Integrated Market Modeling of Hydrogen Transition Scenarios with HyTrans

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Delivery, Storage and Hydrogen Pathways Tech Teams
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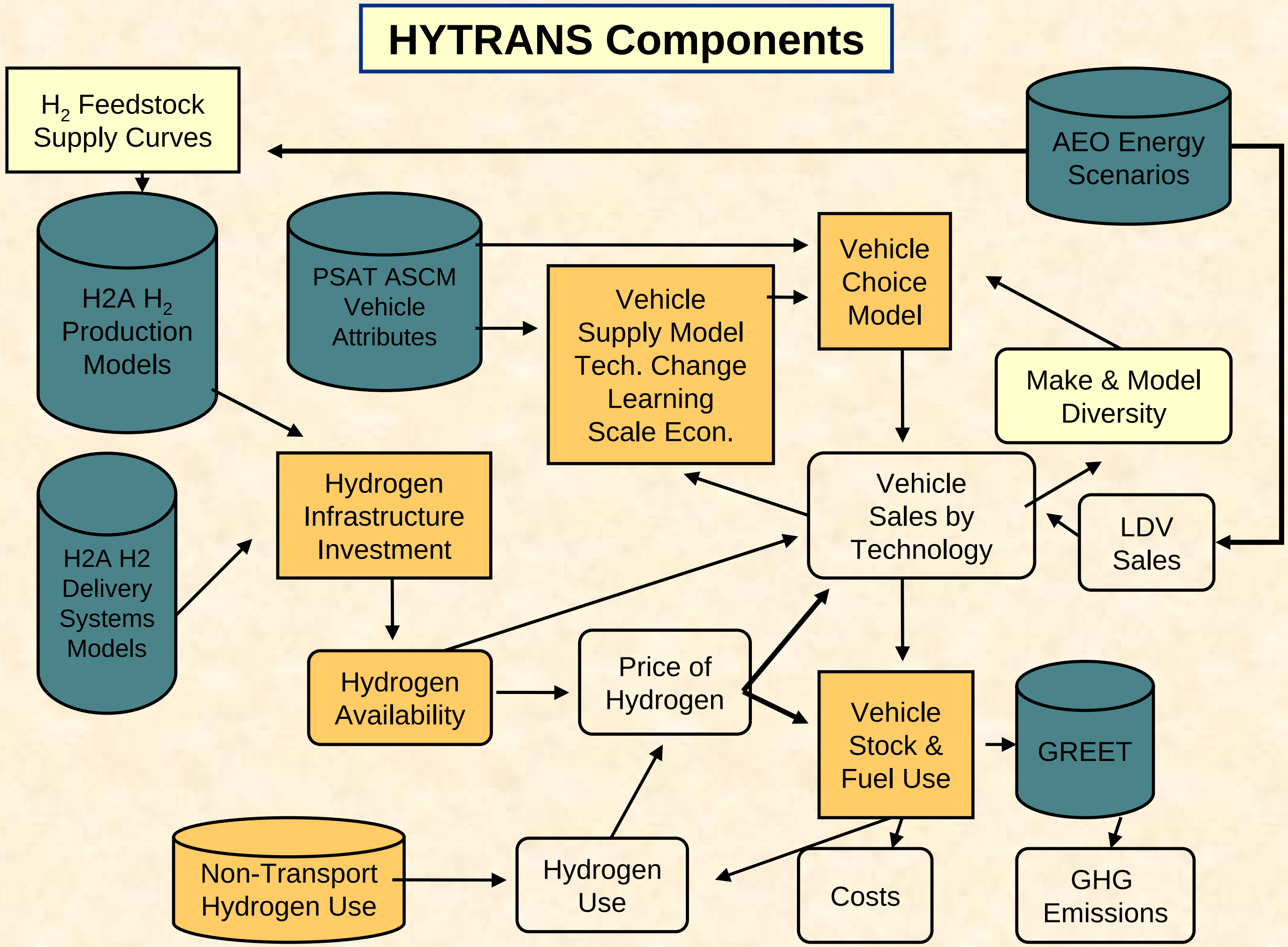
Drawing from several other DOE models, HyTrans integrates supply and demand in a dynamic non-linear market model to 2050.

- H2A
  - **Hydrogen Production**
  - **Hydrogen Delivery**
- PSAT & ASCM
  - **Fuel economy**
  - **2010/2015 cost & performance goals**
- ORNL Vehicle Choice Model
  - **Fuel availability**
  - **Make & model diversity**
  - **Price, fuel economy, etc.**
- Vehicle Manufacturing Cost Estimates (assisted by OEMs)
  - **Scale Economies**
  - **Learning-by-doing**
- GREET GHG emissions
- **Calibrated to** NEMS AEO 2006 **through 2030, the extrapolated to 2050 & beyond.**

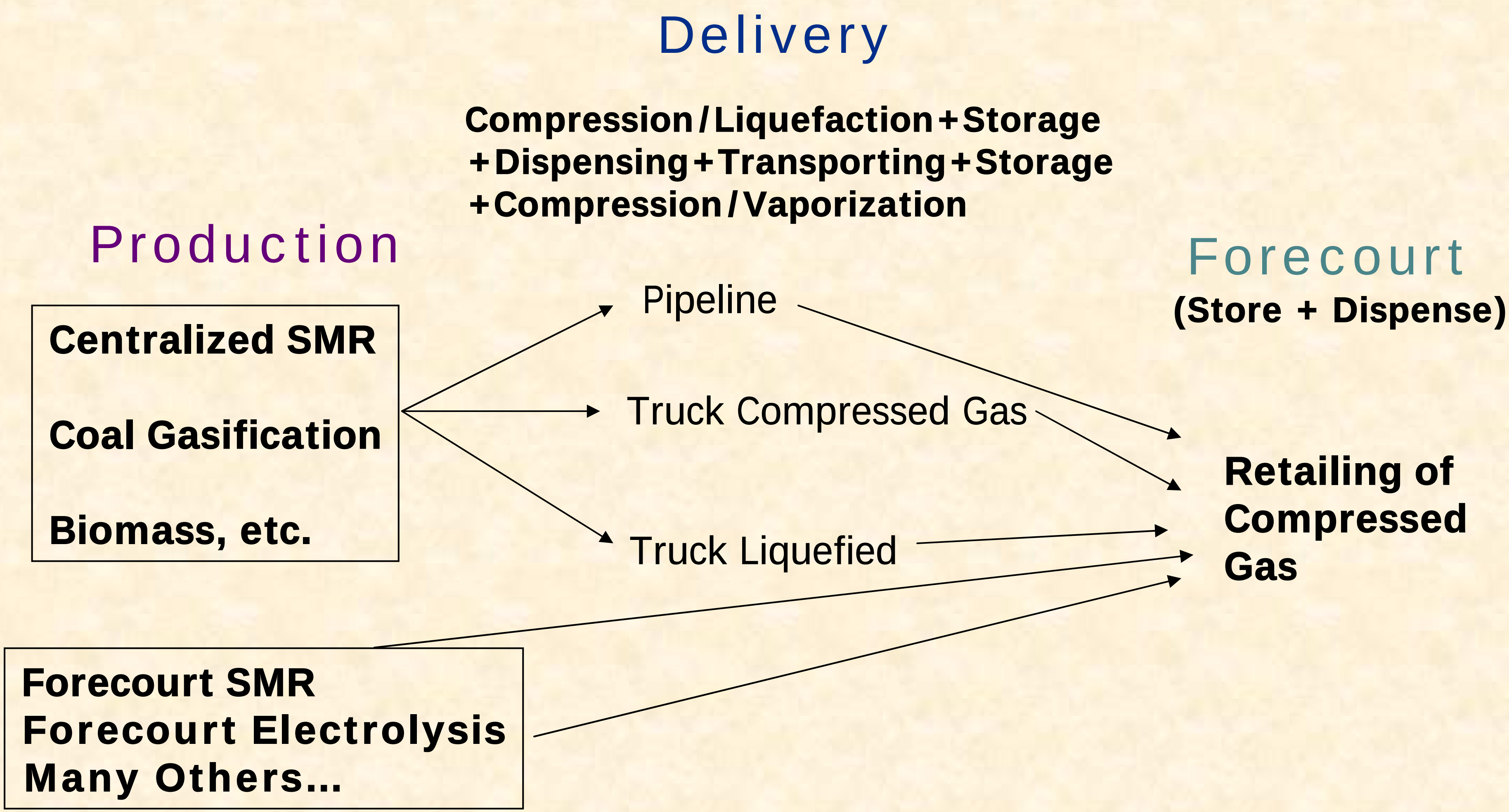
HyTrans represents the key agents: 1) fuel supply, 2) vehicle manufacture, 3) consumer choice.



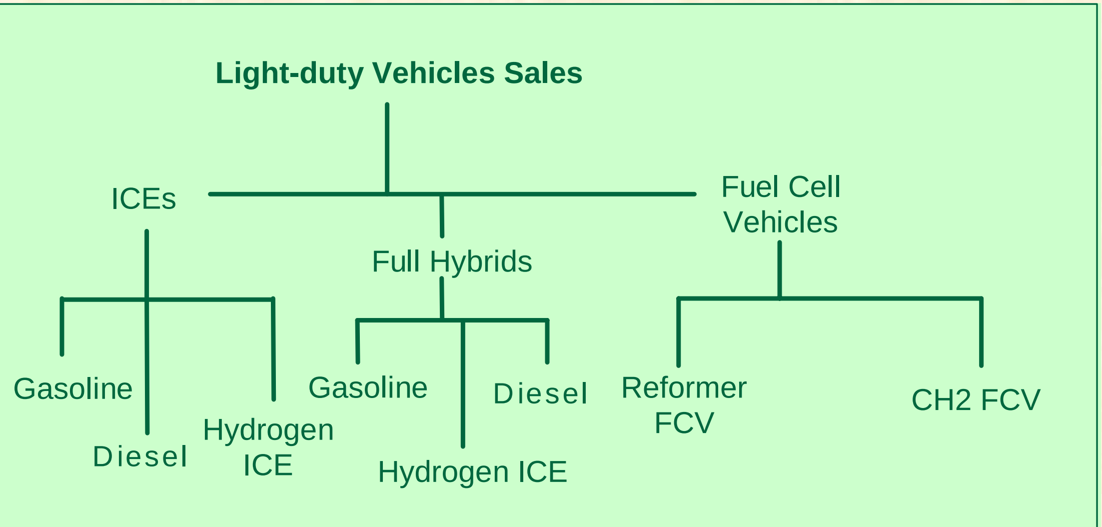
HyTrans' method is economic modeling via non-linear optimization of consumers' and producers' surplus.

- **Production pathways: cost functions (H2A)**
- **Vehicle production: cost functions (PSAT/ASCM)**
- **Consumer demand: NMNL/representative consumer**
- **3 geographic, 3 fuel demand density regions**
- **Key dynamic elements:**
  - **Learning-by-doing**
  - **Technological change**
  - **Scale economies**
  - **Fuel availability**
  - **Diversity of vehicle choices**
- **Positive feedbacks create multiple local optima and necessitate search methods to find global optimum.**

H2 Supply pathway costs are reduced form versions of the DOE H2A production and delivery models.



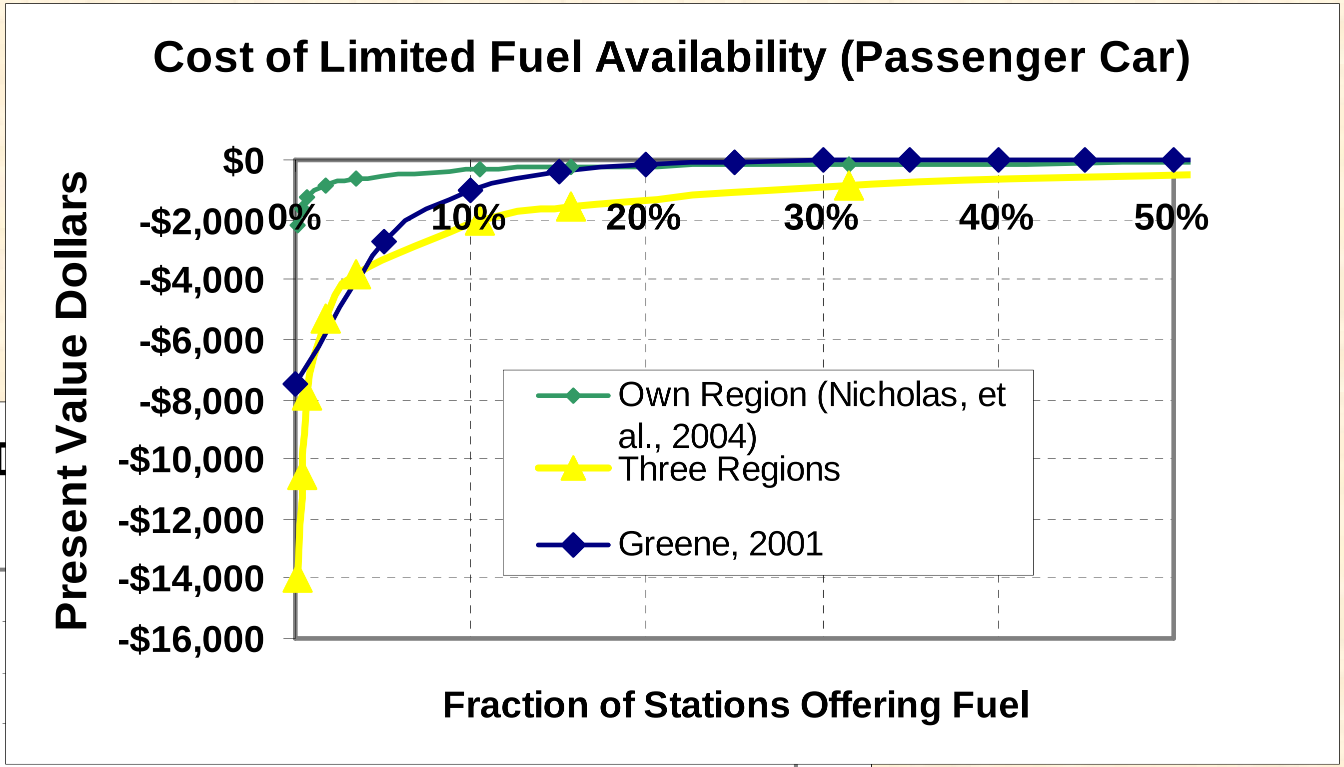
The market shares of alternative drivetrain technologies are modeled as a representative consumer, random utility function of their attributes, fuel availability and the diversity of make and model choice.

