2010 DOE Hydrogen Program Review

Range Optimization for Fuel Cell Vehicles

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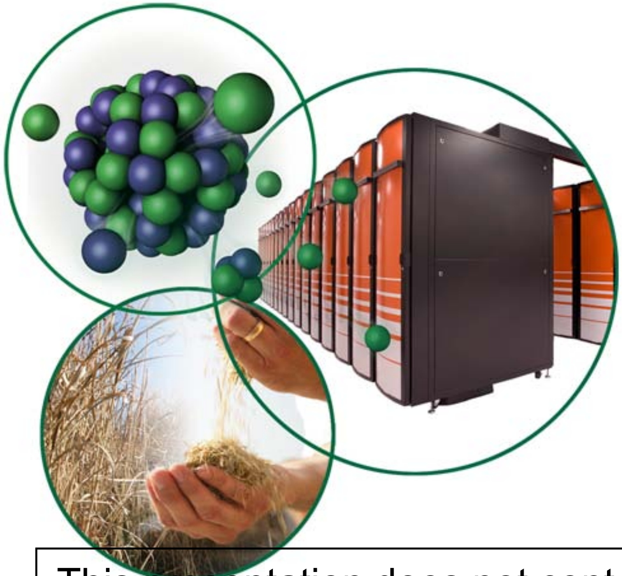


Project ID #: PD075

Timeline

- **Start: Oct 1, 2009**
- **End: Sep 30, 2010**
- **50% complete**

Budget

- **Total project funding**
  - DOE share = $130k
  - No cost share
- **FY09 = $0**
- **FY10 = $130k**

Barriers

- **Barriers addressed**
  - **Storage A.** System Weight and Volume
  - **Storage B.** System Cost
  - **System Analysis B.** Stove-piped/Siloed Analytical Capability

Partners

- **Interactions / collaborations**
  - NREL
  - ANL
  - Industry (energy and auto companies)
  - University of Tennessee
  - UC Davis
- **Project lead**
  - Zhenhong Lin, ORNL

Why Optimizing FCV Range?

400 mile range

200 mile range

400 mile range		200 mile range
$$$$	Upfront Vehicle Price	$$
$$$	Loss of Legroom or Cargo Space	$$
$	Time, Annoyance and Anxiety due to Frequent Refueling and Limited Fuel Availability	$$$$

Possible Consequences If FCV Range Not Optimized

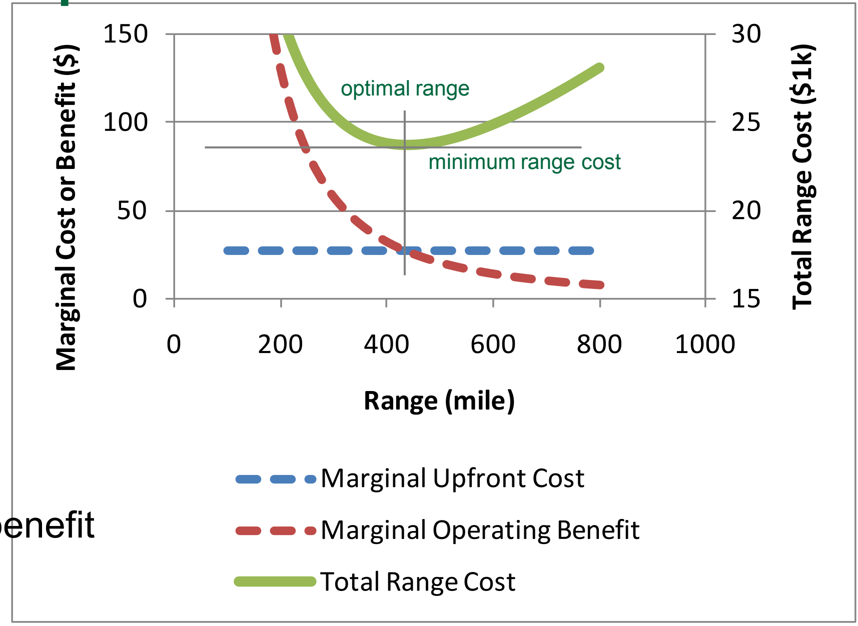
- **Greater Market Barrier**
- **Need for More Consumer Subsidy**
- **Incorrect Assessment of FCV Consumer Acceptance**

To provide a logical framework to assess various H2 on-board storage technologies in context of transitional market

- **Objectives**
  - develop the FCV range optimization model
    - calibration
    - sensitivity analysis
    - scenario analysis
  - to support the DOE WTW analysis, HyTrans project and the *MA*^{3}*T* model on storage and range issues by adopting the range optimization approach
  - expand the method to other alternative fuel vehicles
- **Relevance**
  - provide a tool for decision points on on-board storage technologies
  - facilitate analysis of on-board storage options for 2010 and 2015 targets
  - avoid stove-piped/siloed analytical capability for storage R&D planners

With additional range, consumers pay more for on-board storage hardware, lose certain legroom or cargo space, but benefit from less frequent refueling trips to the sparse H2 stations.

