Team Hydrogen: Final Presentation

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Brian Rogers (Operations Manager)
Scott Burgan (Business Developer / Architect)
Brian Welsh (Financial Manager)

Agenda

- Project Role / Expected Results
- Executive Summary
- Problem Statement, Mission, Goals
- Operational Concept and Context
- Project Development Process
- System Architecture Selection
- Business Strategy
  - Market Analysis and Go-to-Market Strategy
  - Business Case & Investment Strategy (Cost Analysis, NPV and Influence Diagram)
- Conclusions, Recommendations

Project Role / Expected Results

Our project took on the role of an Oil Company looking to add Hydrogen Energy to the company product portfolio:

- Established a supply chain for distribution of Hydrogen for consumer Fuel Cell Vehicles (FCVs), similar to current gasoline and diesel distribution systems

Specific focus of project will be to determine a viable Hydrogen Delivery System which will be economical and efficient:

- Developed a viable architecture for delivery of Hydrogen to the marketplace
- Developed a viable business case (less than 5% negative Net Present Value (NPV)) and investment strategy which makes the case for deploying a Hydrogen Delivery System

Executive Summary

We are entering a period of transition for the energy business, where winners will begin to emerge, and *the long-term viability of the petroleum business will falter*…

- Vehicle fuel prices are rising more rapidly than inflation due to increasing demand, low vehicle fuel efficiency standards and limited cost effective alternatives to petroleum-based fuels.
- Dependence on foreign nations for oil is an economic and national security issue, leading to record trade deficits and an economic dependence on nations that may wish the U.S. ill-will.
- Further, the trend in global warming has been linked to green house gases, one of which, CO_2 needs to be reduced to reverse this trend.

These factors have combined to shift the regulatory and consumer environment against the traditional oil business in favor of alternative energy solutions

Emerging threats to the current business are on the horizon.
The time is now to invest in alternatives such as hydrogen to act as a hedge against competing energy systems and to compensate for declining gasoline sales.

Executive Summary

Recommendations, Conclusions:

- Implement a Hydrogen Delivery System in two Phases:
  - Initial Phase: Hydrogen production occurs at a large centralized facility, is transported to a terminal facility and distributed via truck to the fuel station in Compressed Hydrogen form. The Initial Phase requires partnering with a hydrogen provider in order to share risk and maximize use of current infrastructure to minimize upfront costs while market adoption of Hydrogen Fuel Cell Vehicles (H2 FCV) is low (< 1%) through approximately 2018.
  - Step-Out Phase: During the Step-Out Phase, hydrogen production will be co-located at the terminal facility and delivered via truck or pipeline to the fuel station. The Step-Out Phase in effect flattens the distribution network, allowing the system to be more scalable and cost efficient.
- Our project concluded that a Hydrogen Delivery business is viable with only a 2.5% probability of negative Net Present Value (NPV) and a positive NPV ranging between $53 to $353 M, requiring a five year upfront investment of 67 M.

Hydrogen energy represents one of the most promising and profitable energy alternatives to refined fuels such as gasoline and diesel. Therefore, our team is proposing the company invest in a Hydrogen Delivery System.

Problem Statement

Problem Statement: Cost effective and feasible methods to deliver hydrogen to consumers for use in automobiles does not exist.

Mission: Develop a feasible architecture and investment strategy for a hydrogen delivery system for anticipated usage between 2015 - 2025.

Goals for Hydrogen Delivery:

- By 2017, Cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units *<$1.00 per kg of hydrogen in total or $0.01 / mile @ a Hydrogen Fuel Cell Vehicle mileage of 100 miles / gallon of gasoline equivalent (gge).* [1,2] It is expected that the overall delivery costs will be the largest cost contributor to the hydrogen retail cost.
- By 2017, Delivery System Energy Efficiency (H2 Out / (H2 In + Expended Energy)) of 85% from production to dispensing[1]

Sources:

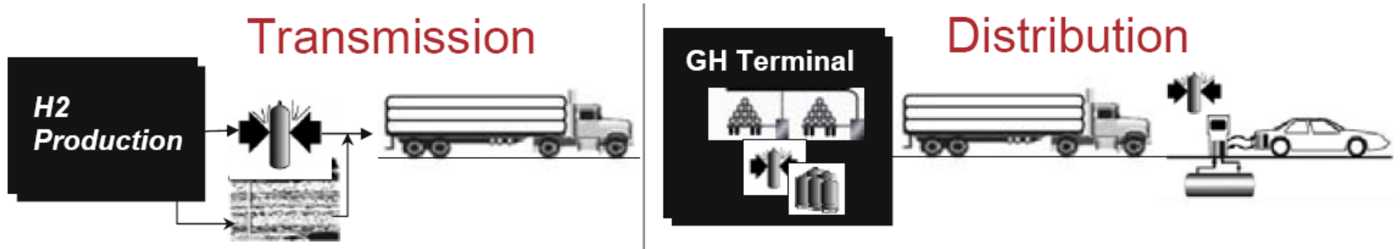
[1] "Hydrogen Delivery Technology Roadmap", pp. 53 - 56, http://www1.eere.energy.gov/hydrogenandfuelcells/delivery/pdfs/delivery_roadmap0207.pdf