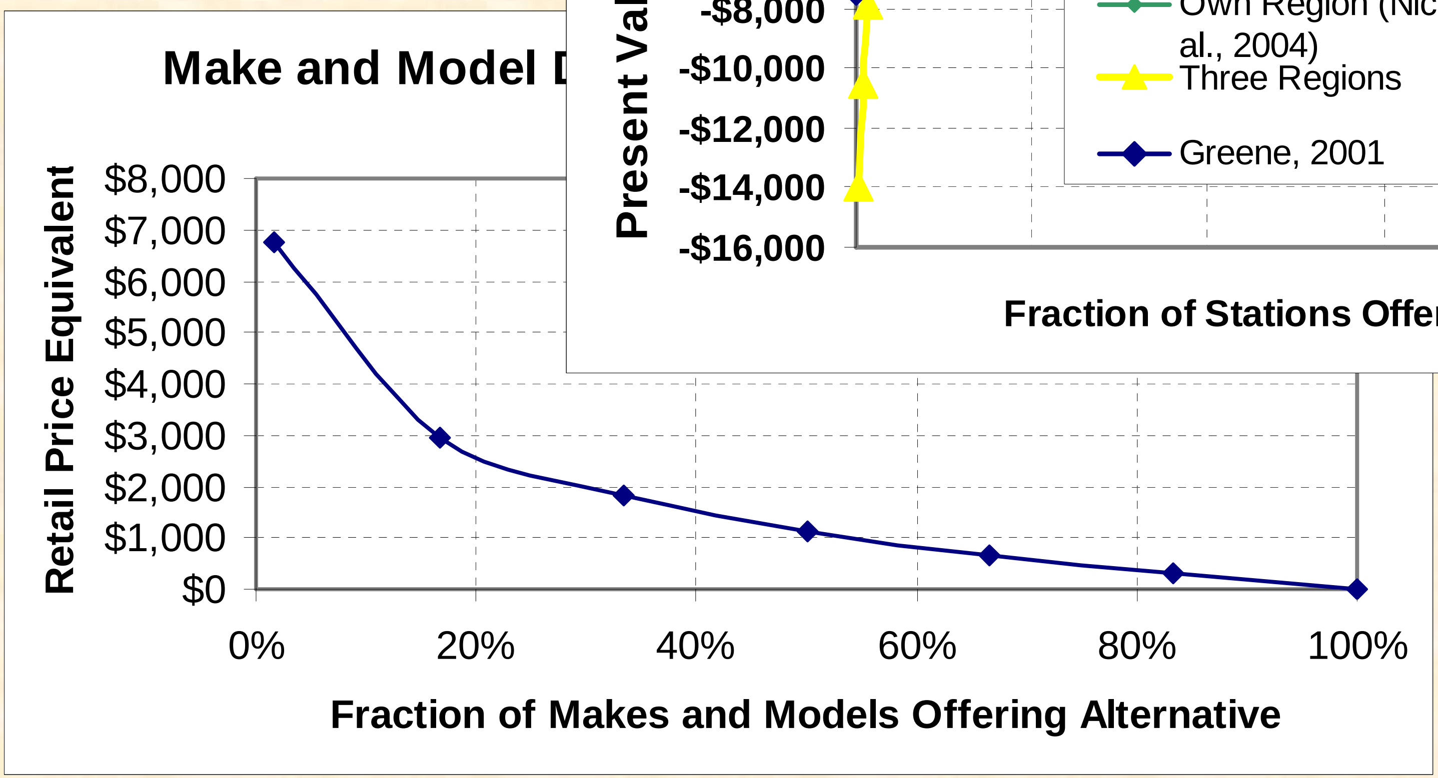


	NAS 2004	HyTrans
Retail Price	X	X
Operating (fuel) cost	X	X
Maintenance cost	X	X
Range	X	X
Passenger/cargo space	X	Cargo
Performance (accel. +)	X	Accel
Quality	X	No
Safety	X	No
Battery cost	No	X
Value of electricity generation	No	X
Extra value of fuel cell vehicle	No	X

HyTrans' vehicle choice model includes most variables the NAS (2004) report listed as important.

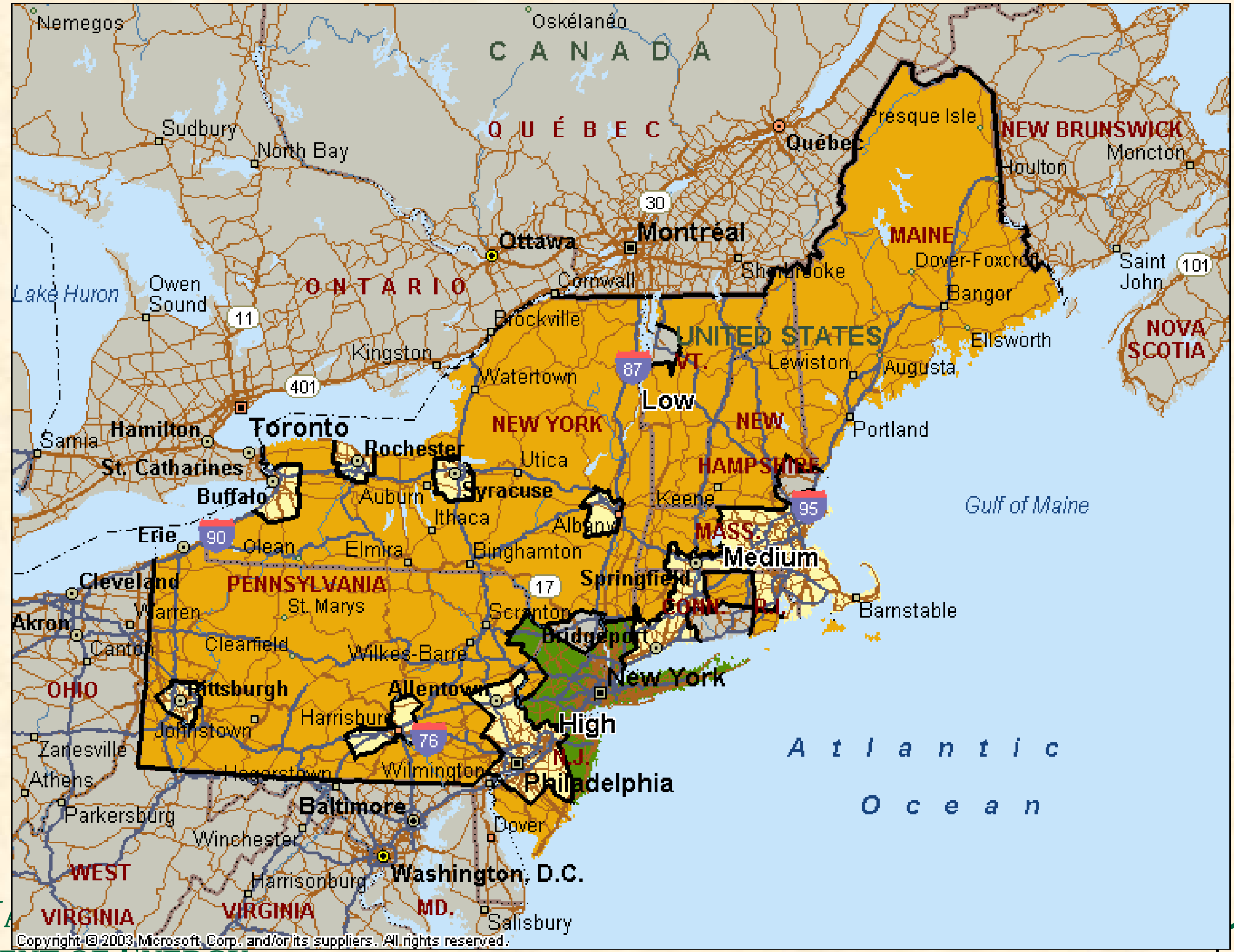
The values of fuel availability and make & model diversity: important to the early transition, but very uncertain.





UT-BATTELLE

The U.S. is divided into 3 geographical regions and each region is divided into three fuel demand density regions. Regions & subregions may have different hydrogen production and delivery pathways & different vehicle technology choices.



Hydrogen Delivery Representation in HyTrans

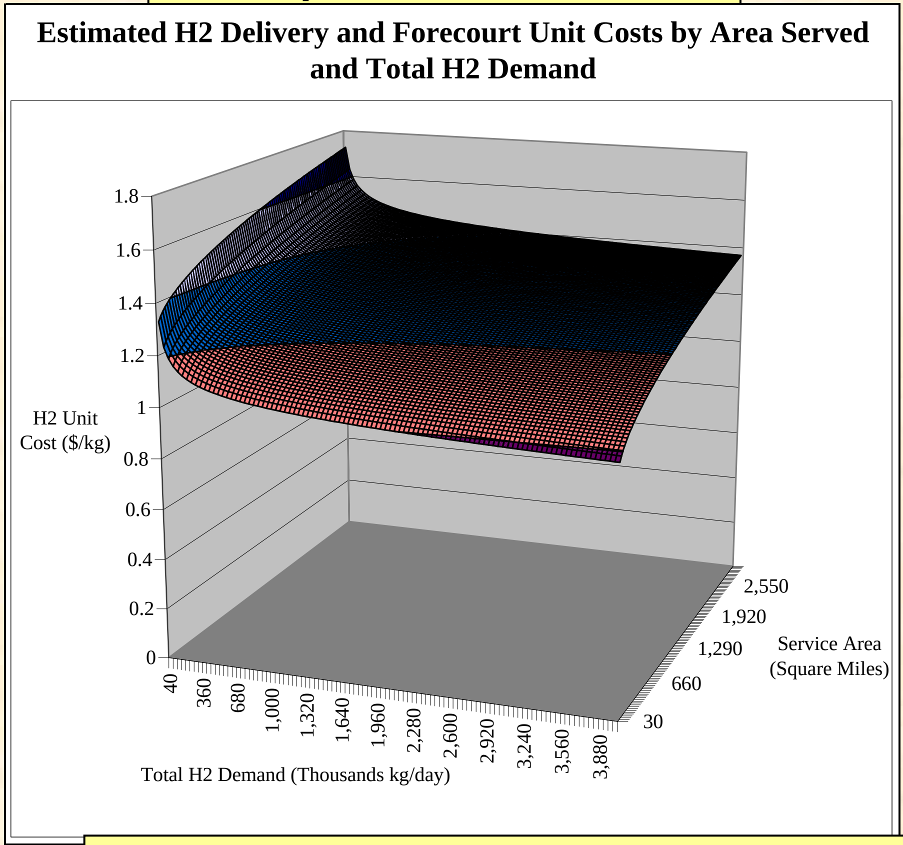
- **Two types of production processes**
  - Central and distributed
- **Define the delivery options available for each central process**
  - One delivery mode selected endogenously for each plant
    - No mixed modes, or multiple modes
  - Current modes: liquid truck, gaseous truck, pipeline
  - Cost and energy use of delivery technologies can evolve over time (as exogenously specified)
- **Closely benchmark delivery costs to H2A/HDSAM**

Delivery: For each mode, H2A/HDSAM Costs are Accurately Represented in Reduced Form by a Smooth Function of Scale and Density

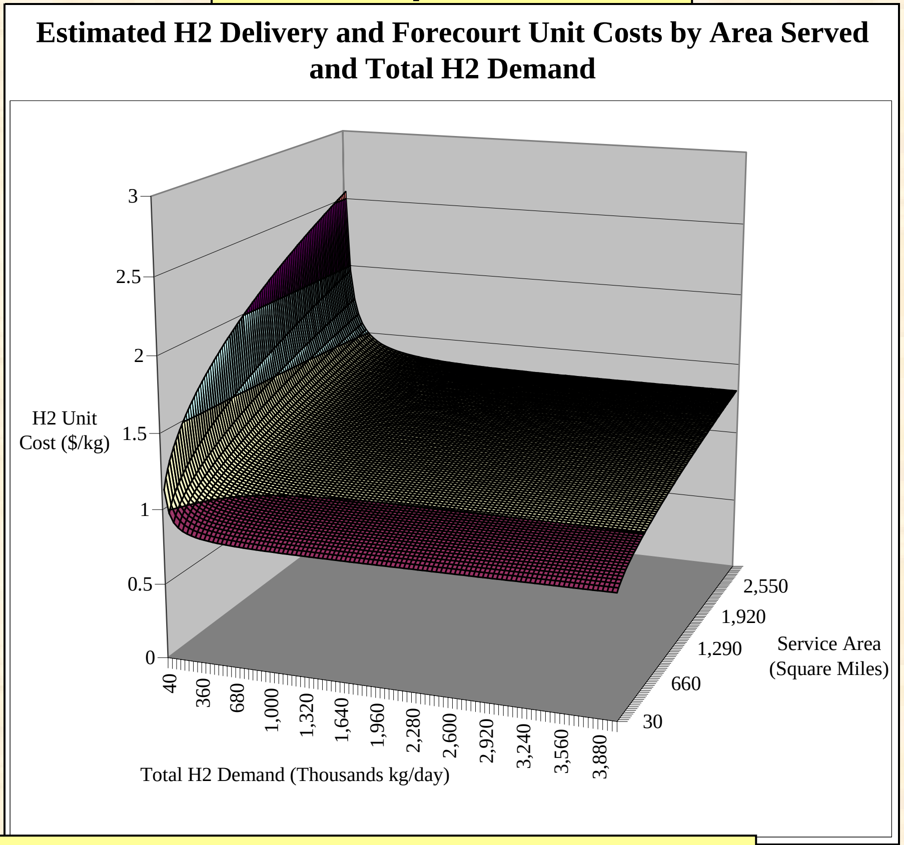
- **Delivery distance to city edge is currently specified exogenously (currently 31 miles)**
- **Currently, scale of delivery operation/infrastructure is matched to scale of plant**
  - **Need to consider extension to shared infrastructures**
  - **Key point: liquefier scale matches plant scale, except scale economies limited to 100 TPD**
- **Given delivery scale Q, plant service area A can be determined from region's average demand H2 density D_H**
  - **Mode-dependent relationship between L and D**
- **Retail station size influence cost thru ave. distance and scale**
  - **Station size currently fixed and exog specified (1.5 TPD, 70% c.f.)**

Delivery: H2A/HDSAM Yields Smooth Costs as Function of Demand Volume and Area (Very different shapes by mode)