- The upfront part of range cost:
  - $ storage system hardware
  - $ loss of space, e.g. legroom, cargo volume, etc
- The "operating" part of range cost
  - $ limited fuel availability
  - $ wasted fuel in locating disperse stations
  - $ time on dispensing fuel
  - $ station time overhead
- The optimal range is one
  - where marginal upfront cost = marginal "operating" benefit
  - that minimize range cost
  - that maximize consumer value of range



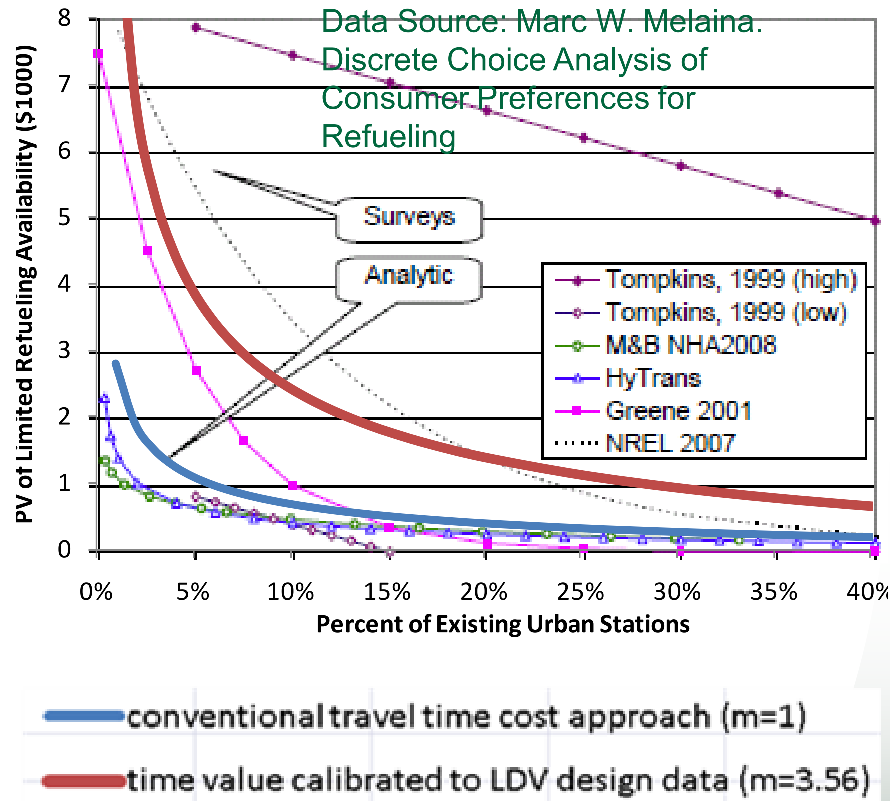
- Sensitivity Analysis w.r.t., storage density, storage cost, fuel availability, etc
- What-if Analysis
  - implication of DOE goals
  - prioritizing R&D efforts
- Scenario Analysis
  - adapt FCV range to technology and infrastructure development
  - benefits of range optimization

The range optimization model relies on key inputs from various DOE projects and aims at benefiting these projects.

DOE project	Input to this project	Potential benefits from this project
the ORNL HyTrans and MA^3T models	fuel availability, calibration of fuel accessibility cost	better quantification of consumer value of ATVs
the ANL PSAT model	vehicle characterization	improved ATV configuration
the ANL H2A model	H_2 cost	improved ATV characterization
the NREL fuel availability study	calibration of fuel accessibility cost	result comparison and validation
all the DOE-funded storage assessment projects	storage technology characterization	guidance on R&D activities

Real LDV design data provides critical insights for better estimate of fuel accessibility cost and helps explain the gap between analytic and survey estimates.