[2] "2007 Technical Plan - Delivery", pg. 3.2-1, http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/delivery.pdf

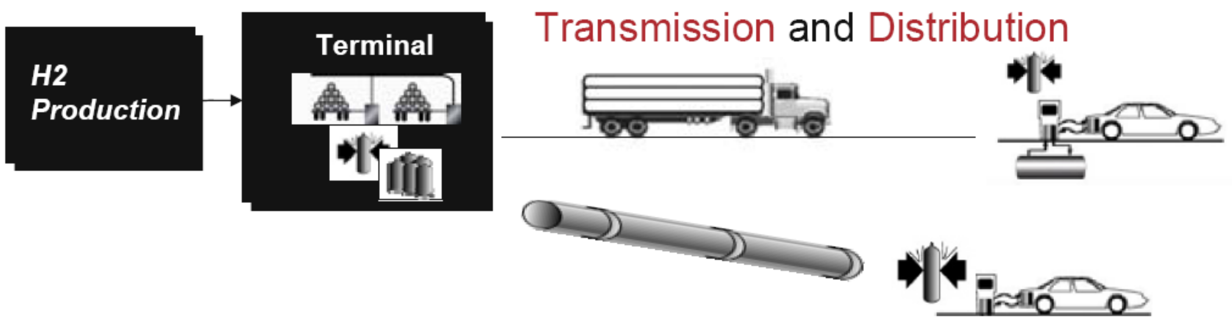
Operational Concept

The following delivery scenarios will be supported by the system:

- Initial Phase Scenario: (Centralized Production) Hydrogen production occurs at a large facility and delivered to a terminal facility for distribution to the retail fuel stations



- Step-Out Phase Scenario (Centralized Hybrid Production) Hydrogen production occurs at a smaller facility co-located at the terminal facility for distribution to retail fuel stations



In more developed areas particularly along "right-of-ways" such as highways, pipeline infrastructure will be more cost-effective for distribution. In remote areas, distributed production will be more prevalent and / or home delivery of hydrogen may be required.

p-Diagram

Uncontrollables:
- Supply and demand of alterative energy sources
- Competing Alternatives
- Unanticipated hydrogen technologies that change the solution space
- Supply chain impacts: nature and human caused events
- Laws, Regulations, Codes and Standards
- Business and Operational Goals
- Fuel Cell Technology (H2 FCV Application)

Inputs:
- Hydrogen (H2)
- Forms
    - Compressed H2
- Suppliers
    - Praxair
    - Air Liquide
- Transactional Information
- Delivery Requests
- H2 Supply Information
- Parts & Equipment Supply
- Resources, Support (I.T., Equipment)