Compressed Gas Truck



Pipeline

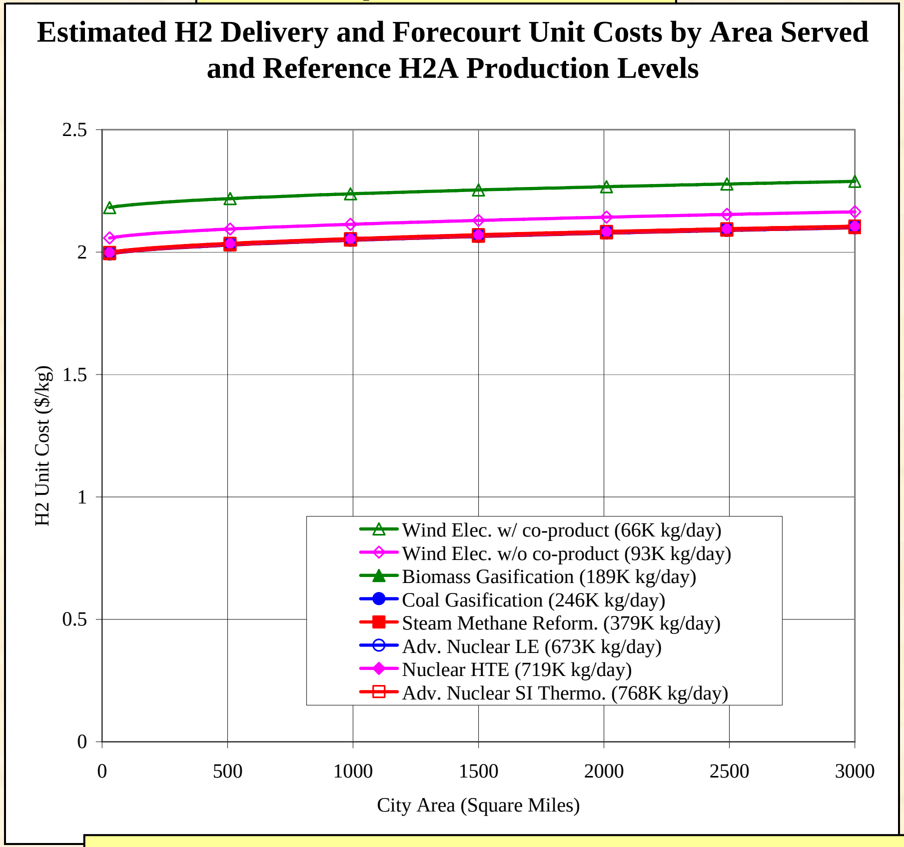


Distance to city 31 mi, Retail station throughput 1.05 TPD

Current benchmarking source: \HDSAM\Scenario_Components_V1.0_050206 2017 _v6_2007Feb12_exportedToHytrans.xls

Delivery: Equivalently, for each production plant type at its max scale, can determine cost vs. plant's service area

Liquid Truck



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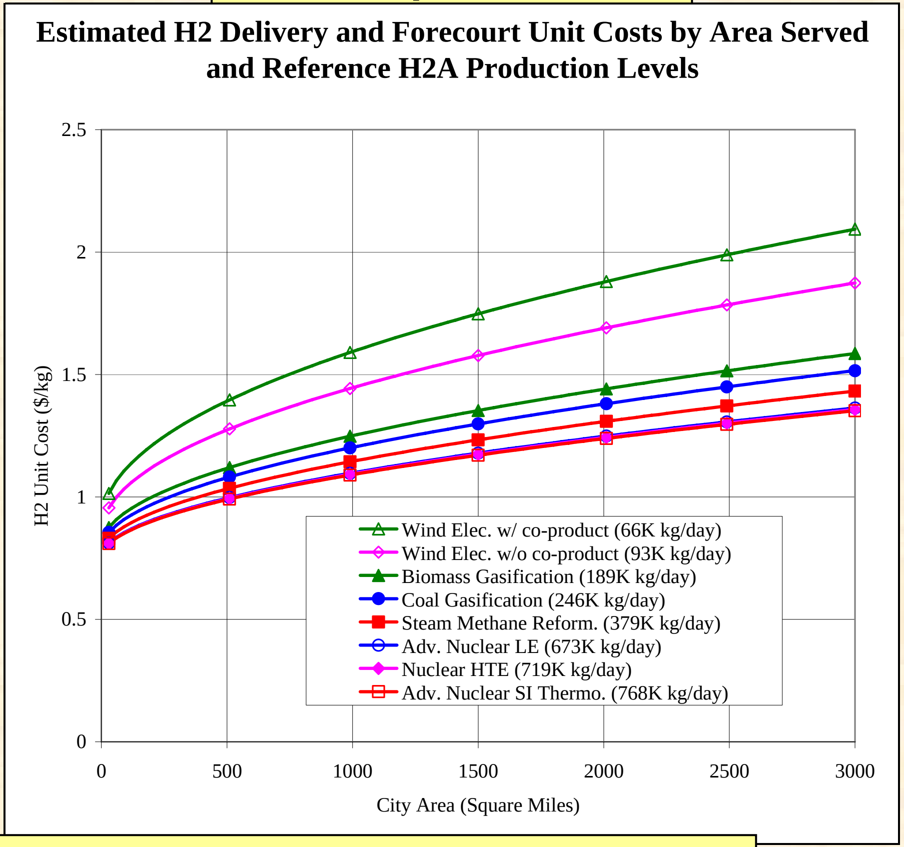


Distance to city 31 mi, Retail station throughput 1.05 TPD, Liquefier max scale 100 TPD

Current benchmarking source: \HDSAM\Scenario_Components_V1.0_050206 2017 _v6_2007Feb12_exportedToHytrans.xls

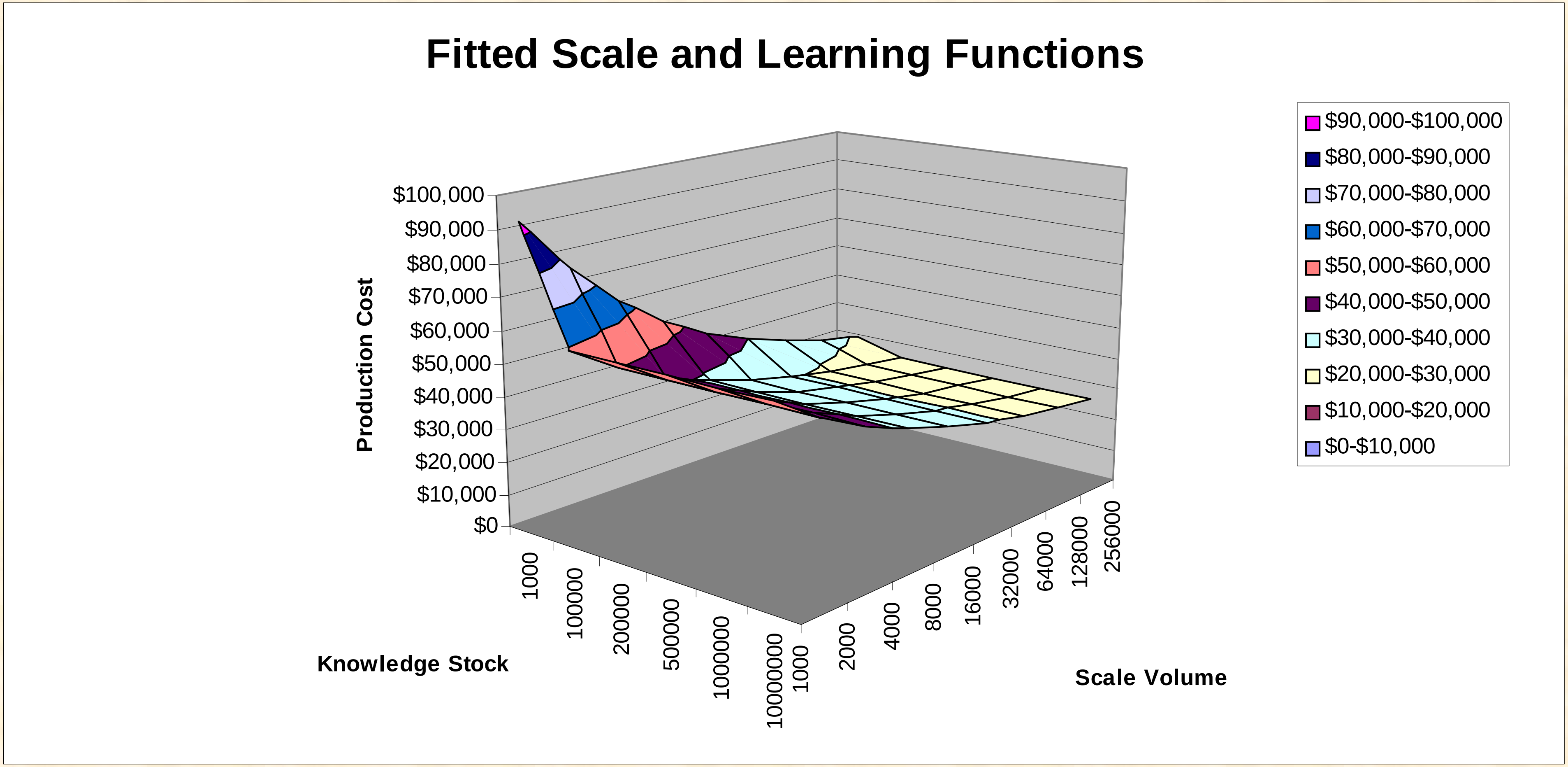
A new vehicle cost model was calibrated with data provided by OEMs.

- **Three multiplicative factors:**
  - **Independent tech-progress,**
  - **Learning-by-doing and**
  - **Scale economies.**
- **Vehicle Price =**

  Glider Cost +

  Long-run Drivetrain Cost x Technology(time) x Learning-by-doing(stock) x Scale(volume)
- **Independent Technology progress**
  - **calibrated to DOE 2015 goals**
  - **"in the lab" + available in vehicles in 5 years**
- **Learning & Scale**
  - **calibrated to central tendency of manufacturers' cost estimates.**

Learning is exponential and **asymptotic** to the program goals (not usual functional form), scale has a constant elasticity of approximately -0.25.



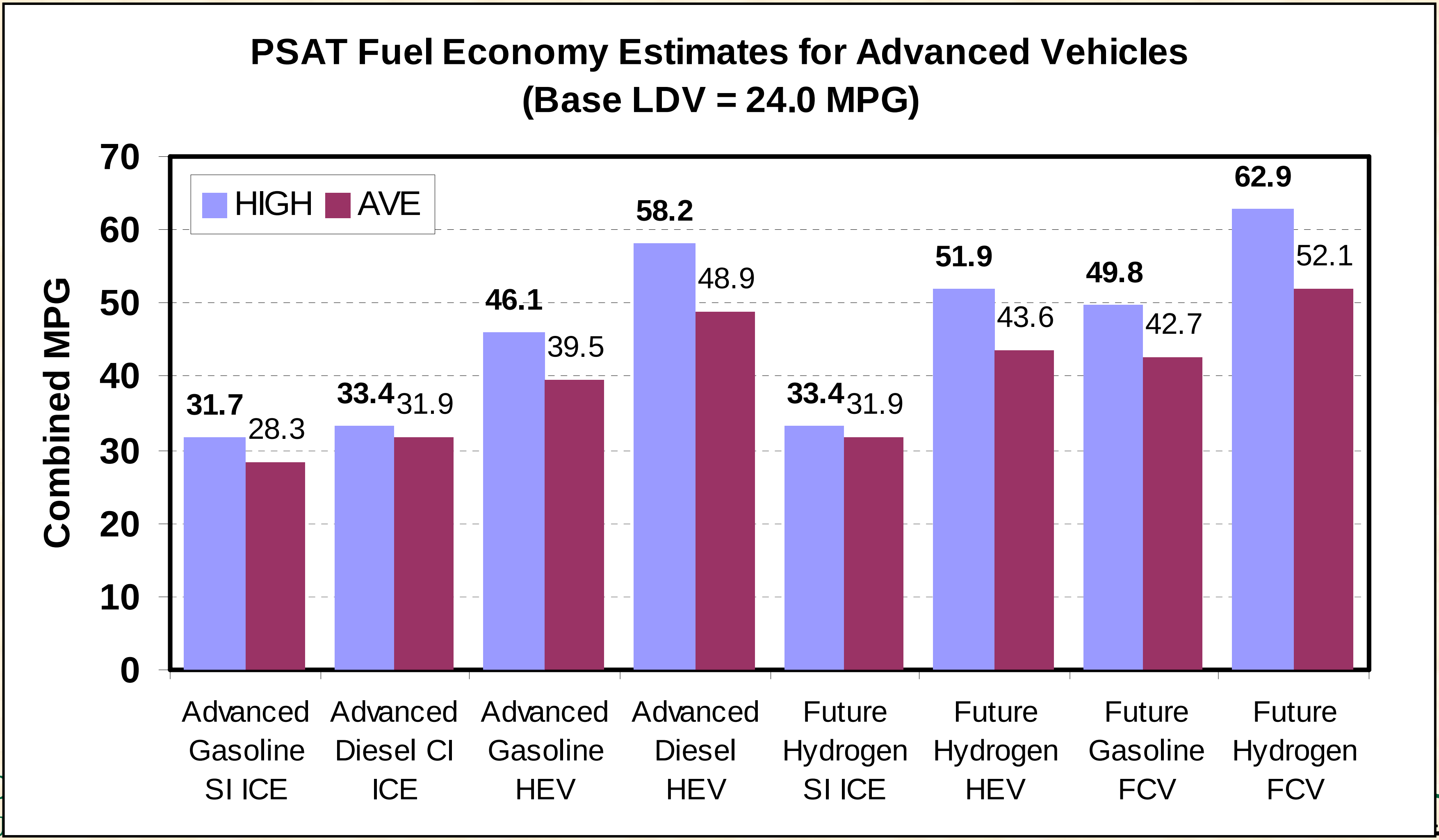
HyTrans was used to evaluate the impacts of early transition scenarios.