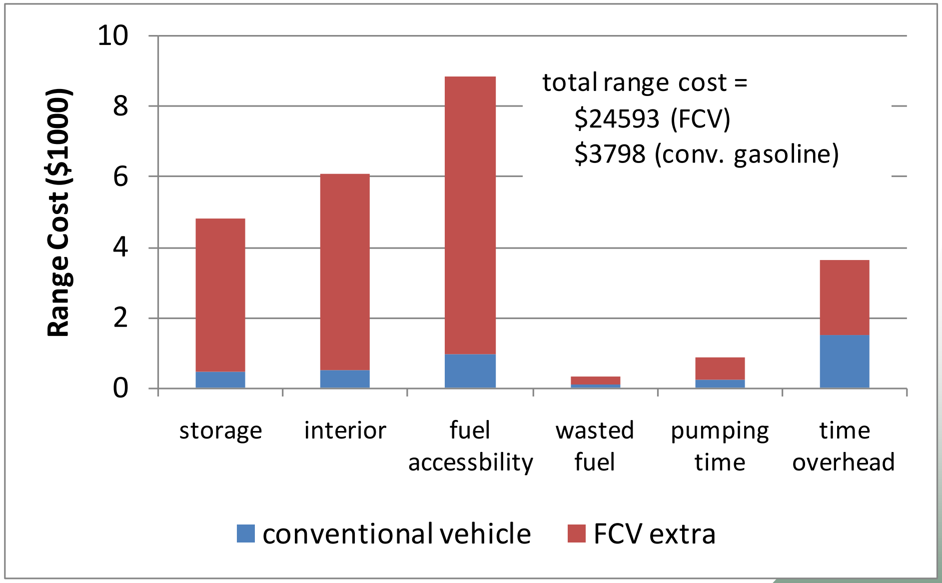
- On estimating fuel accessibility cost due to limited fuel availability, significant and consistent gap exists between survey and analytic estimates
- Since conventional analytic estimation is based on travel time cost, possible reasons for the estimation gap:
  - Refueling travel time is more valuable than normal travel time
  - Refueling travel involves stresses that are not captured by travel time cost
  - Such stresses may be termed as annoyance, anxiety, or worry
  - And they may be a function of refueling frequency, time, or time uncertainty
- A time multiplier (m) is introduced to reflect these stresses and calibrated to design data of 5850 existing LDVs
  - Assuming the current LDV ranges reflect gasoline storage cost, fuel availability and consumer preferences
  - Result: m=3.56, std.E.=0.08, R^2=0.61
  - Possible interpretations of m



•These two curves are generated from this project and plotted on Melaina's original graph

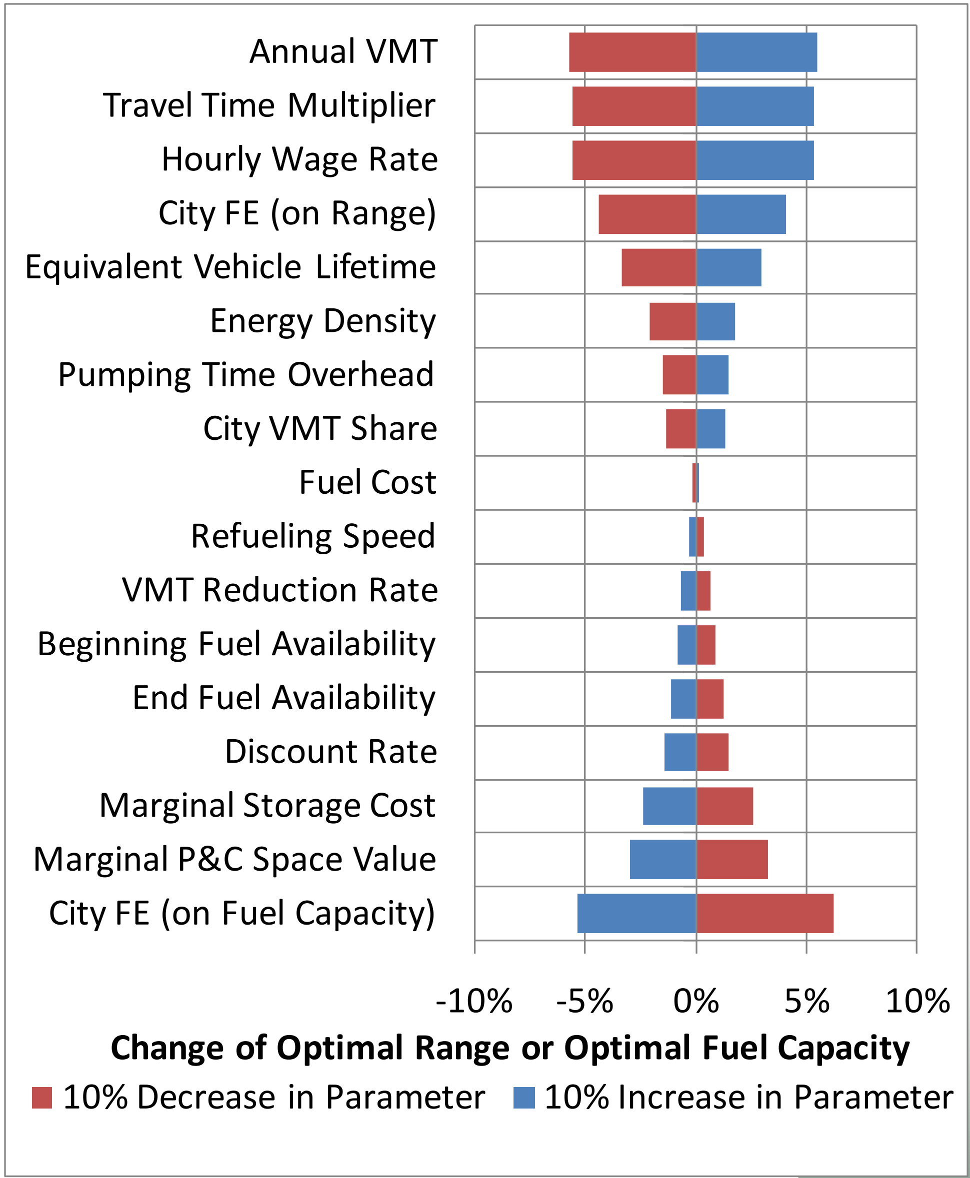
FCV range -- critical barrier for early market.

