Early adoption reduces majority's risk aversion and builds scale economies.



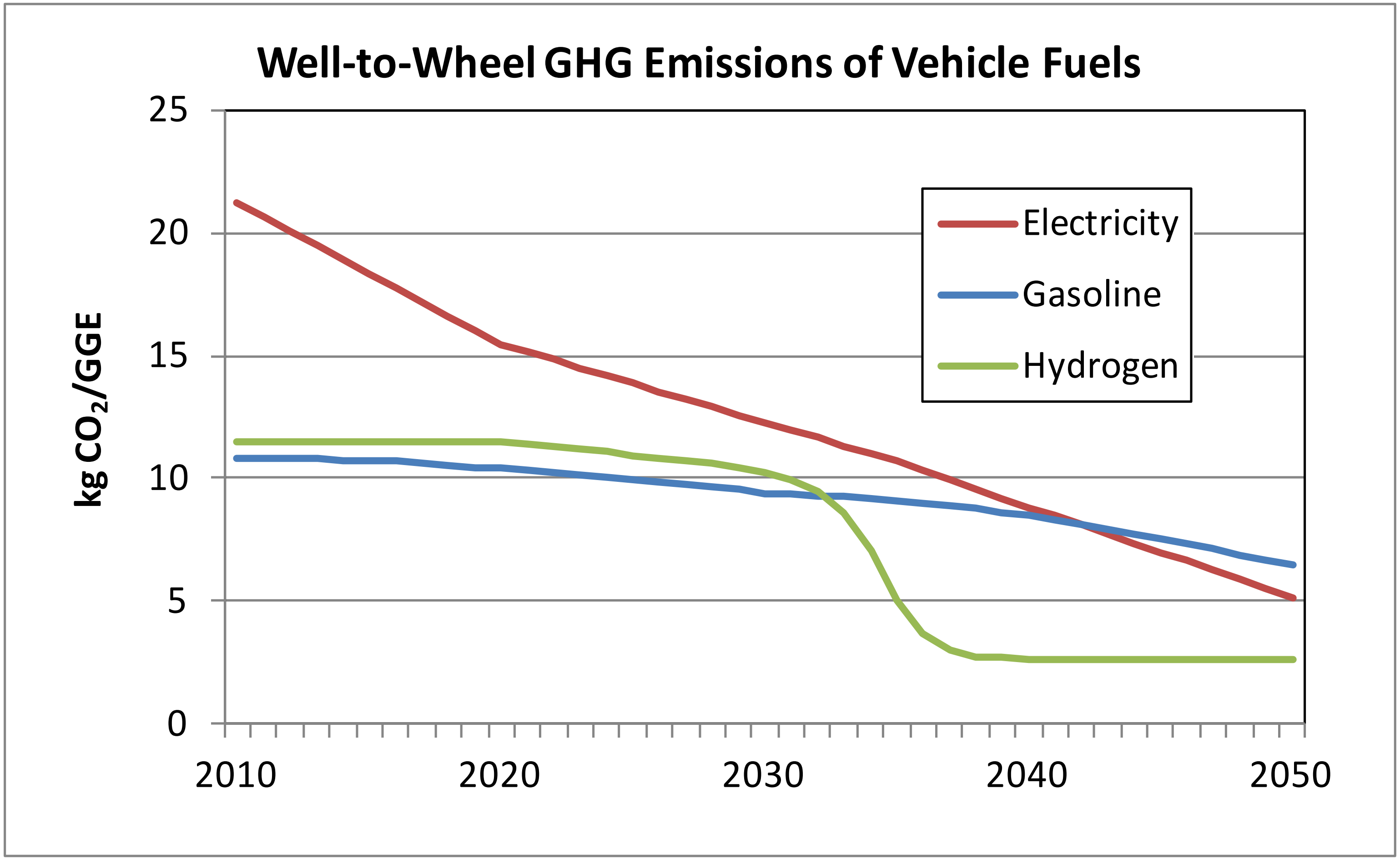
The implied subsidies are large but are no longer needed after 2030.