- **In the early transition, the model is constrained to meet the scenario sales targets.**
  - **2010/15 DOE technology targets assumed to be met.**
  - **HyTrans estimates costs of vehicles and hydrogen, infrastructure investments and implicit subsidies.**
  - **HyTrans estimates benefits of learning-by-doing, scale economies, fuel availability and market diversity.**
- **In the later period (2025-2050) no vehicle and fuel subsidies are assumed. Are they needed for a durable transition?**
  - **Evaluate impacts of achieving program goals, or not**
  - **Investigate competition with other advanced technologies**
  - **"Cost out" the transition, to government & industry**
  - **Calculate benefits to oil dependence, GHG emissions**

Two sets of technology assumptions were considered: "Success" and "Shortfall" for FCVs.

	DOE 2015 Goals "Success"	Rousseau et al. Average Progress "Shortfall"
Fuel Cell System ($/kW)	$30	$60
On-Board H2 Storage ($/kWh)	$2	$10
Motor ($/kW)	$4	$4.50
Batteries ($/kWh)	$20	$25
Gasoline ICE Engine Only ($/kW)	$21	$22
Diesel ICE Engine Only ($/kW)	$21	$24

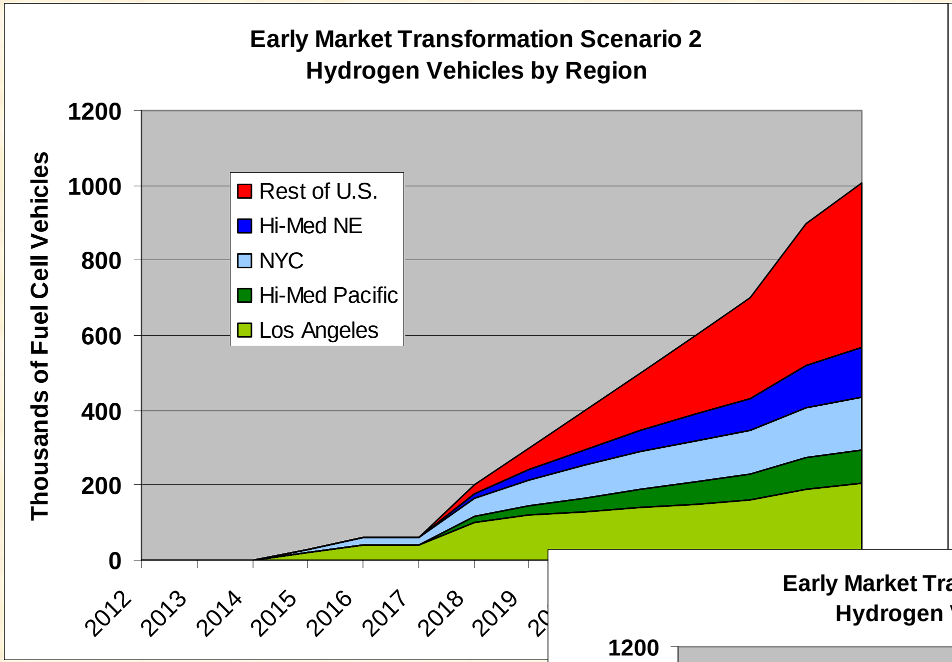
The Tech. Success scenario estimates higher MPG, especially for electronic drive systems.

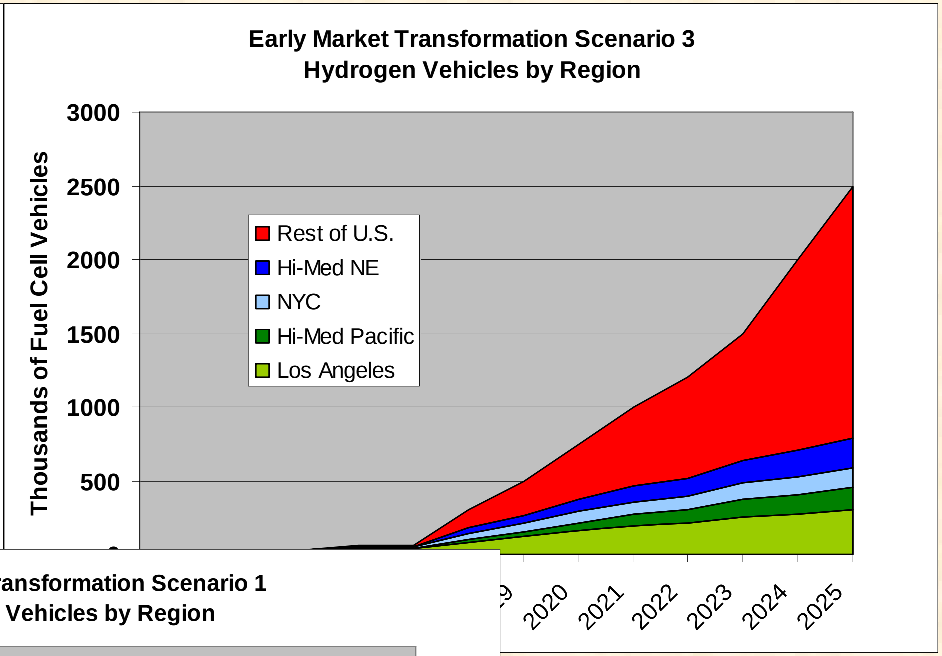


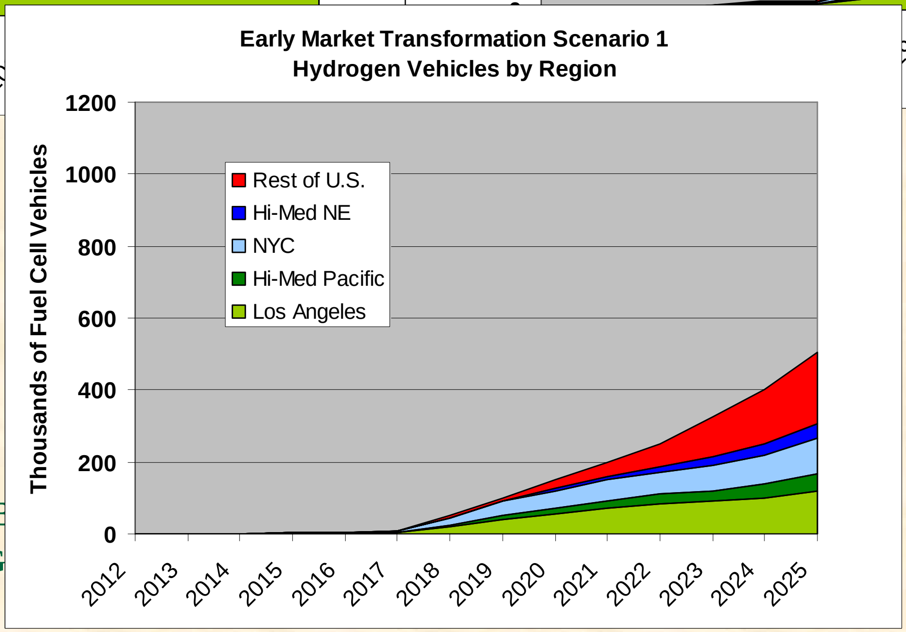
12 “Futures” were analyzed.

Future	Vehicle Tech Success Assumptions	AEO 2006 Oil Price Case	CO_2 Constraint	BioFuels Program	Early Transition Scenario	Policy Cases	Post-2025 Policies
1.	Technology Success	High	No	No	0	All 3 cases	None
2.	Success	High	No	No	1	All 3 cases	None
3.	Success	High	No	No	2	All 3 cases	None
4.	Success	High	No	No	3	All 3 cases	None
5.	Success	High	Yes	No	0	All 3 cases	None
6.	Success	High	Yes	No	1	All 3 cases	None
7.	Success	High	Yes	No	2	All 3 cases	None
8.	Success	High	Yes	No	3	All 3 cases	None
9.	Technology Shortfall	High	Yes	No	3	Case 2	None
10.	Success	Reference	Yes	No	3	Case 2	None
11.	Success	High	Yes	Yes	3	Case 2	None
12.	Success but $8/kwh storage	High	Yes	No	3	Cases 2 & 3	None

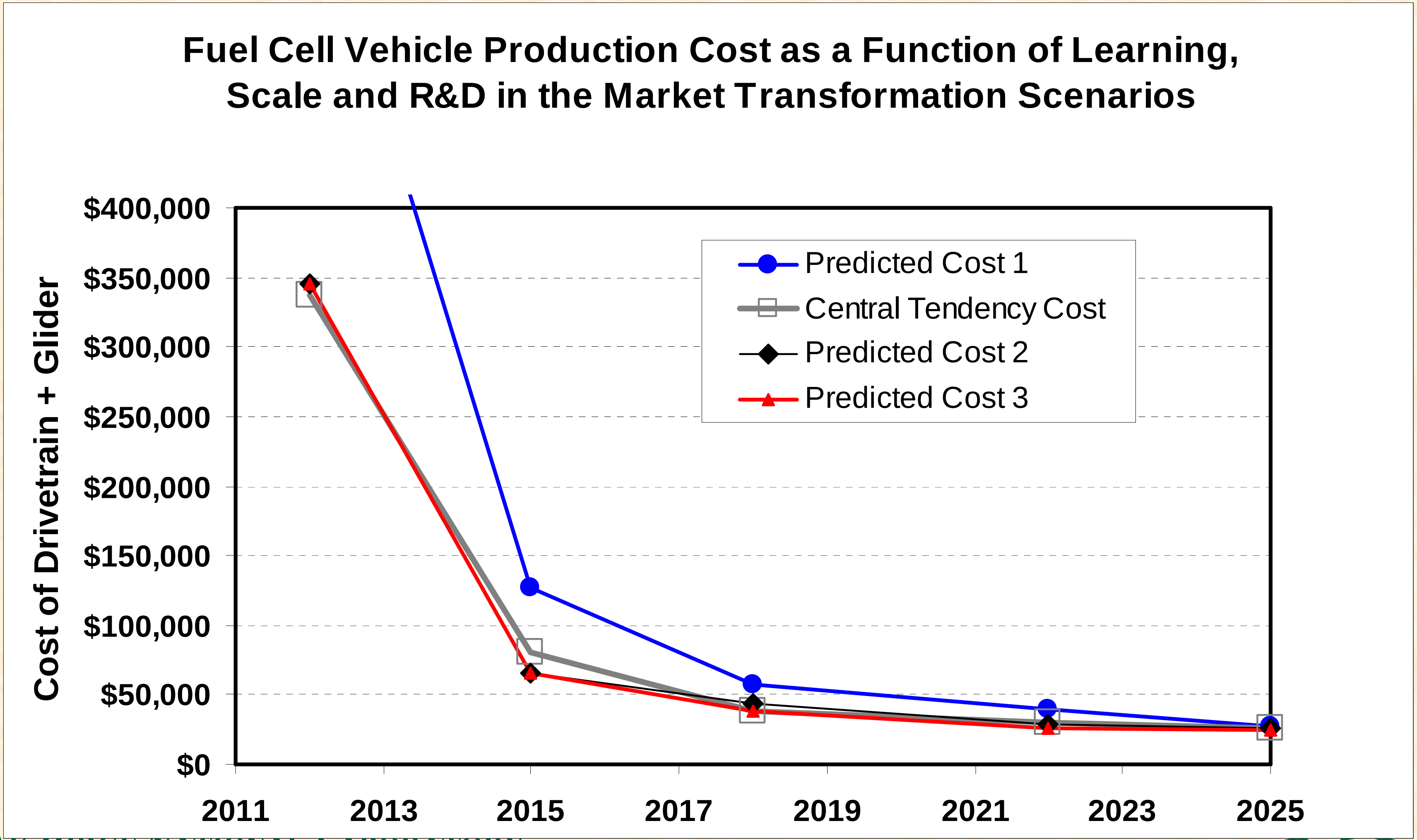
3 scenarios were analyzed requiring 2, 5 and 10 million hydrogen FCVs on the road by 2025, respectively. In all, 12 scenarios with differing technology and policy assumptions were run.