- In the early market, the optimal range is estimated to be 404 mile, enabled by 6.25 kgH_2 usable fuel capacity onboard, based on:
  - un-adj FCV fuel economy (mpgge) = 74.2 (city) and 78.9 (highway)
  - marginal storage cost = 15.6 $/kWh
  - marginal energy density = 0.6 kWh/L
  - marginal vehicle interior space value = $500/cu.ft.
  - percentage of stations providing H_2 = 1% at time of FCV purchase, growing to 10% in 10 years of vehicle lifetime
- Even with optimal range, the range cost for early FCV owners is extremely high, reflecting the **lower bound** of the barrier caused collectively by limited F.A. and unsatisfactory storage tech. status.
  - The range cost with optimal range is $24,593, compared to $3798 range cost for a conventional gasoline vehicle with the same range.
  - The range barrier becomes greater if FCV range is not optimized
- Little effect of H_2 price on range cost



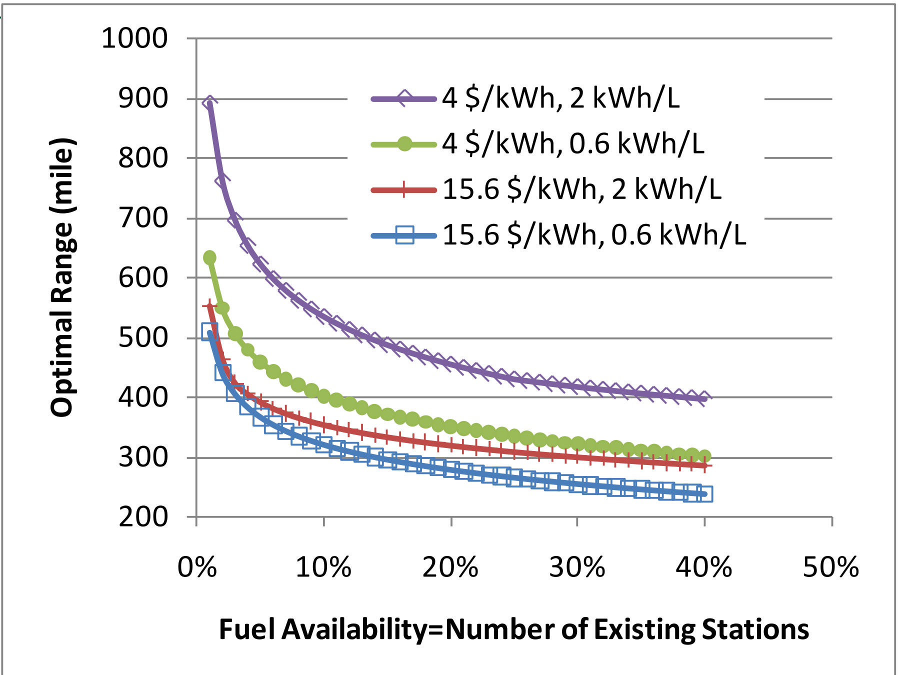
Sensitivity analysis appears to indicate the robustness of range optimization.