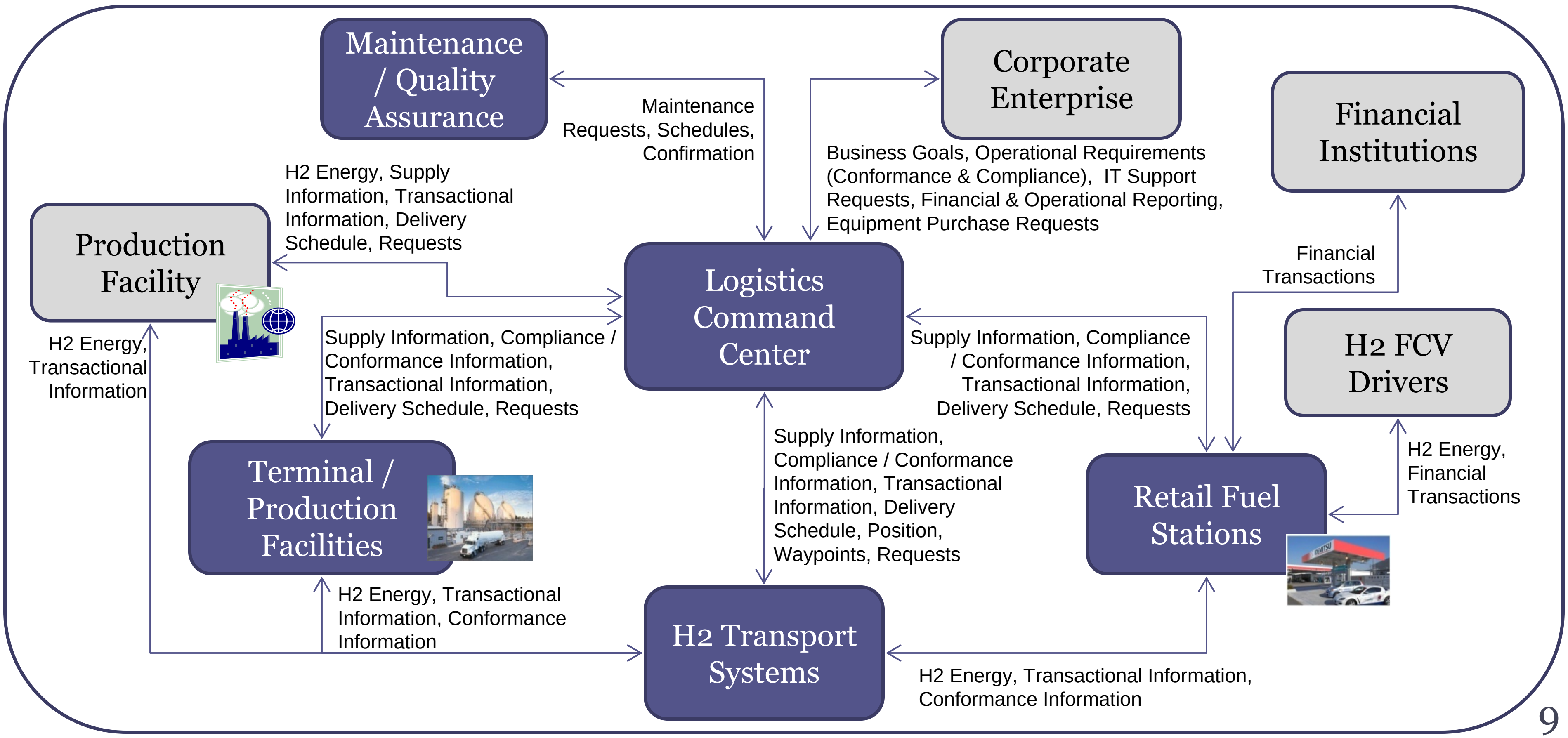
Hydrogen Delivery System

Outputs:
- Energy for vehicle propulsion
- Emissions
- Conformance Information
- Delivery Schedule
- Transactional Information
- Demand Information
- Resource & Support Requests

Controllables:
- Fuel station, Distribution Center locations
- Vehicle storage volume
- Storage
- Production Processes
- Fuel state
- Delivery method (Pipe line, tanker, etc.)

Operational Concept / Context

<u>Context:</u> Competing Alternatives, Unanticipated Hydrogen Technologies, Energy Supply Impacts, Government Laws & Regulations, Vehicle Manufacturers & Suppliers, Delivery System Suppliers, Codes & Standards Bodies, Competition, Special Interests (Environmentalists)