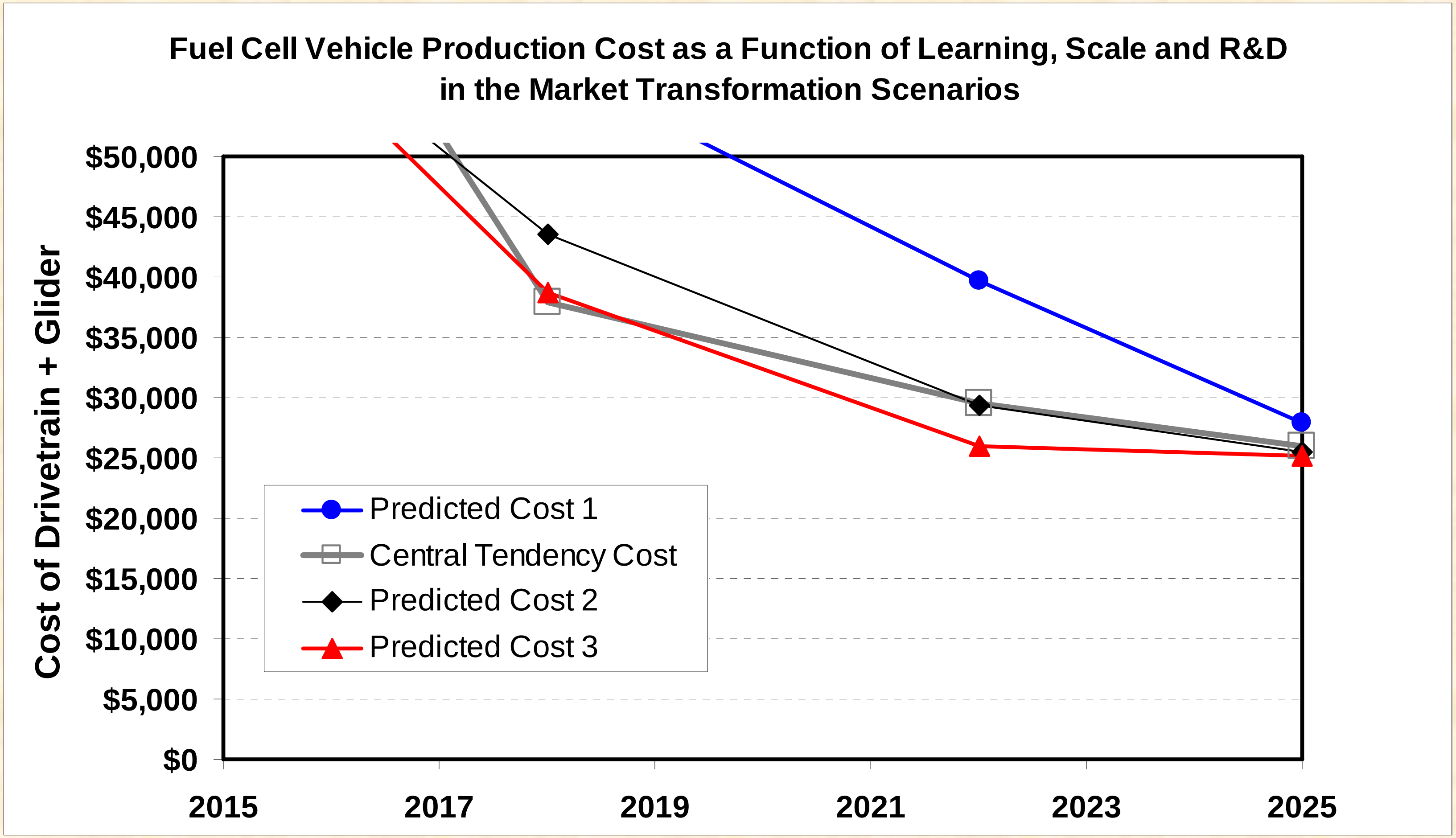




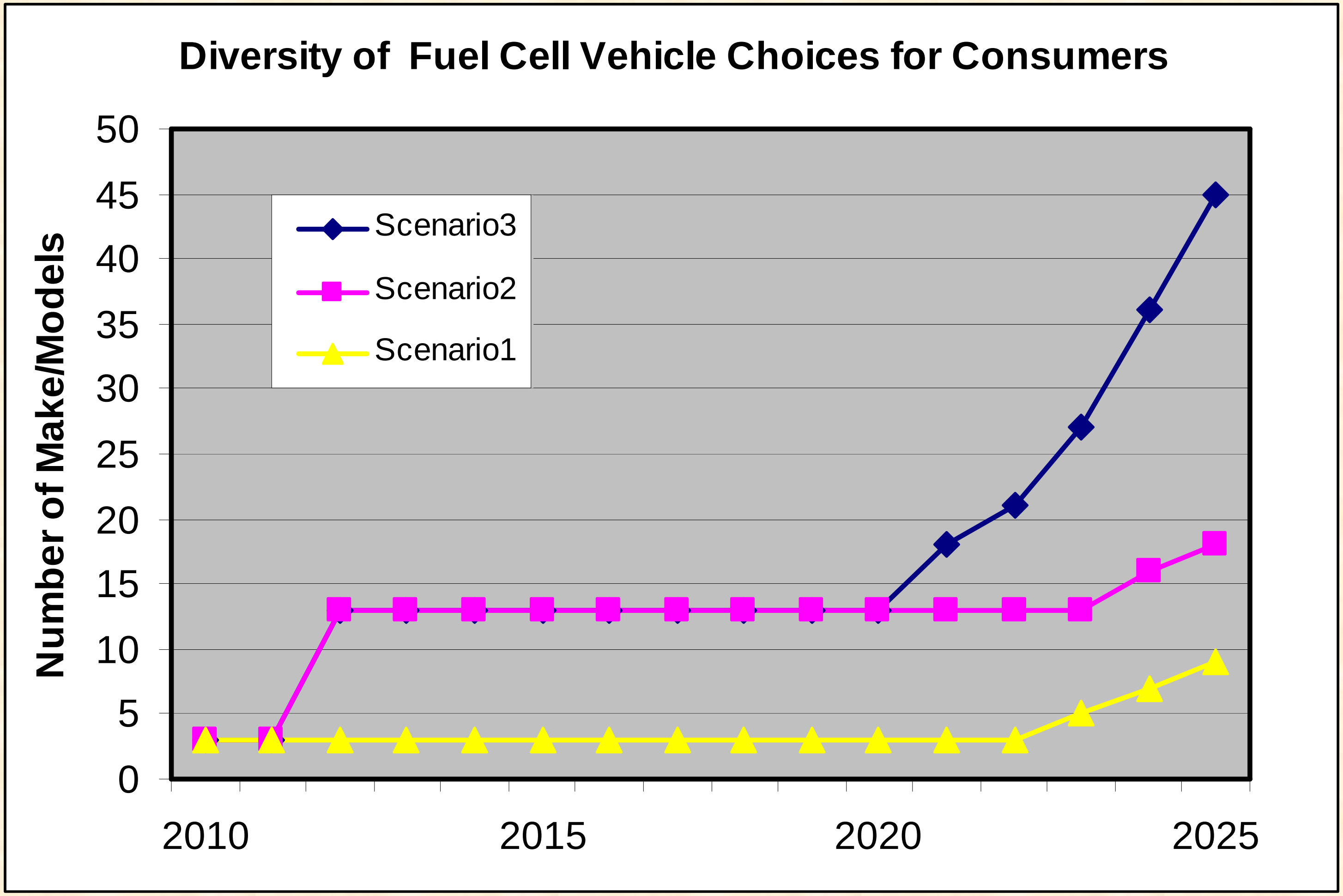
In all scenarios FCV costs decline dramatically, in line with the central tendency of the manufacturers' estimates, as a function of year, scale and cumulative production.



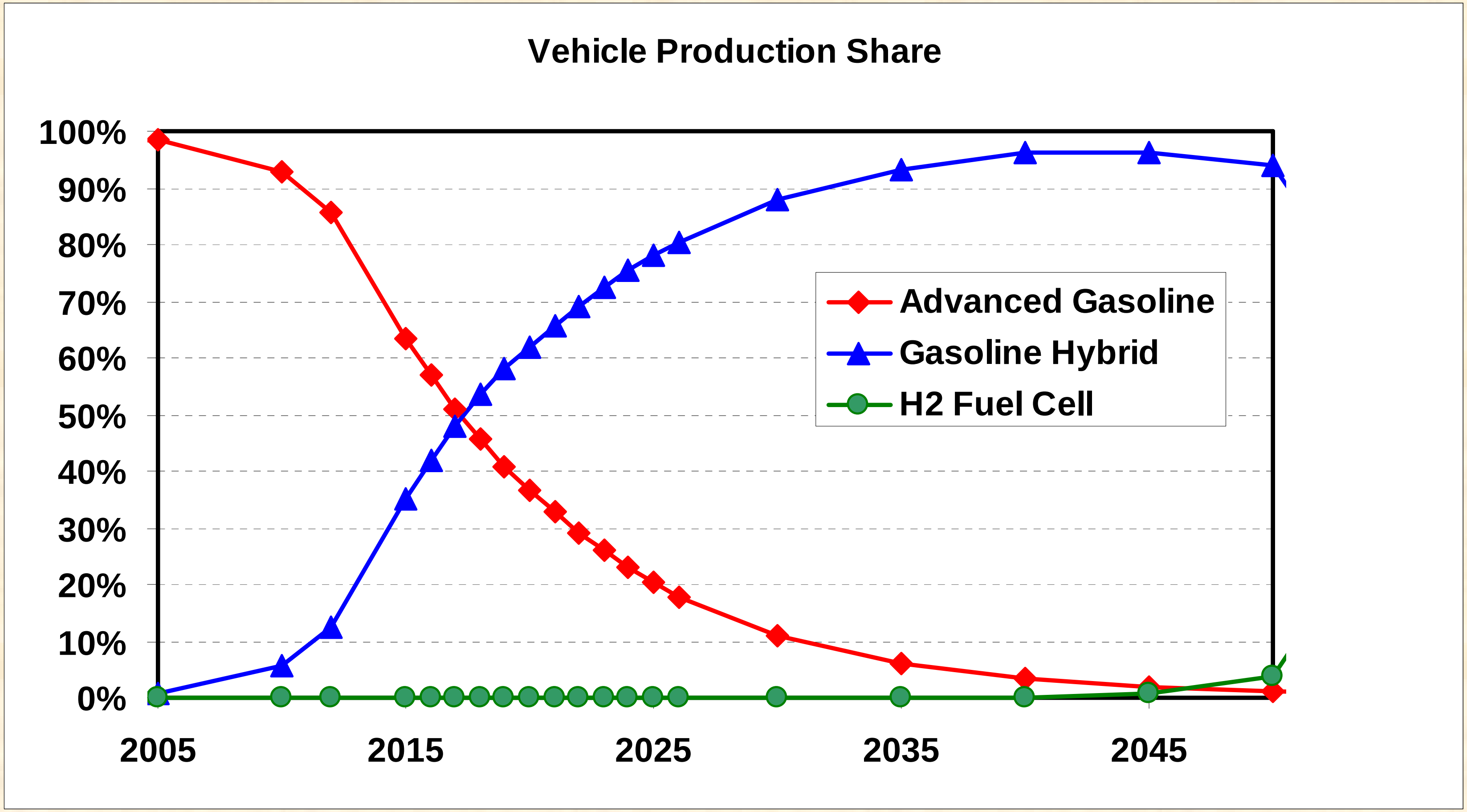
A closer look shows that only scenario 3 meets the long-term price target by 2025. The cost implications are quite important.



The key differences among scenarios are the 1) degree of fuel availability, 2) diversity of make and model choice and, 3) level scale economies achieved by the different production schedules.

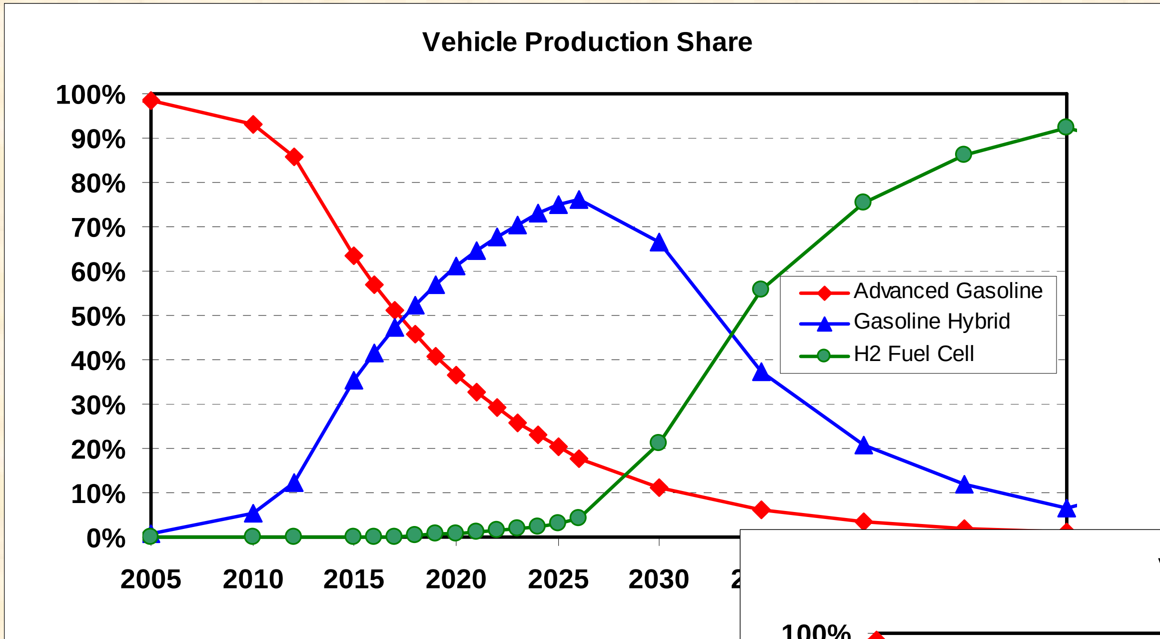


In the absence of the early transition FCV requirements, HyTrans predicts market dominance by advanced gasoline hybrid vehicles that also meet DOE's technology goals.

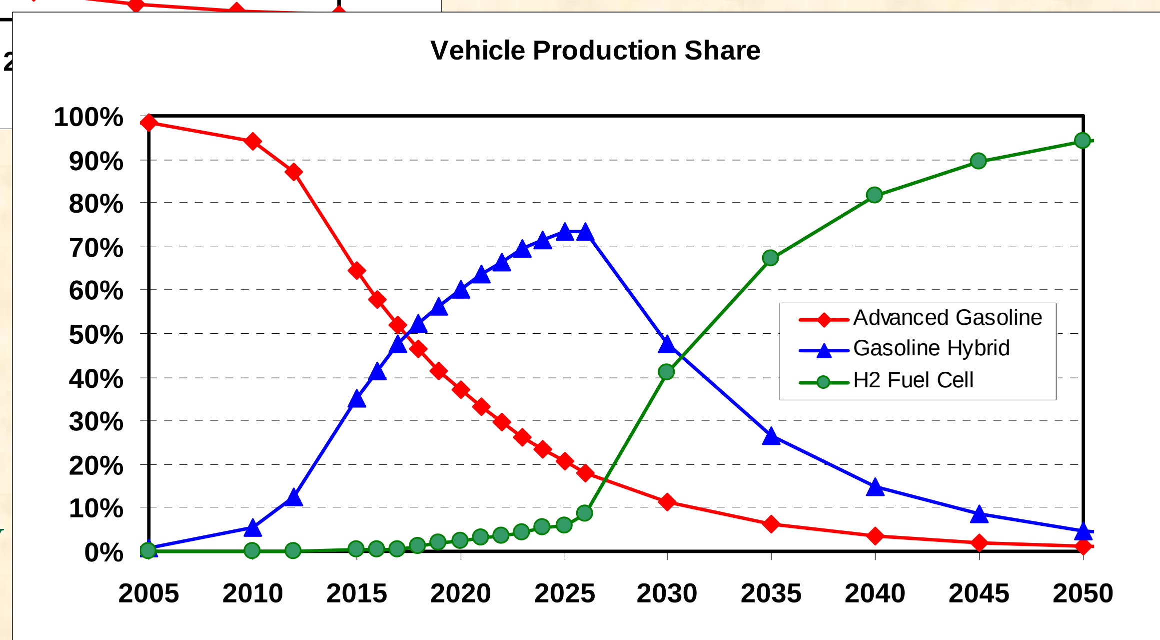


All 3 transition scenarios lead to a sustainable transition to hydrogen fuel cell vehicles.