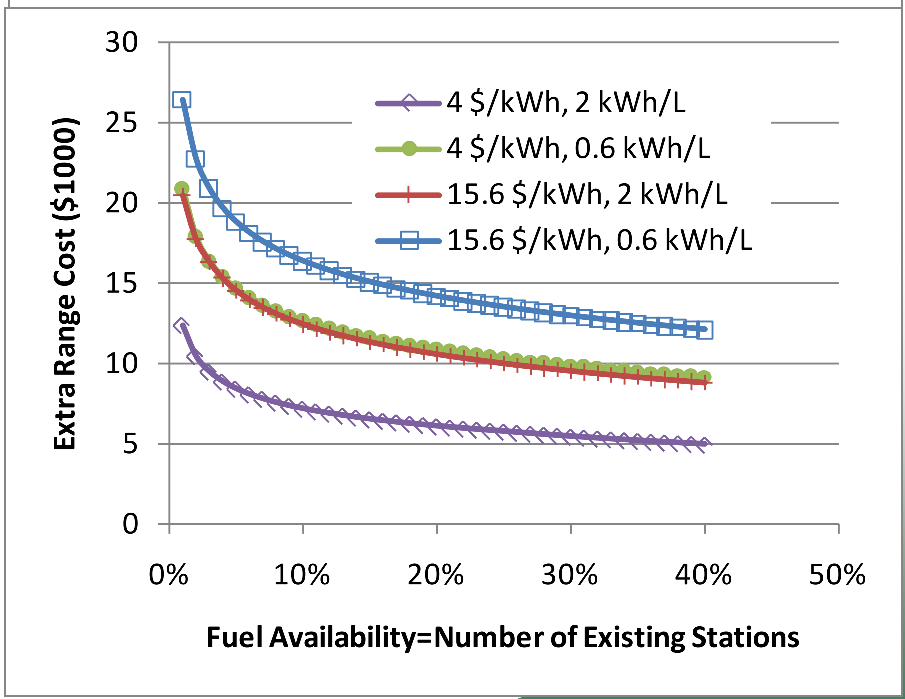
- Except for fuel economy, variation of each parameter results in the same variation of optimal usable fuel capacity or optimal range.
- Better fuel economy reduces the optimal usable fuel capacity while increase the optimal range.
- The +/-10% variation in each of the 16 input parameters results in a range of -5.7 ~ +6.2% change in the optimal usable fuel capacity and the optimal range.
- Vehicle miles-traveled, value of time, time multiplier and fuel economy are the most influential inputs.



The FCV optimal range and associated range cost is a function of storage cost, energy density and fuel availability.

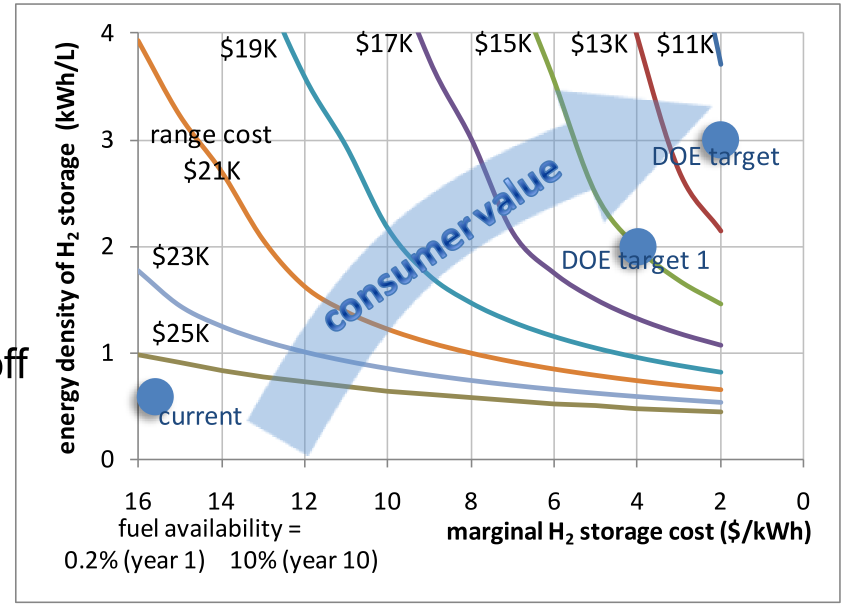
- With extremely limited fuel availability, a large FCV range is necessary to lower the extra inconvenience cost of limited range for consumers, especially when storage technology is significantly improved and the offset becomes more affordable.
- Either one of the 2010 cost and energy density targets brings about the same amount of value to consumers.
- The lower fuel availability, the more valuable the improvement of storage technology.



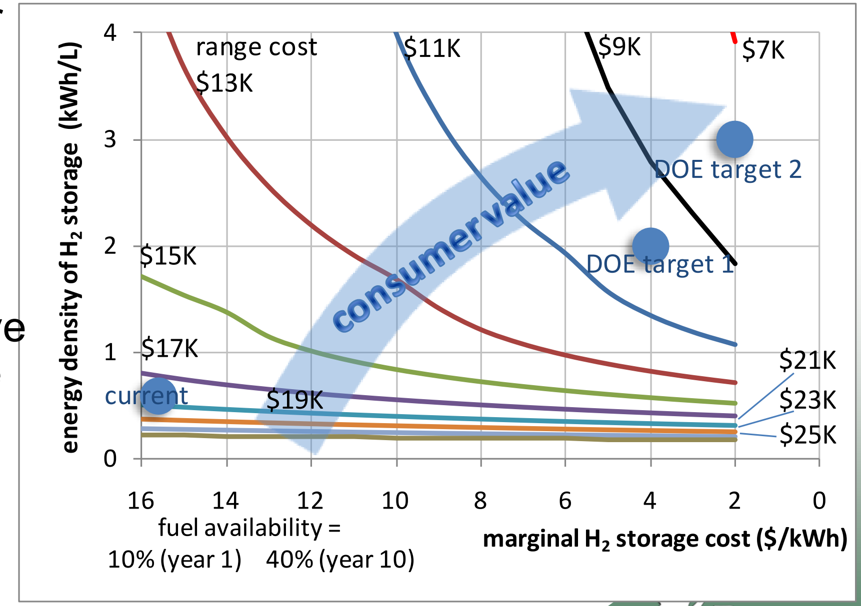


Equi-Range-Cost Map: translating on-board storage tech. status into consumer value