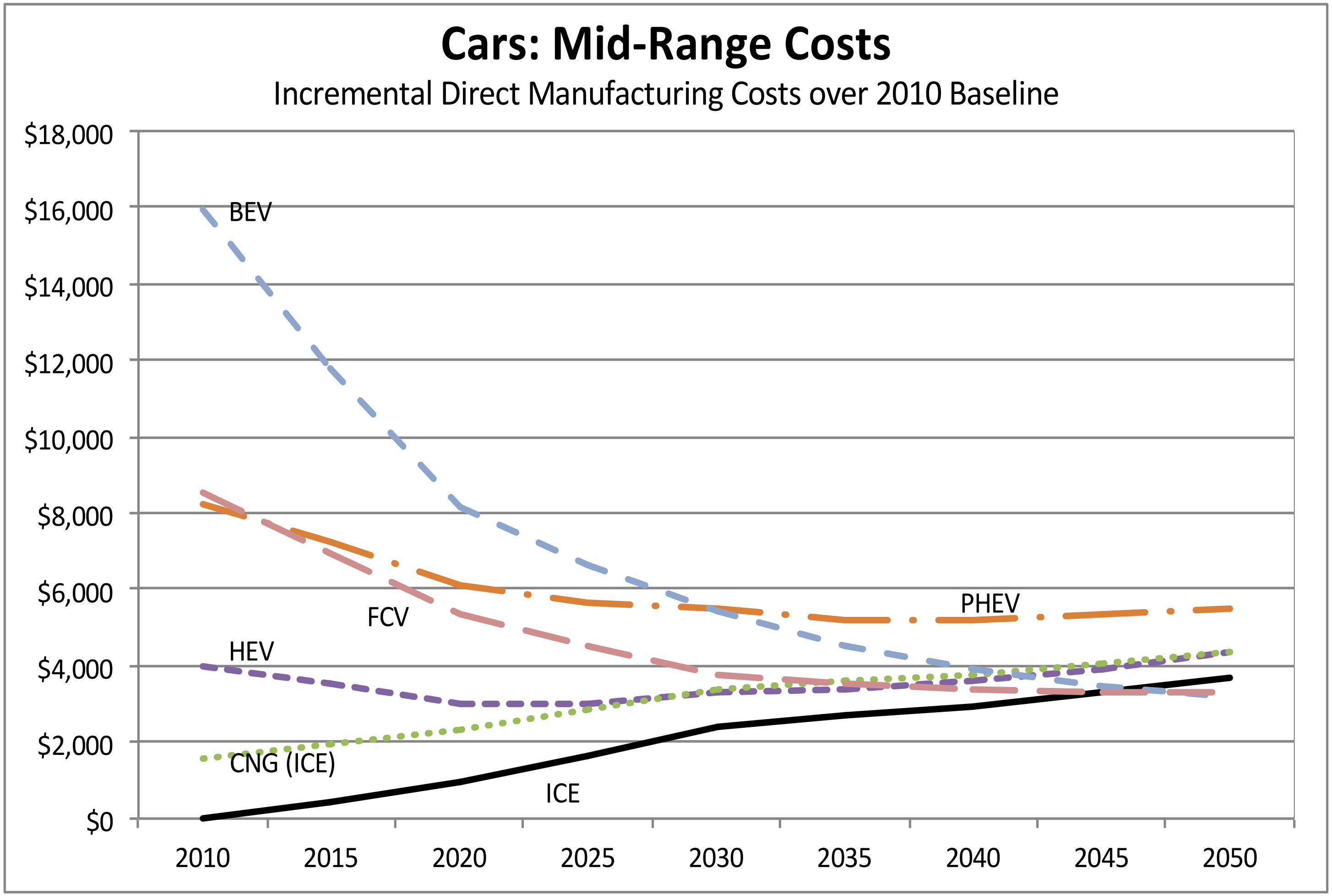
According to the parameter assumptions, innovators and early adopters drive the market for at least a decade.



All fuels reduce their WTW emissions. Gasoline becomes increasingly derived from biomass.



This graph shows high-volume, fully-learned incremental manufacturing costs.



NRC assumed battery costs would decrease in line with EPA/NHTSA/ARB assessment.

- EV range was assumed constant at 100 miles.