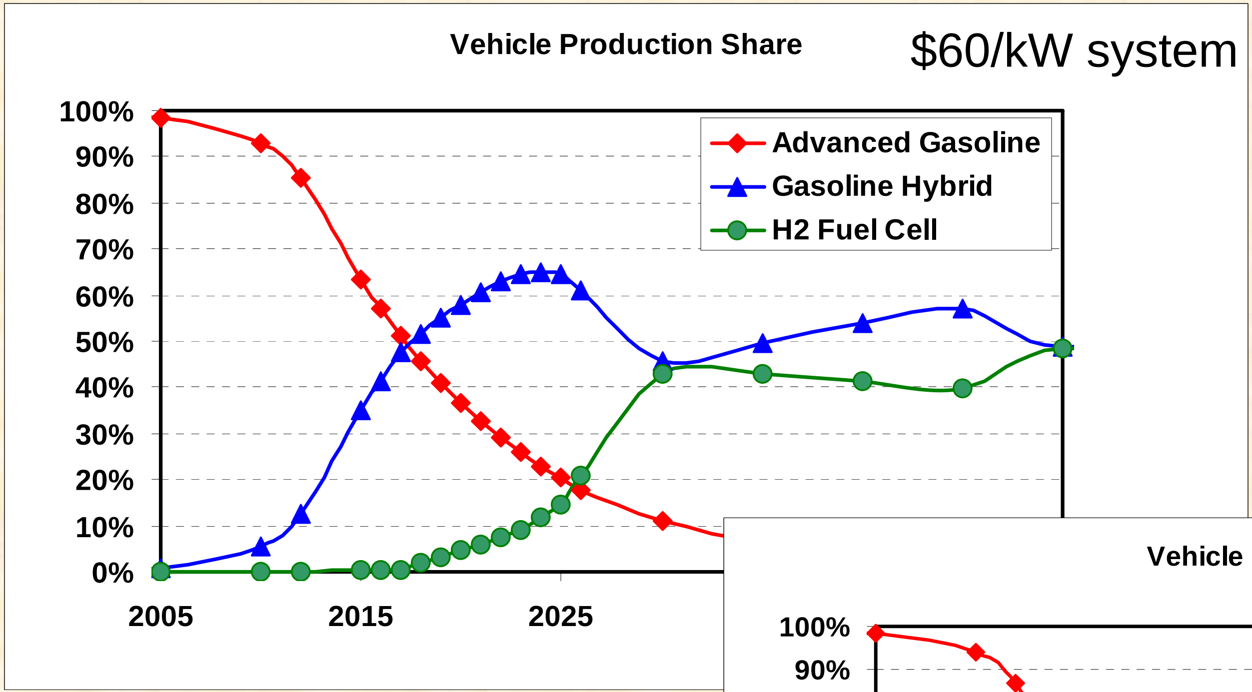
Scenario 2

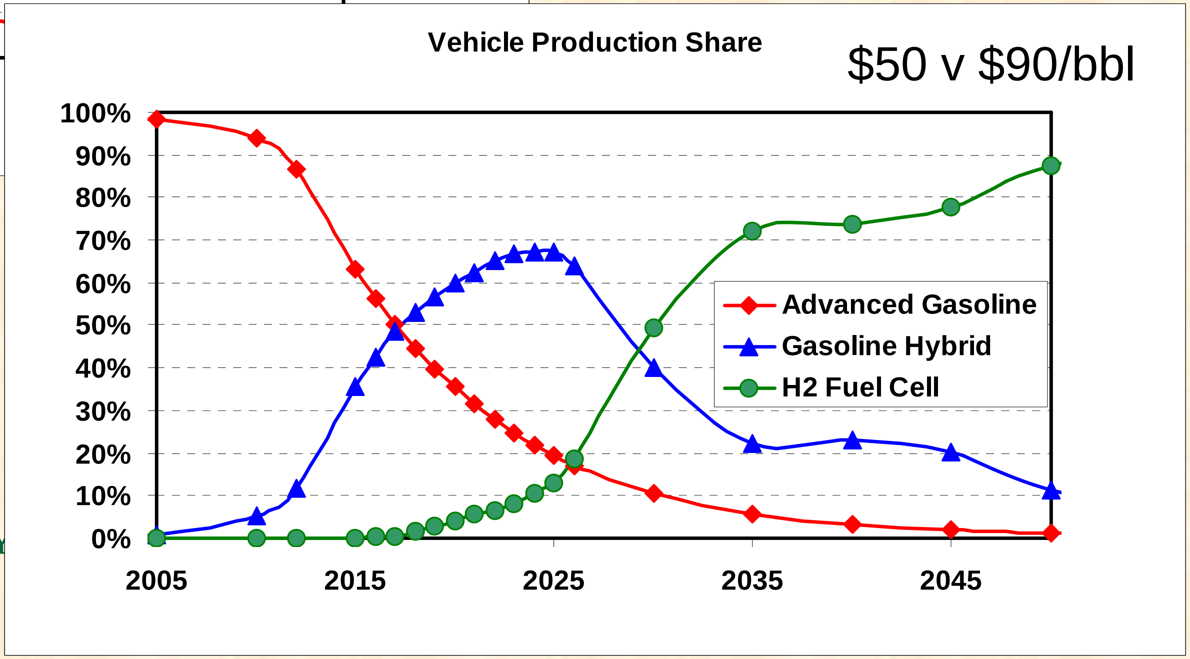


Scenario 3

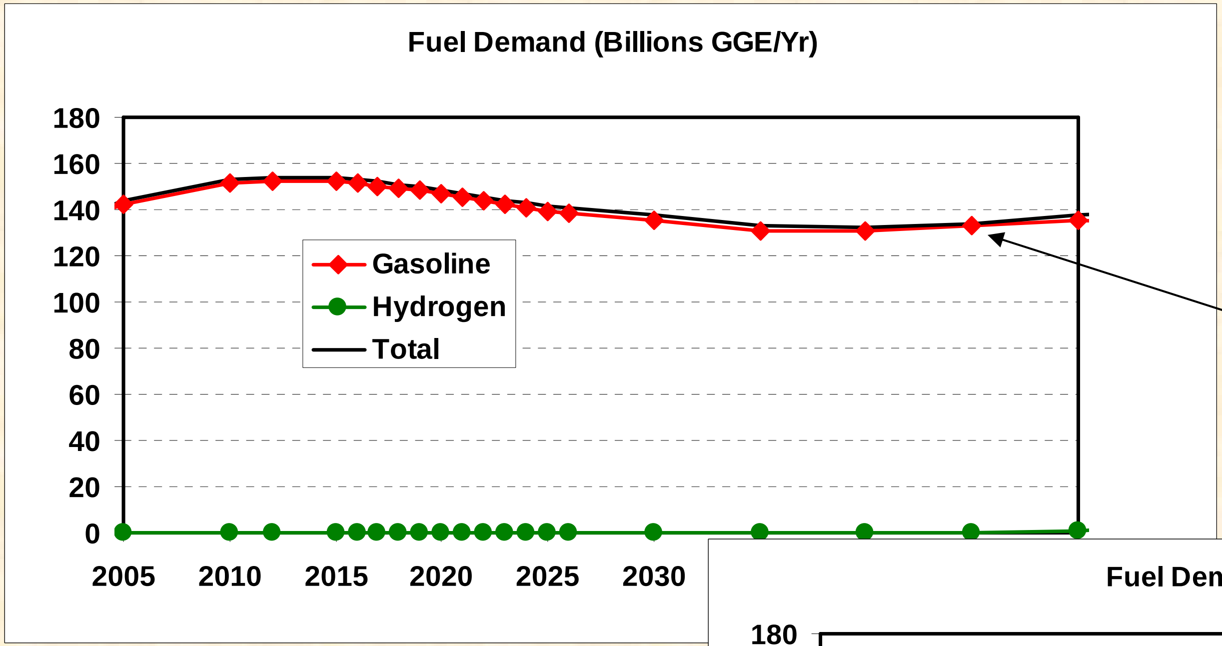


But if fuel cell technology does not fully meet program goals ($60/kw v. $30/kW FC system cost, or if oil prices are not high, the transition may not be complete or sustainable.

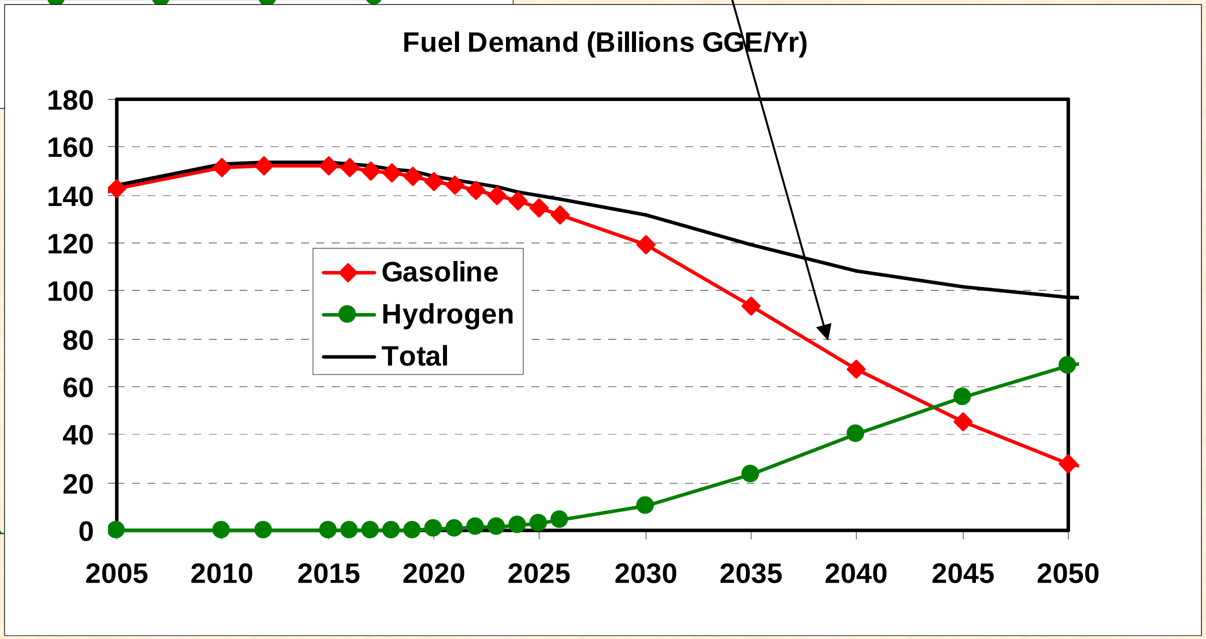




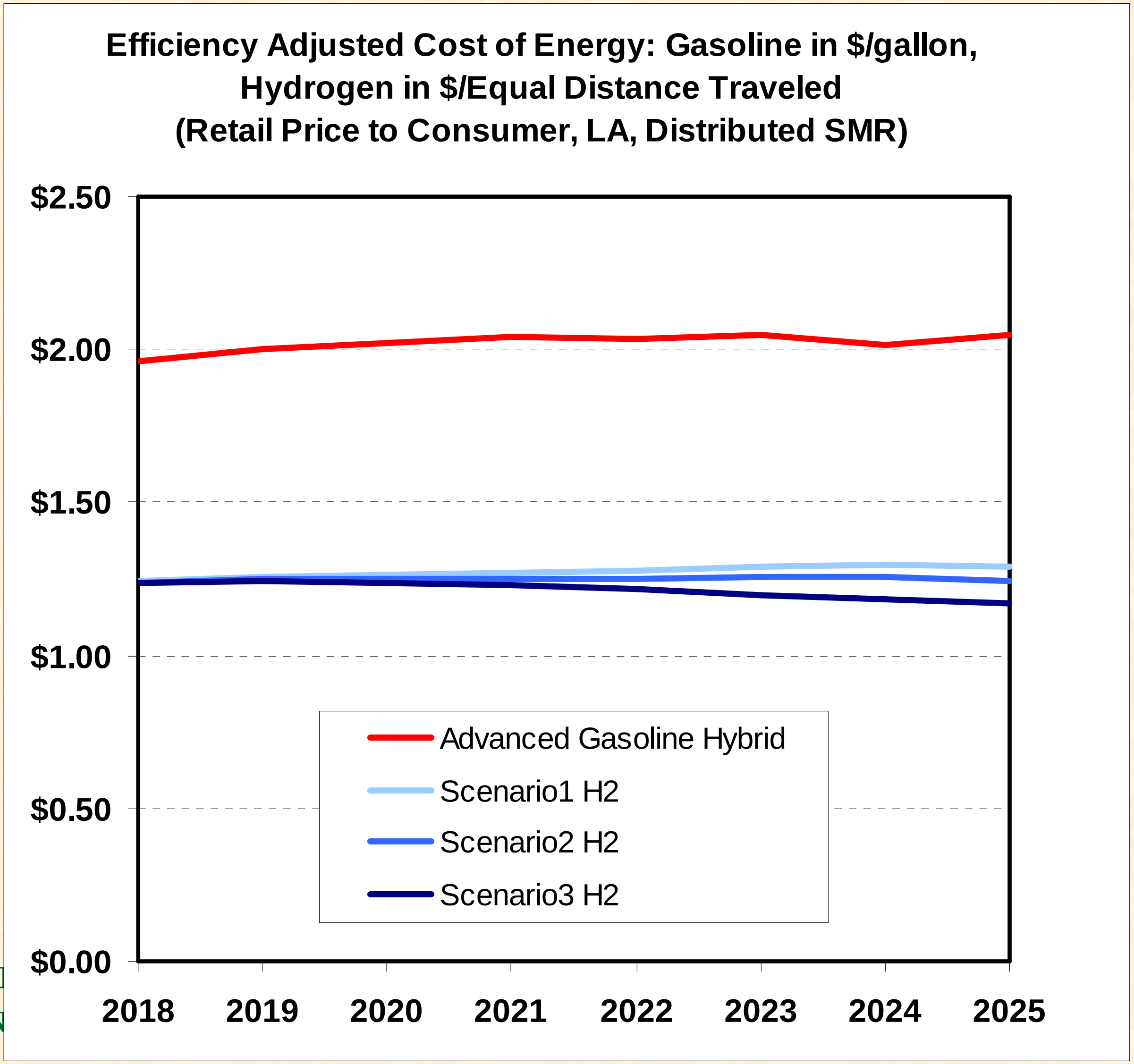
The advanced hybrid’s efficiency holds oil use constant but the FCV drives it towards zero.