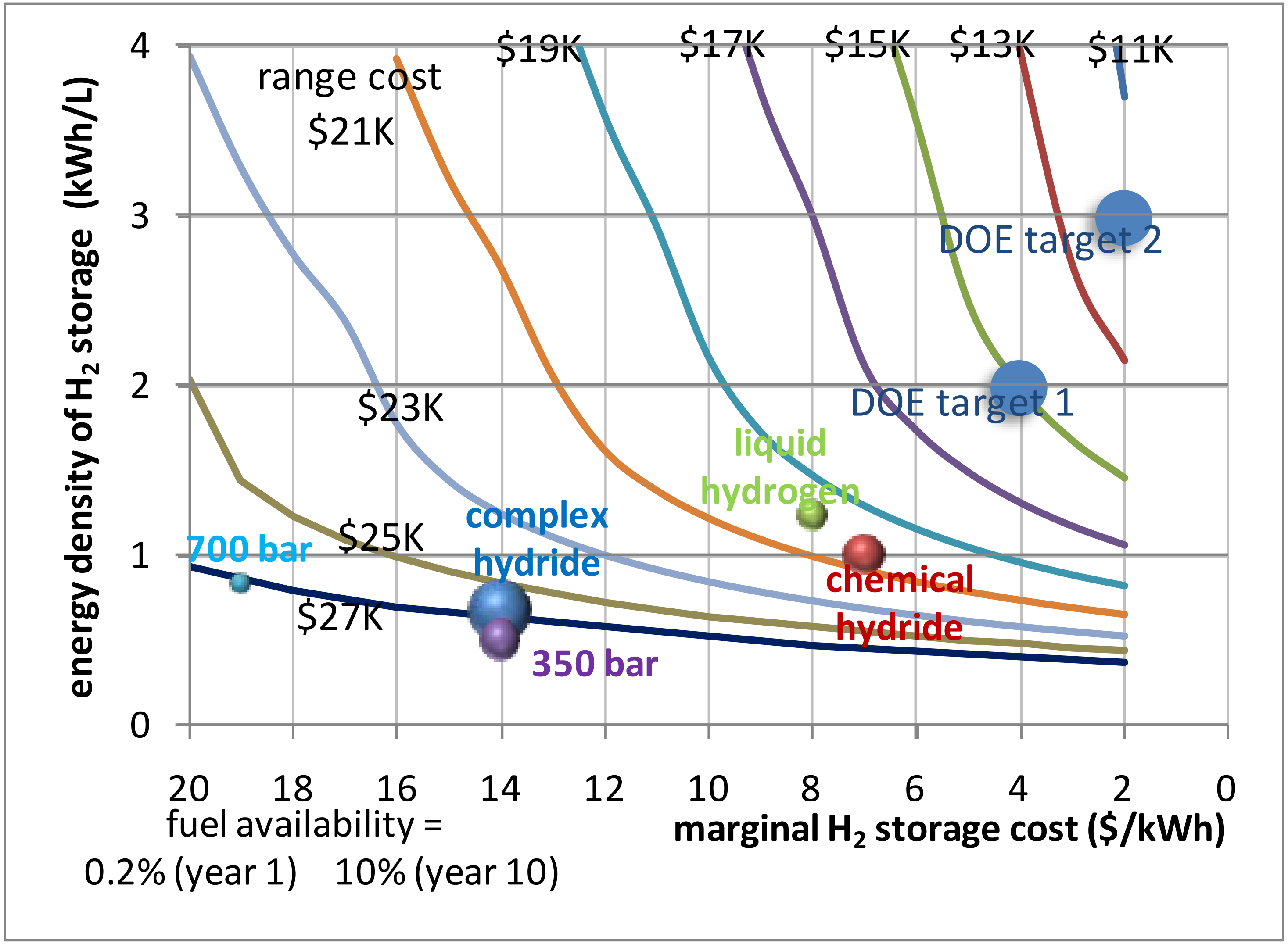
- The Equi-Range-Cost Map
  - Across equi-range-cost curves: range cost can be reduced by reducing storage cost and/or increasing storage density
  - Along each equi-range-cost curve: trading off storage cost and density without affecting consumer value
  - The two maps illustrate two fuel availability conditions.