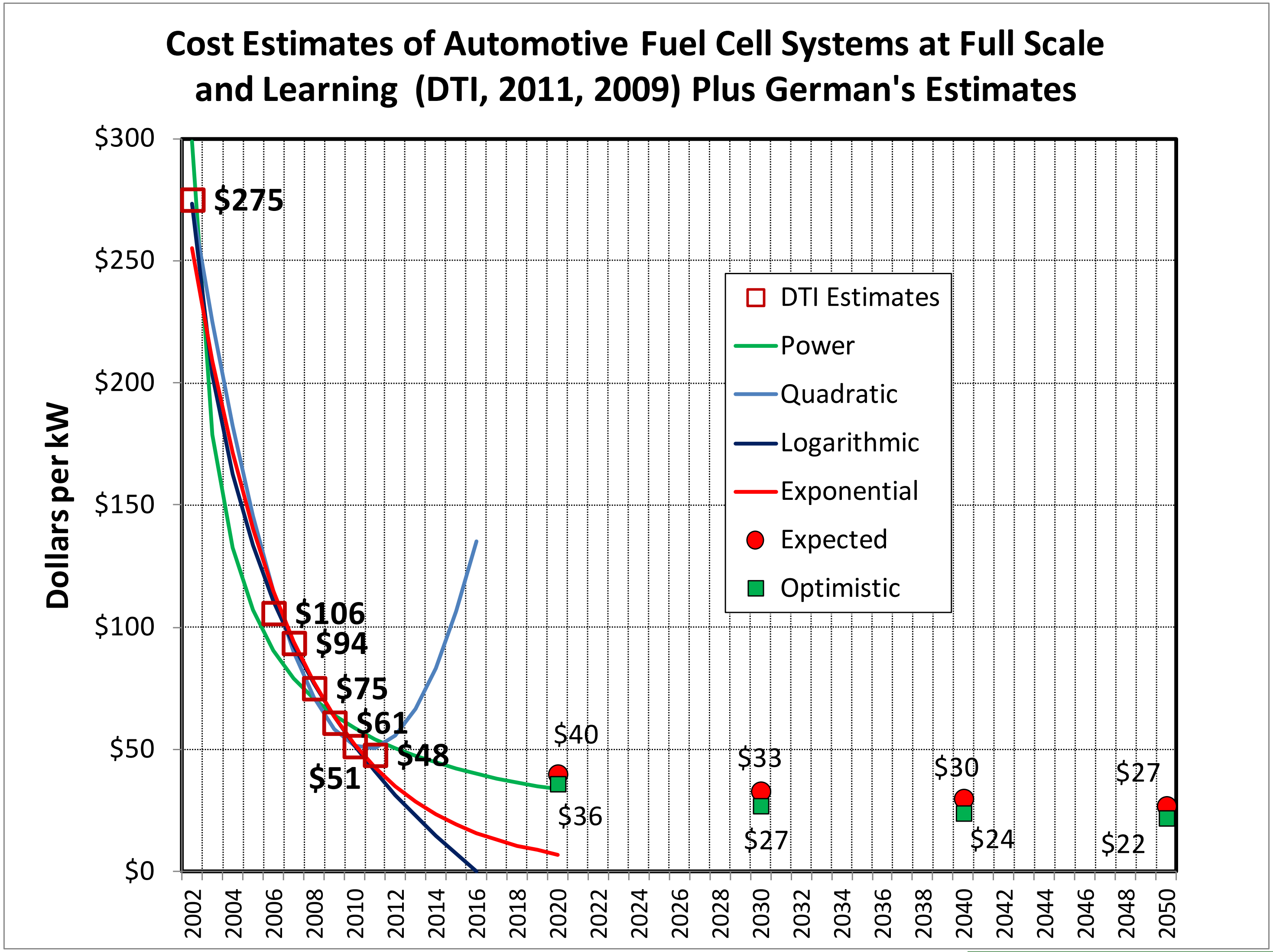
Technology	Units	2010	2030 (Mid/Opt)	2050 (Mid/Opt)
BEV battery	$/kWh	$450	$250/$200	$160/$150
PHEV battery	$/kWh	$550	$320/$260	$200/$190
HEV battery	$/kWh	$2,000	$750/$650	$650/$650
FC system	$/kW	$50	$33/$27	$27/$22

- Technological advances were taken as cost reductions.
- However, limited range and long charging times remain barriers to consumer acceptance.

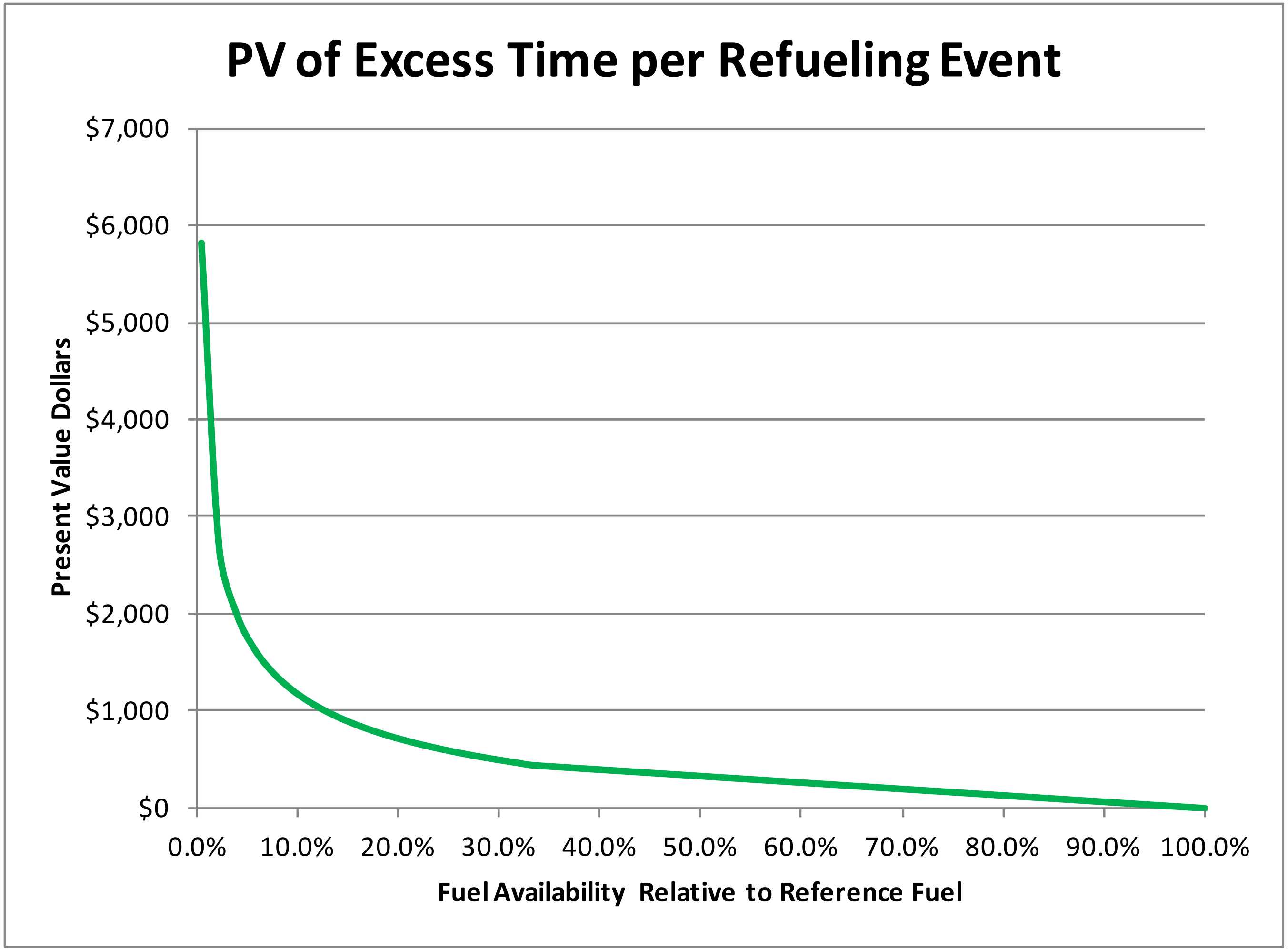
A significant amount of drop-in bio-fuel is in every scenario.