Gasoline Use



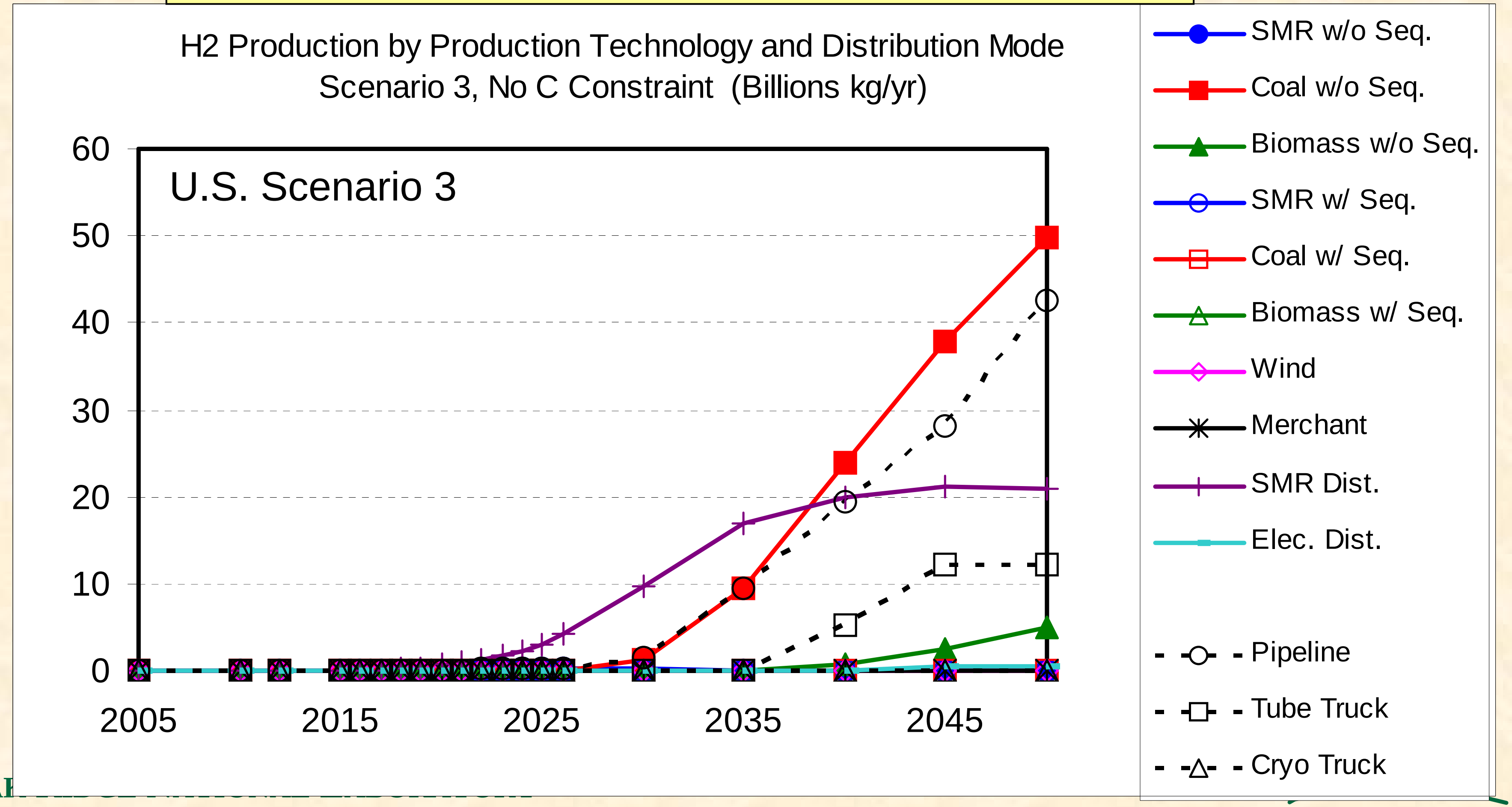
Due to the greater energy efficiency of FCVs, hydrogen is cheaper on a per-mile basis.



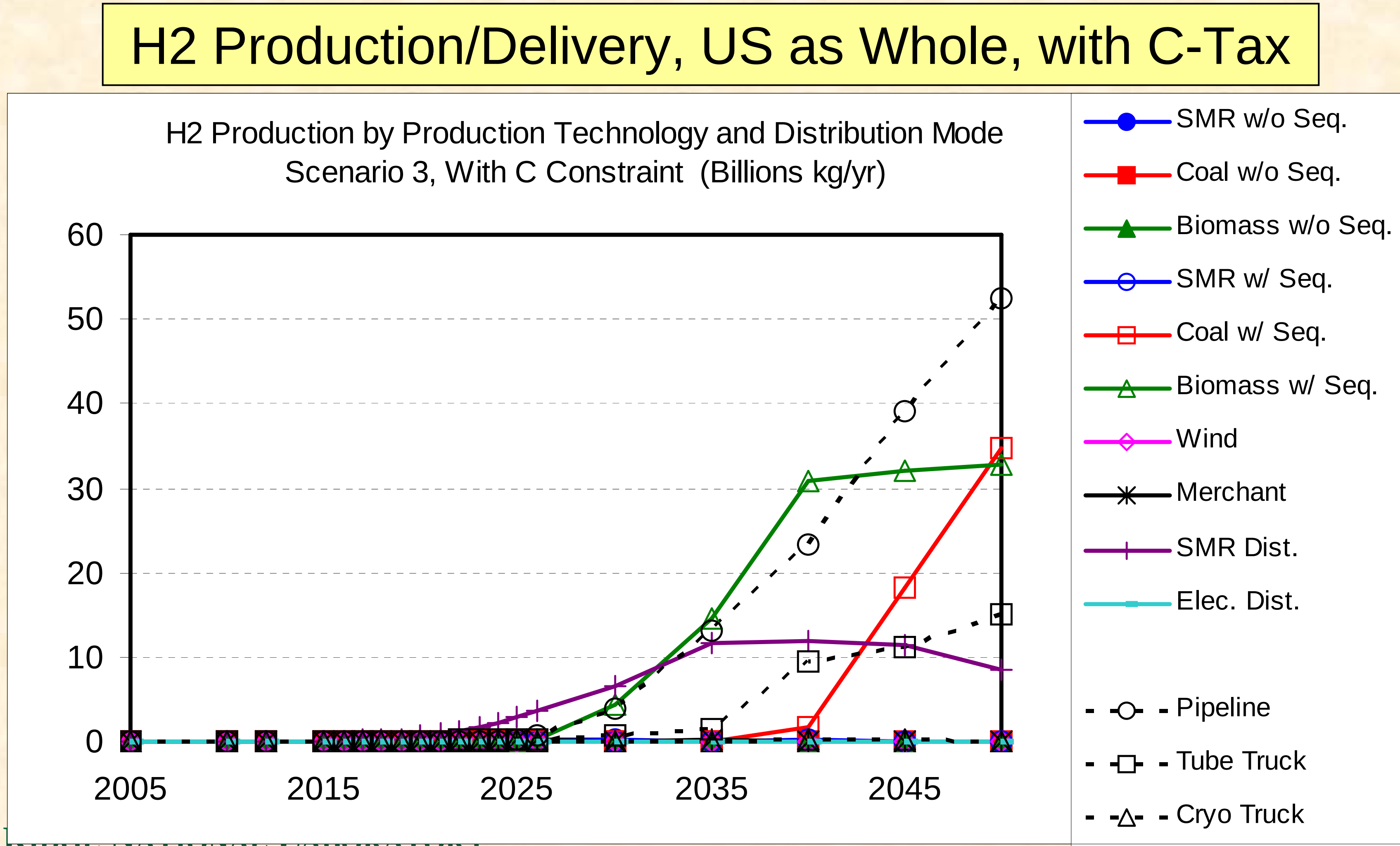
H2 Prices Reflect $0.50/kg subsidy, declining to $0.30 by 2025

HyTrans also estimates hydrogen production by pathway. However, many pathways have similar costs. Thus, details are not of great significance and sensitive to small changes.

H2 Production/Delivery, US as Whole

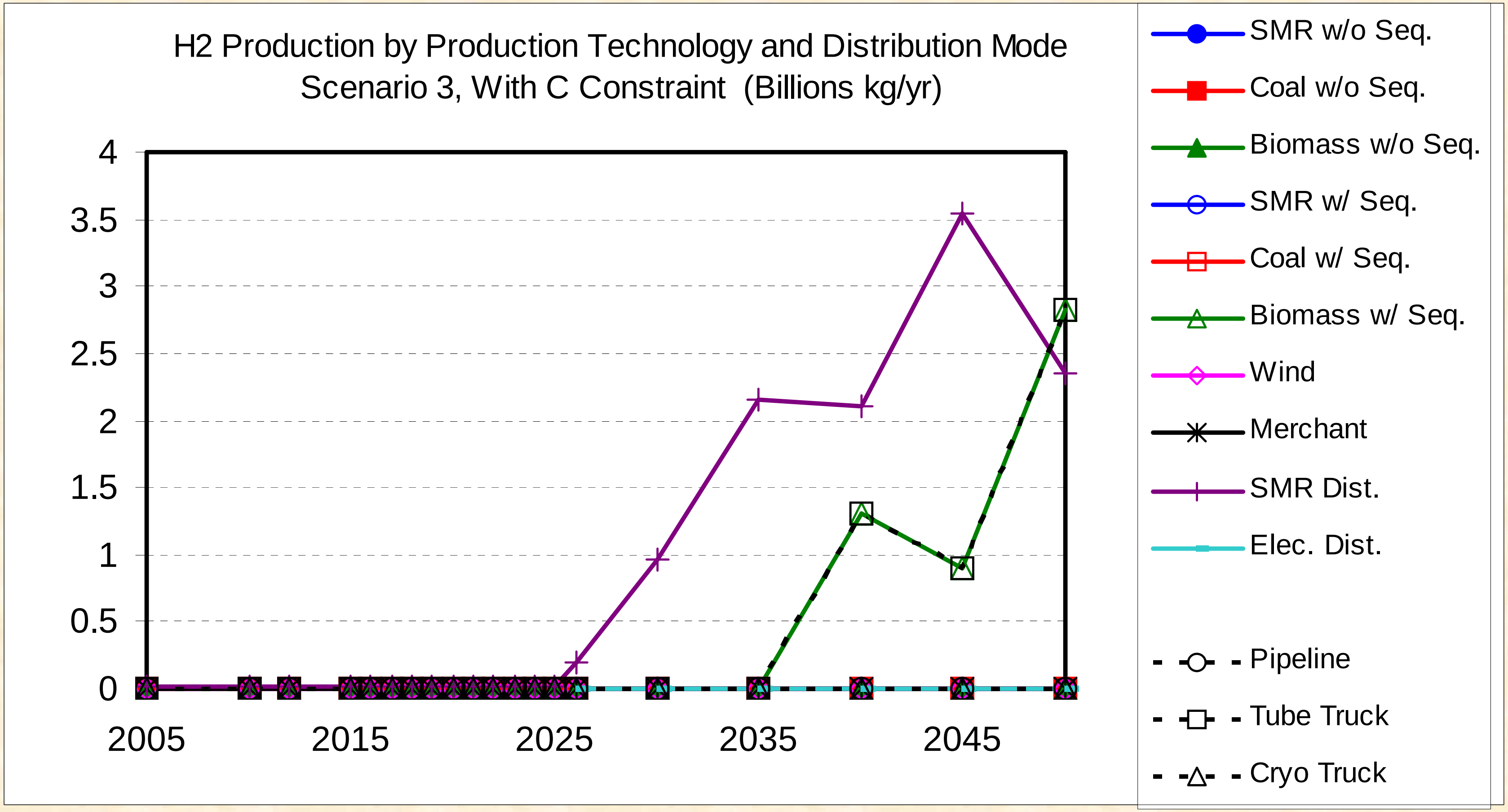


Adding a carbon tax starting at $10/tCO_2$ in 2010 & increasing to $25/tCO_2$ by 2025 changes the mix of pathways substantially.

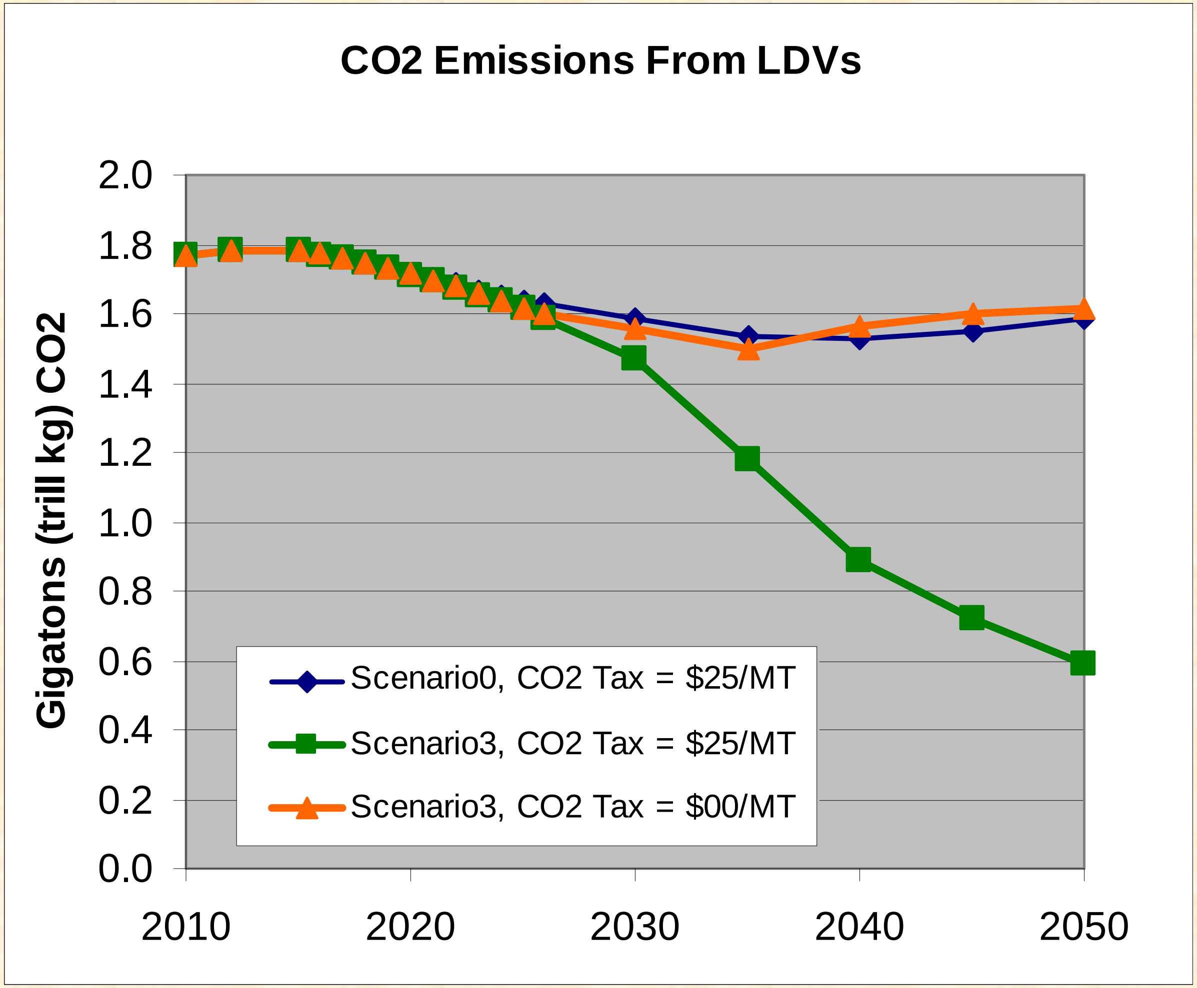


Pathways are also sensitive to fuel demand density. The low density areas of region 9 (Pacific) rely on distributed SMR and biomass (w/seq) delivered by advanced compressed gas trailers.