- Which is more urgent to improve, storage cost or energy density?
- What is the "shortest path" to the DOE targets?
  - Need to measure "distance" on the map by R&D cost.
- under what circumstances is it more cost-effective to build more stations than add on-board storage or drive down the cost of storage?
- The equi-range-cost curve provides a relatively objective tool to compare H2 on-board storage technologies.



Based on current tech status, liquid H_2 and chemical hydride appear to offer lower range cost, and no significant difference in range cost is observed between 300bar and 700bar



but what if infrastructure costs are considered?

The optimal range adapts to the developments of storage technology and infrastructure.

The FCV sales is based on DOE Scenario 3 adjusted by 5-year delay. The 2015 DOE target on storage technology is assumed to be met by 2065.

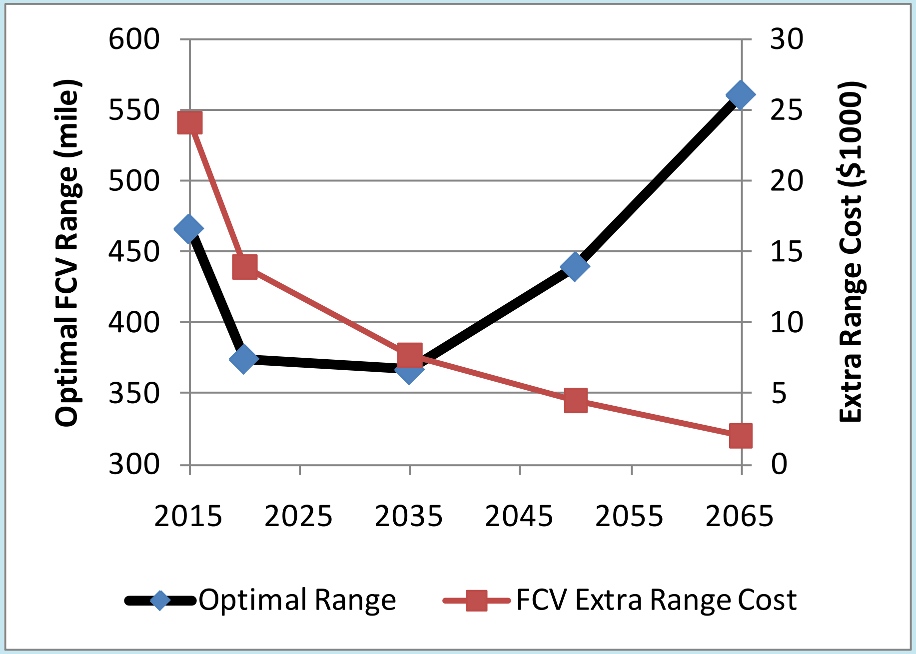
Over time, the extra range cost of FCV decreases significantly due to the improved storage technology and fuel availability.

The optimal range does not always increase over time. It adapts to the relative progress of storage technology and infrastructure developments.

Year	Urban mpgge	H2 Stations	$/kWh	kWh/L	FCV Sales
2015	74	100	15.6	0.6	500
2020	86	2770	14.2	0.8	30000
2035	97	10779	10.2	1.4	7182826
2050	101	18788	6.1	2.1	18762835
2065	101	26797	2.0	2.7	22993239

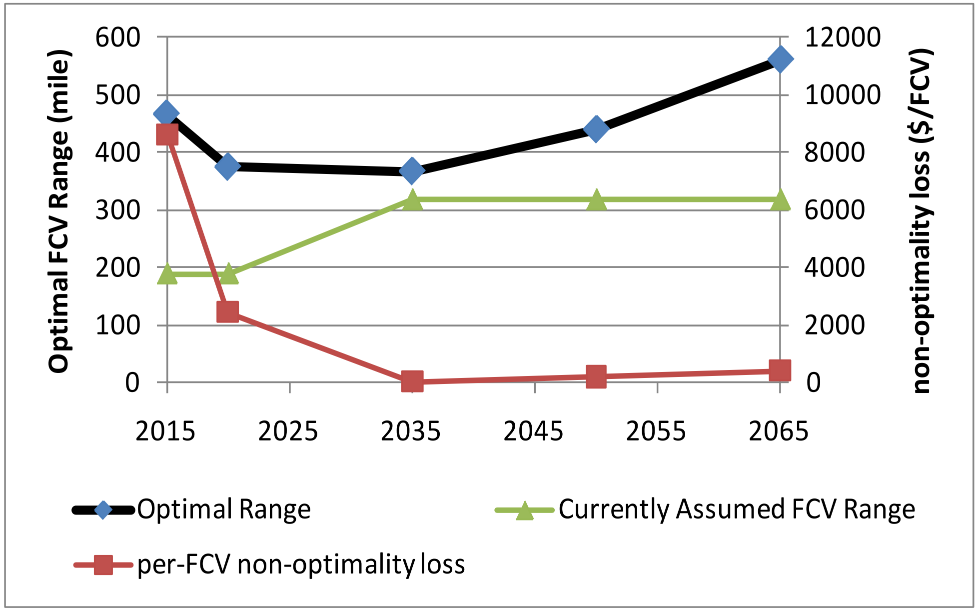
Table: scenario assumptions.