- Drop-in Biofuels (direct replacement for gasoline) can be produced from cellulosic biomass and introduced without major changes in delivery infrastructure or vehicles
- Achievable production levels at acceptable cost are uncertain, but the potential is large.
  - Maximum 2050 production:
    - 45 BGGE/700 Mt biomass/58M acres
  - Reference Assumption:
    - 13.5 BGGE/210Mt biomass/17M acres
- Drop-in Biofuels coupled with high efficiency ICEVs and HEVs could be a major contributor to reducing petroleum use and GHG emissions.

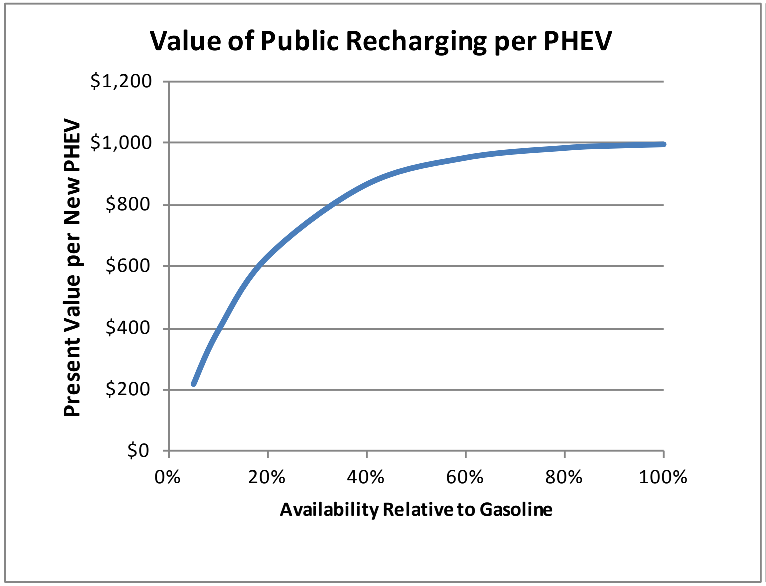
The historical progress of batteries and fuel cells is relatively clear. Future progress could be much slower and goals would still be met.