H2 Production/Delivery, Pacific Region, Low Density



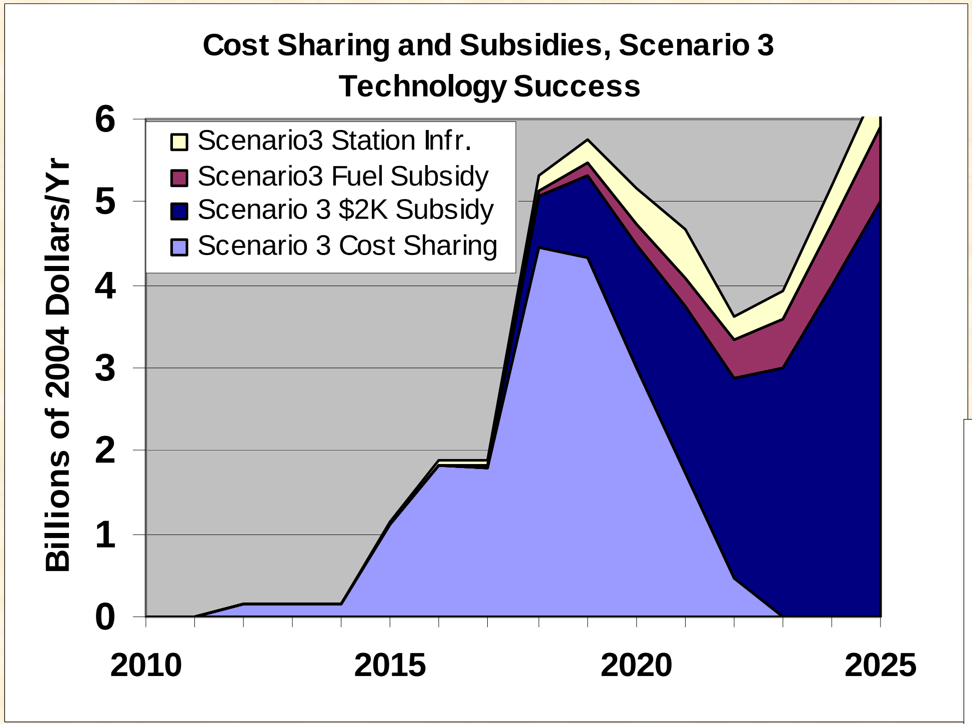
Reducing C emissions requires both carbon-constraining policy ($10/tCO2 in 2010 increasing to $25 in 2025) and the hydrogen transition. Given both, dramatic reductions are possible.

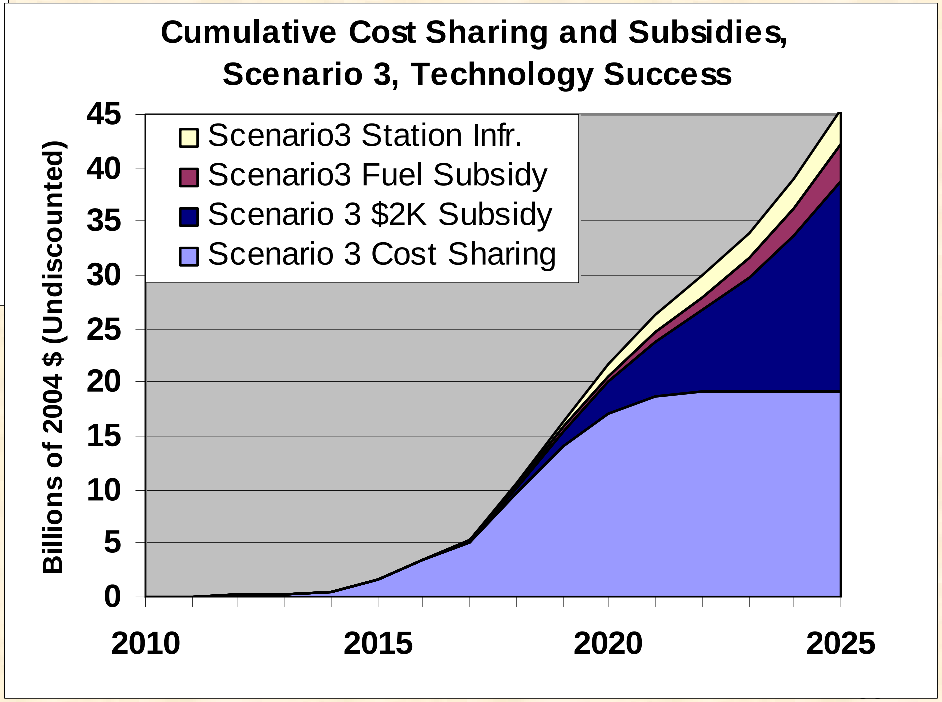


Three policy cases with different cost sharing by government were evaluated.

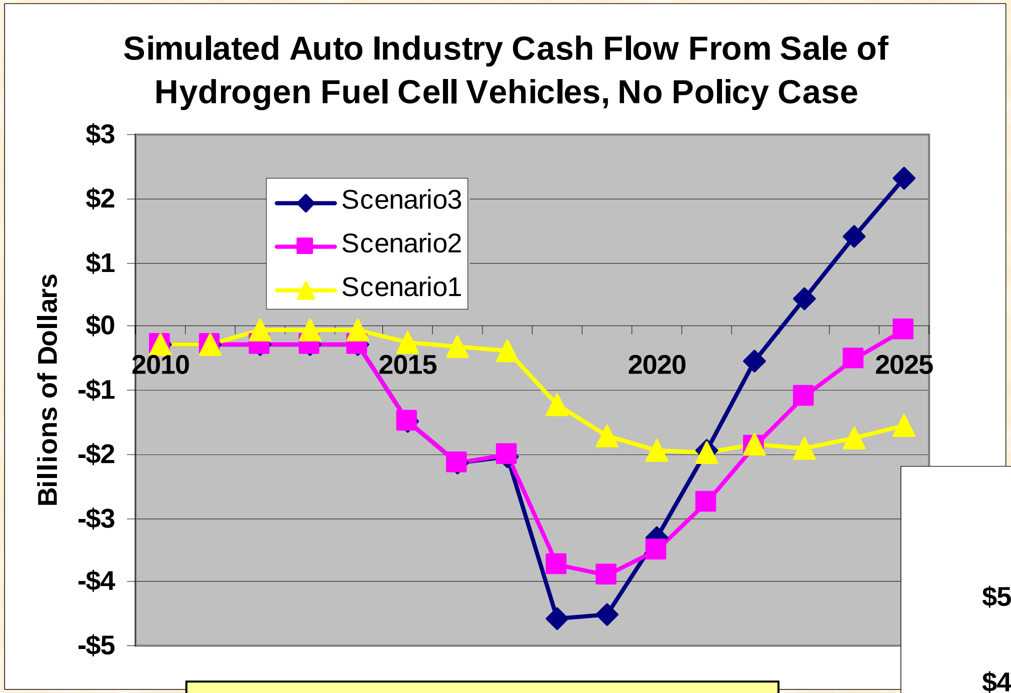
		2012-2017	2018-2021	2022-2025
Vehicle Cost Sharing	Case 1:	50/50 incremental cost share	50/50 incremental cost share	50/50 incremental cost share
	Case 2:	50% total vehicle	None	None
	Case 3:	50% total vehicle cost share	None	None
Vehicle Tax Credits	Case 1:	None	None	None
	Case 2:	None	100% of incremental cost	100% of incremental cost
	Case 3:	None	100% of incremental cost plus $2,000/vehicle	100% of incremental cost plus $2,000/vehicle
Station Cost Sharing	All Cases:	$1.3 Million/Station	$0.7 Million/Station	$0.3 Million/Station
H2 Fuel Subsidy	All Cases:	$0.50/kg	Decreasing starting in 2018 to reach	$0.30/kg in 2025

Even in the most expensive cost-sharing cases evaluated, costs to the government were not daunting.



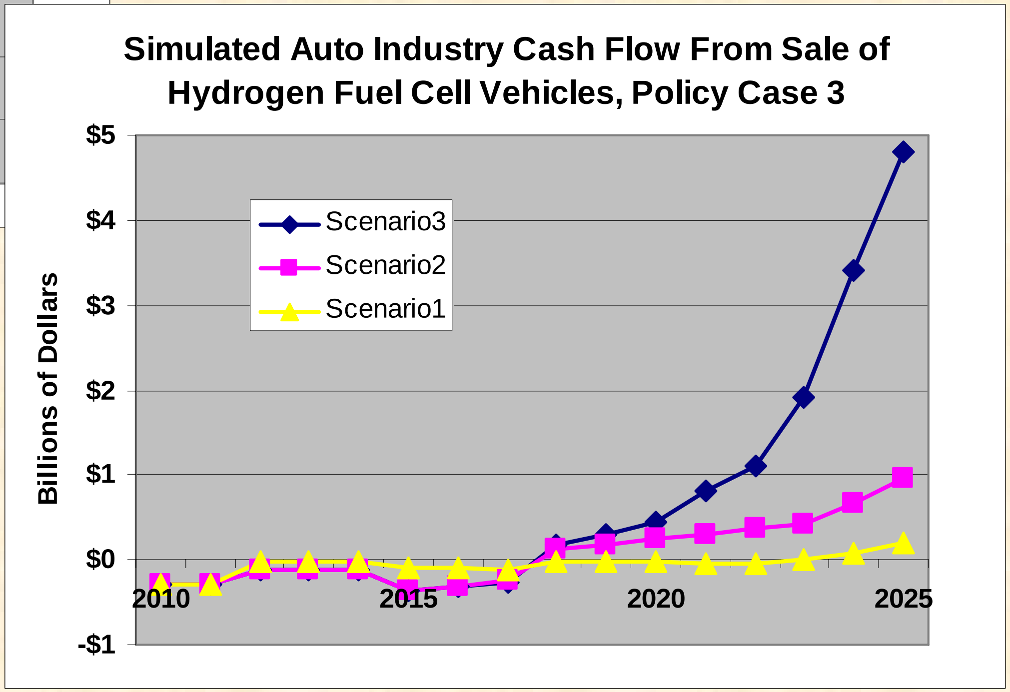


Without government cost sharing it seems unlikely that industry would attempt transition to hydrogen vehicles. Further development is needed to adequately address risk.



No Cost Sharing

Case 3 (Highest) Cost Sharing



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Summary

- The first integrated market model of the transition to hydrogen powered transportation in which the supplies and demands for vehicles and fuels and their prices are simultaneously and endogenously determined was completed and applied.
- Transition scenarios analysis satisfies a key Systems Analysis program goal.
- The HyTrans model results indicate:
  - if the DOE technology goals are met,
  - AND if a vigorous transition effort is undertaken by government and industry,
  - Then a sustainable transition to hydrogen powered vehicles is achievable.

What have we learned?

- Given that technology goals are met, a sustainable transition to hydrogen can probably be achieved at a reasonable cost, given a concerted, sustained effort.
- Technological success is the most important determinant.
- Oil costs matter but less so.
- If the technology is there, faster might be better (scale economies, risk perception) but will we know?
- It might take as few as 2 million vehicles to start a sustainable transition (if technology is there).
- Hydrogen creates the potential for near-zero carbon emission vehicles but policies must realize that potential.
- There appear to be several ways to produce & deliver hydrogen at about the same cost (conditional on H2A estimates).
- Production and delivery pathways will likely differ by region and over time (esp. wrt. fuel demand density)

Thoughts on Delivery

- **Tradeoffs *not* in H2A/HDSAM**
  - **Distance to city: delivery cost vs siting costs, resource costs, or scale economies of serving more than one city**
  - **Multi-fuel vs single fuel station design: fuel availability vs station cost**
  - **Station size: scale vs availability/distance to station**
    - **Strong effects of station scale may dominate**
  - **Station design: Consumer convenience vs cost**
    - **E.g. Delays during peak (time equivalent to travel time to refuel or travel to another station)**

THANK YOU.

Recent Publications

1. Leiby, P.N, D.L.Greene, D. Bowman and E. Tworek, "Systems Analysis of Hydrogen Transition with HyTrans", *Transportation Research Record No. 1983*, Transportation Research Board, National Research Council, 2006.

2. Greene, D.L, P.N. Leiby, D. Bowman, E. Tworek, "Integrated Analysis of Market Transformation Scenarios with HyTrans", forthcoming, ORNL/TM, Oak Ridge National Laboratory, Oak Ridge, TN, June 2007.

3. Gronich, S., et al., 2007. "Analysis of the Transition to a Hydrogen Economy and the Potential Hydrogen Energy Infrastructure Requirements", Summary Report, U.S. Department of Energy, Washington, D.C.

Many important methodological and factual questions remain.

1. How best to represent technological change and its components, including LBD?
2. How best to represent interactions with other energy markets, especially feedstock supply costs?
3. How best to represent interactions of global vehicle markets during the transition stage (LBD and scale economies, especially)?
4. How to better represent interdependent technological advances?
5. How to advance the state of knowledge of consumers' valuation of fuel availability and diversity of make and model choice? (Part of larger issues of modeling demand for novel technology.)
6. What level of geographic detail is adequate to evaluate, for example, the lighthouse regions concept?
7. How best to represent risk and expectations?
8. How can models of market transformations to novel technologies be validated?