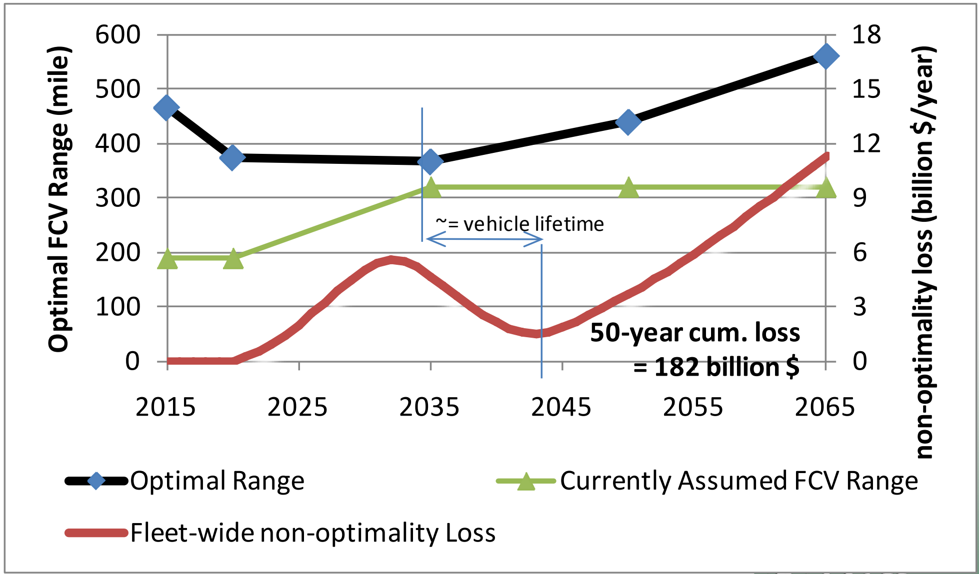
Figure: the resulting optimal range and the extra range cost compared to conventional vehicles.



Benefits of range optimization: improve FCV penetration (short-run) and reduce total consumer cost (long-term)

- Optimal tradeoff between storage costs and range benefits suggest that DESPITE higher early storage tech costs, the optimal range in the early period of limited fuel availability is SUBSTANTIALLY GREATER THAN what is being assumed by standard FCV range scenarios.
- FCV design without range optimization could aggravate FCV transition barrier by imposing substantial non-optimality cost to consumers.
- Considering different FCV designs (storage capacities and range) would lower estimated costs of the FCV transition
- Compared to standard FCV range, the optimized FCV range can reduce total consumer costs by about $182 billion cumulated over 50 years, or about $28 billion discounted 7%/year to year 2015, or $317/FCV for 573 million FCV sold.





The Range Optimization project depends on research of collaborators from other national labs, industry and universities.

- Collaboration Partners
  - NREL and UC Davis: provides key insights on fuel accessibility
  - ANL: develop H2A and PSAT and share data
  - Industry: interaction including personal exchange and several phone conferences; provides insights on vehicle range design
  - University of Tennessee: share vehicle data that allows model calibration.
- Also interact with these projects/activities:
  - DOE Hydrogen Storage Systems Analysis Working Group
  - DOE Delivery Tech Team
  - DOE HyTrans Project
  - DOE *MA^3T* Project

Proposed Future Work

- FY10
  - peer reviewing and model refinement
    - value of vehicle interior space
    - marginal storage cost
    - urban vs rural travel
  - model documentation, report, and/or publication
- FY11
  - improved calibration with diesel and CNG vehicle design data
    - diesel vehicles face a lower fuel availability and their data may allow better calibration
  - to include infrastructure cost in range optimization
    - choice of storage technologies affects risks and costs from building up the H_2 supply infrastructure
  - compare storage technologies based on their associated range value
    - assessment of storage technologies can be conducted with the range optimization model in an integrated way.
  - market segmentation
    - driving intensity
    - income level or time value of the prospective early FCV consumers

Range optimization can reduce early market barrier, reduce needs for subsidy, and guide H2 storage R&D.

- **Trade-off**
  - The FCV range should reflect the conflicting needs to adapt to fuel availability and storage technology developments.
- **Robustness**
  - The range optimization is overall robust, but relatively more sensitive to driving intensity, and time value.
- **Significance**
  - Improve FCV market acceptance
  - Reduce total consumer loss and therefore reduce needs for subsidy
- **FCV range**
  - Should increase with better storage technology
  - Should decrease with better fuel availability
  - Overall should be adaptive

THANK YOU

Any questions, please contact:

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