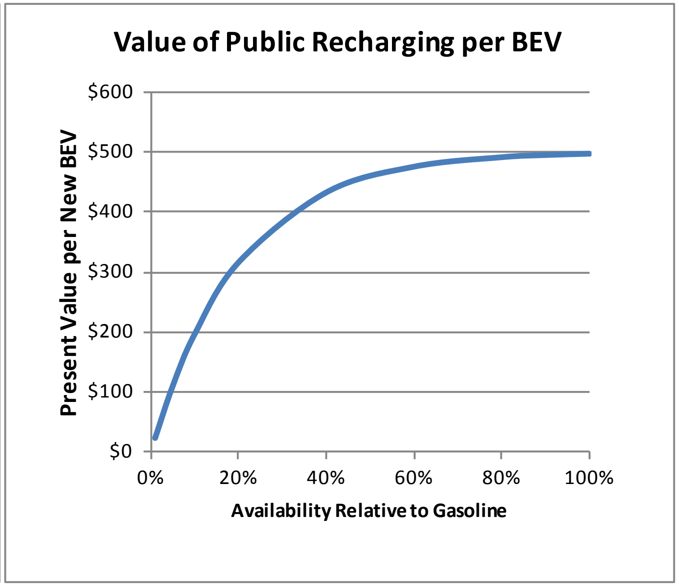


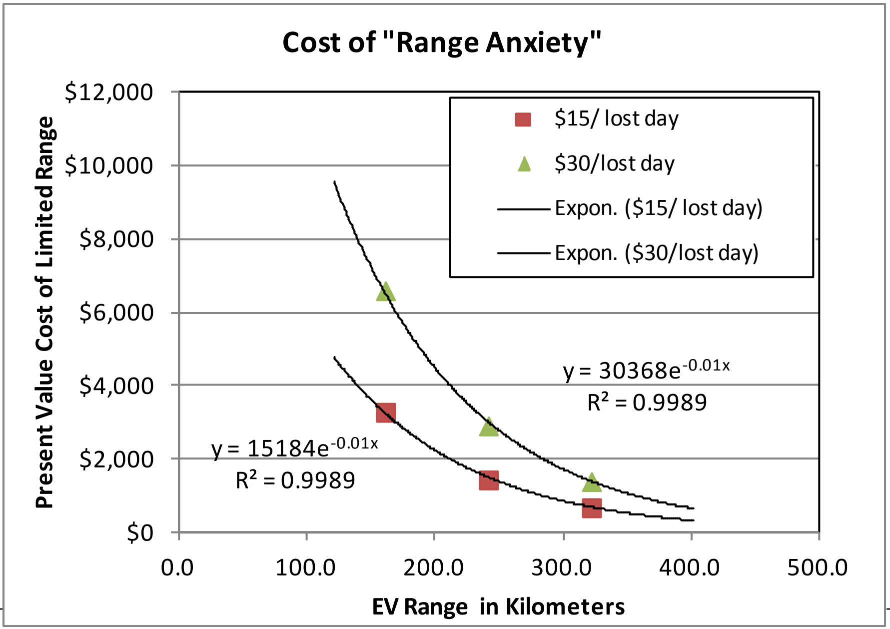
The cost of limited fuel availability is represented by the capitalized cost of increased time to travel to scarce stations.



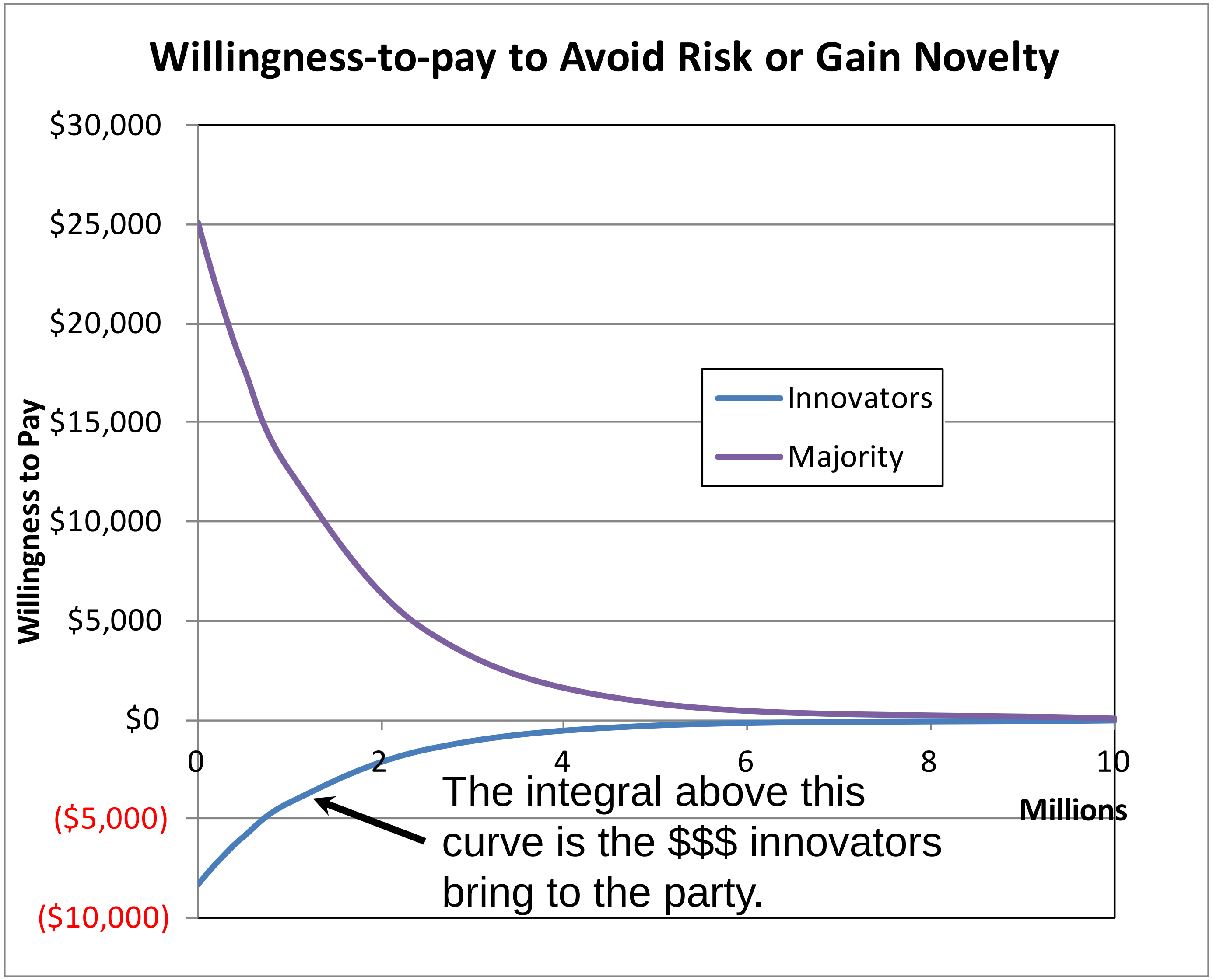
Costs of limited range/long refueling time, values of public recharging are capitalized in the price of vehicles.







The majority resists, innovators/early adopters will pay more for advanced technologies.



Other key parameters.

- Payback period for fuel savings: 3 years
- Price elasticities of vehicle choice:
  - Buy/No-buy: -1.0
  - ICE/HEV/PHEV: -4.8
- Economies of scale
  - Scale elasticity: -0.2
  - Full scale: 200,000 units
- Progress ratios: 0.95
- And more…

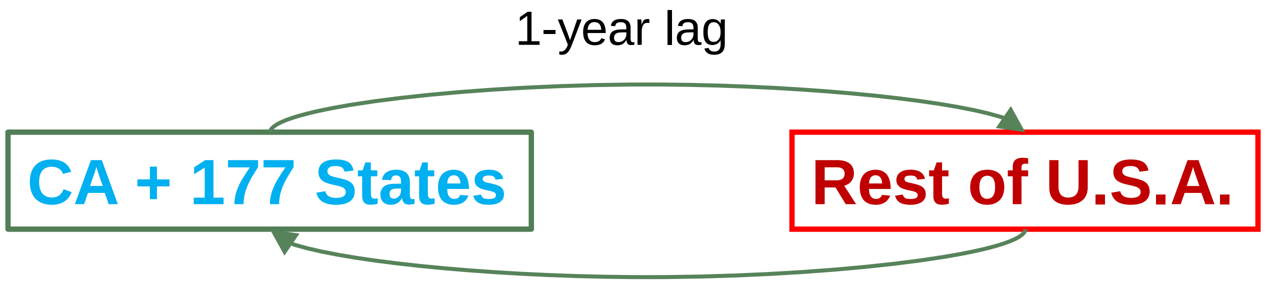
Most of the key parameters are not well understood. So do a sensitivity analysis.

Parameters	Distribution	Min	Mean	Max
Importance of diversity of makes and models to chose from	Triangle	0.50	0.67	0.9975932
Value of time ($/hr.)	Triangle	$10.00	$20.00	$39.86
Maximum value of public recharging to typical PHEV buyer	Uniform	$500	$1,000	$1,500
Cost of one day on which driving exceeds BEV range	Uniform	$10,002	$20,000	$29,999
Maximum value of public recharging to typical BEV buyer	Uniform	$0	$500	$1,000
Importance of fuel availability relative to standard assumption	Triangle	0.67	1.00	1.67
Payback period for fuel costs (yrs.)	Triangle	2.0	3.0	5.0
Volume threshold for introduction of new models rel. to std. assumptions	Uniform	0.80	1.00	1.20
Optimal production scale relative to standard assumptions	Uniform	0.75	1.00	1.25
Scale elasticity relative to standard assumptions	Uniform	0.50	1.00	1.50
Progress Ratio relative to standard assumptions	Uniform	0.96	1.00	1.04
Price elasticities of vehicle choice relative to standard assumptions	Uniform	0.60	1.20	1.80
Percentage of new car buyers who are innovators	Triangle	5.0%	15.0%	20.0%
Willingness of innovators to pay for novel technology ($/mo.)	Uniform	$100	$200	$300
Cumulative production at which innovators WTP is reduced by 1/2	Uniform	1,000,000	2,000,000	3,000,000
Majority's aversion to risk of new technology ($/mo.)	Uniform	-$900	-$600	-$300
Cumulative production at which majority's risk is reduced by 1/2	Uniform	$500,000	$1,000,000	$1,500,000

Transitioning to electric drive vehicles presents a new challenge for public policy.

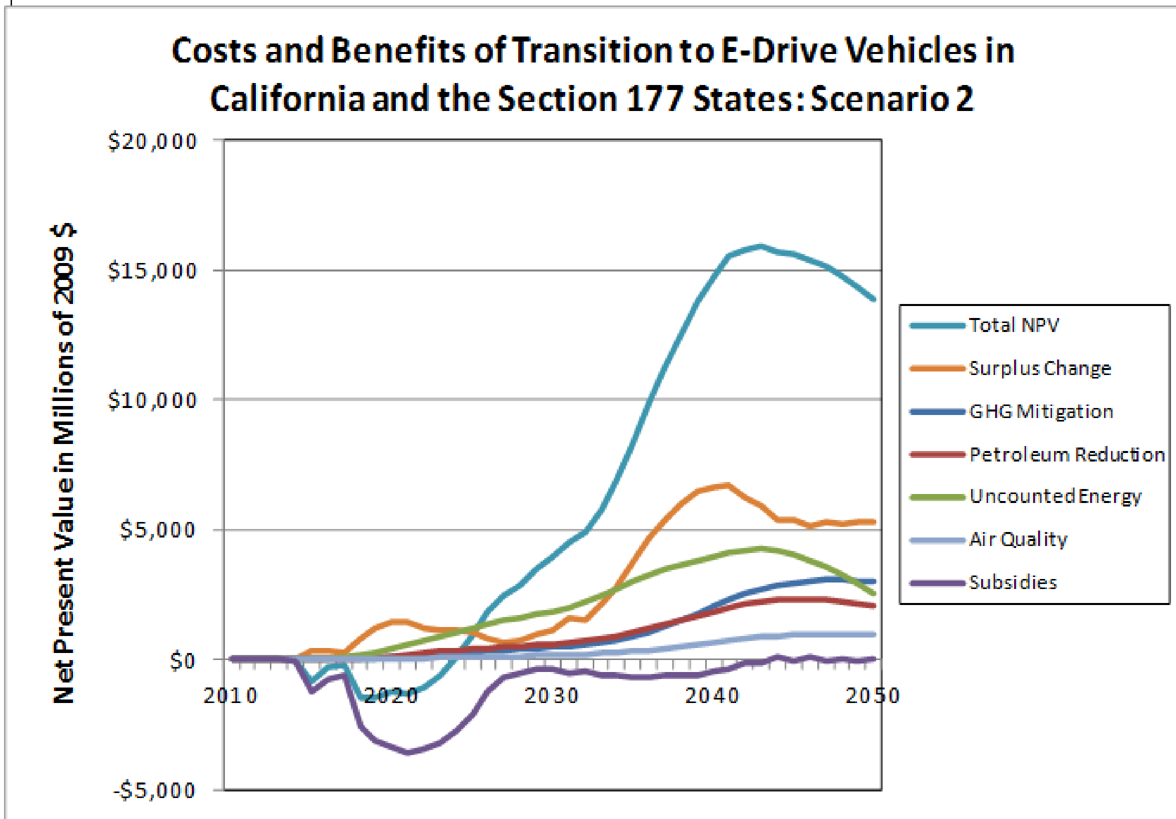
- The petroleum/internal-combustion-engine system has been refined over 100 years of use.
- The benefits sought are public goods:
  - Reduce GHG and other pollutant emissions
  - Reduce dependence on petroleum
- The transition will require 2-3 decades and the "valley of death" will last about 10 years.
- Today, the alternative technologies are not competitive without subsidies. Will they ever be?
- Internalizing external costs likely not enough; may need to internalize network external benefits too, and more.

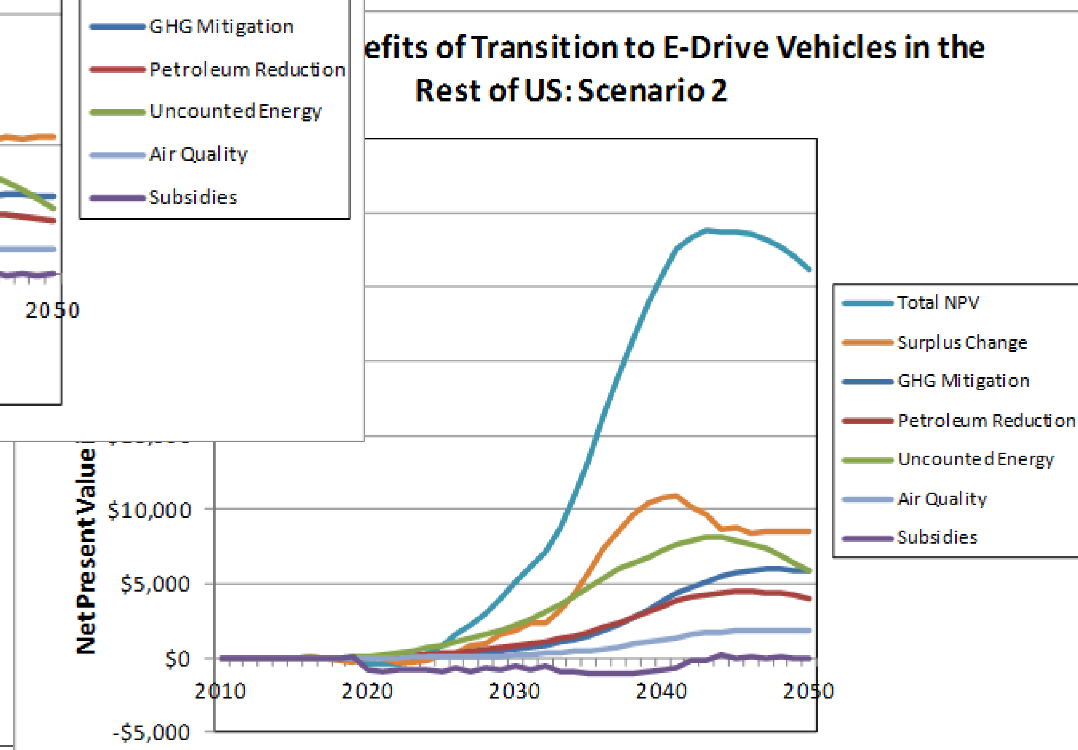
The analysis for CA and 177 states links 2 LAVE models together.



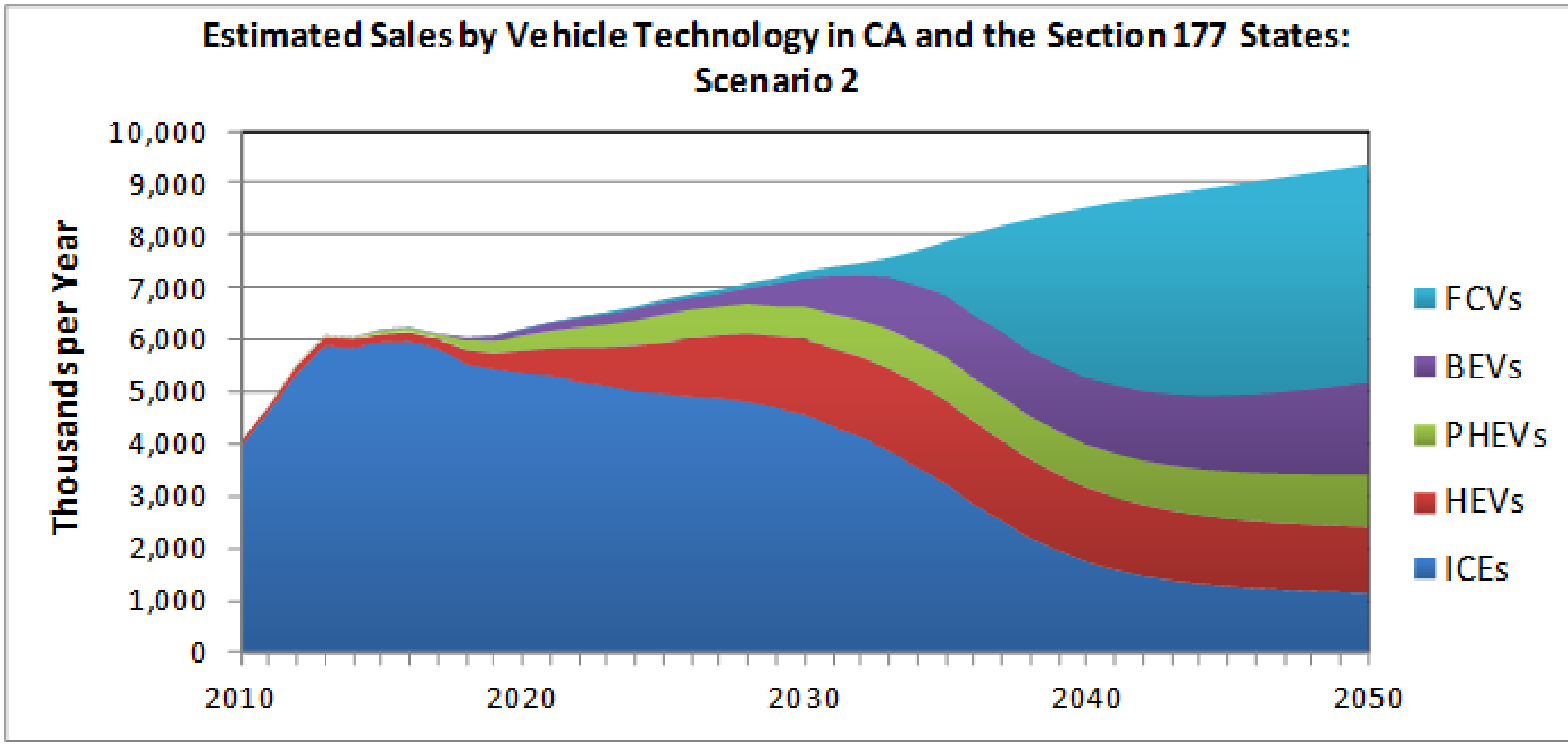
Benefits exceed costs by about an order of magnitude (technological success assumed).

(Co-benefits, co-benefits…)





With comparable US policies lagging by 5 years there is an earlier, more complete transition.



Society's determination was reflected in assumed marginal social values for oil and GHG reduction.