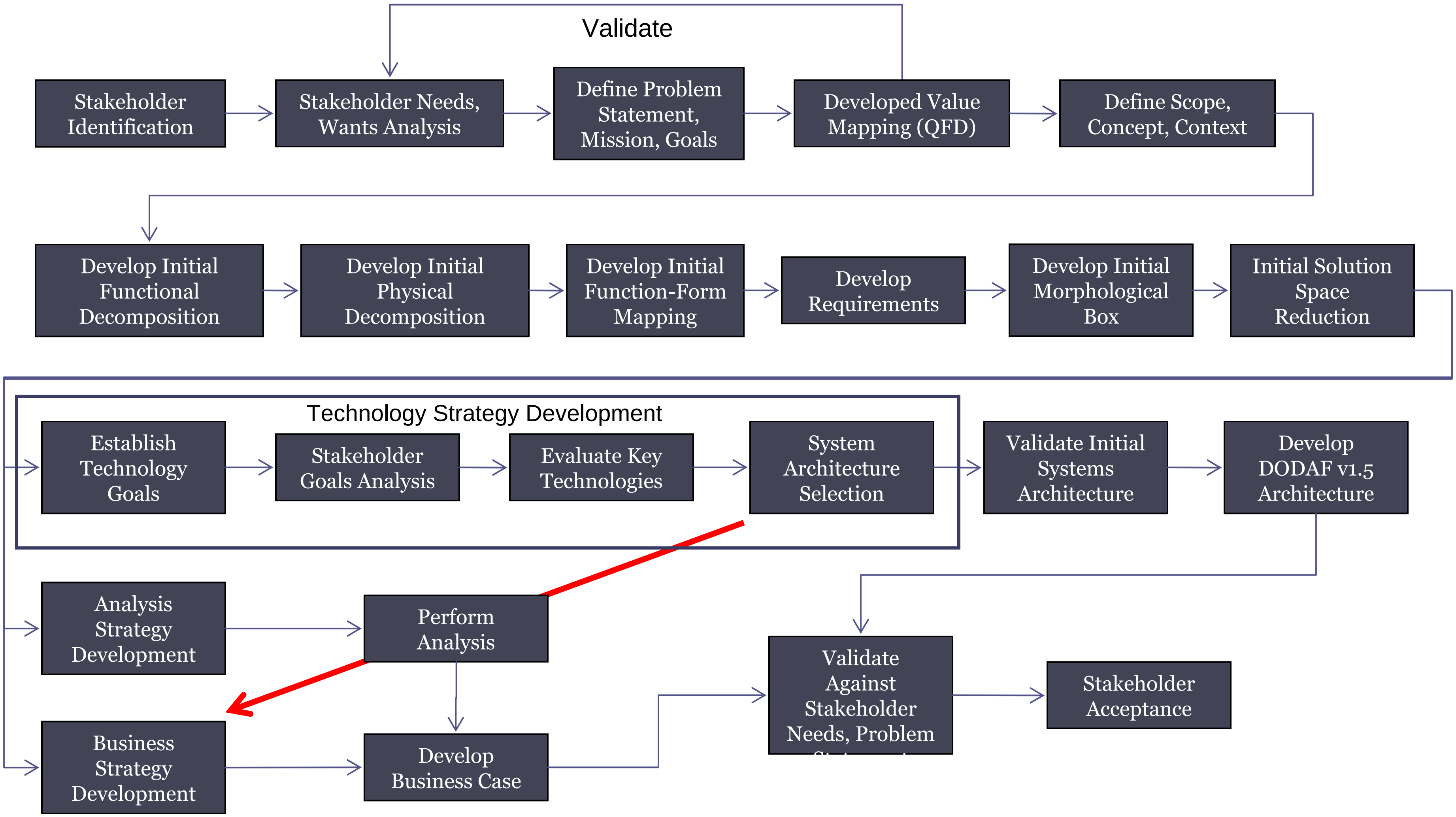


Base Functional Model

Key Risks

- DOT regulation restrict tube trailer pressures to less than 200 bar (2640 psi). Based on DOE projections for average fuel station usage statistics (Average: 1,050 Kg of H_2 / day, Peak Average: 1,500 Kg of H_2 per day):
  - Current tube trailers at 2640 psi transport up to 280 Kg H_2, equating to approximately 50 - 60 fill ups, potentially requiring multiple deliveries per day.
  - Tube trailers with 10 K psi can transport up to 1500 Kg of H_2 per day and may be required for compressed H_2 vehicle transport to be feasible. Further, there are advances in cryo-cooling of compressed H_2 gas, which can significantly increase the volumetric capacity of a storage tank, further improving delivery capacity.
- Laws restricting urban pipeline pressures to 125 psi, whereas 500 - 2,200 psi is more desirable:
  - This limits capacity and reach of distribution in urban settings. As a result, transporting H_2 via vehicle trailer may be the only option.
- Volatility in Gasoline, Diesel, Ethanol Prices impact price Hydrogen can be sold, affecting overall Net Present Value (NPV) for the system

Project Development Process



Vehicle Storage: (Solid Storage)
Solid Storage is the superior solution for Hydrogen Fuel Cell vehicles due to it's high volumetric capacity at much lower compression levels (< 2000 psi), which results in higher efficiency dispensing and lower maintenance costs. Picking Solid Storage over Liquid, eliminates the possibility that a Liquid Carrier will be used as a distribution state in the system.

H2 Transport: (10 K psi tube trailer):
10 K psi offers the best capacities for Compressed H2 and is the only solution that comes close to meeting the average expected daily usage at a retail site by DOE (1500 Kg). However, the DOT has a limit of 2640 psi on all large compressed vehicle payloads. As a result, we will develop the system to use either 2640, 5 k and 10 k psi pending changes to DOT regulations. We will also develop cryo-cooling technologies which when applied could boost capacities of large 2640, 5 k and 10 k psi tanks.

Row #	Stakeholder Goals \ Architecture Alternatives	Vehicle Application: Solid Carrier (< 2,000 psi)	Compressed H2 (@ 5K psi)	Compressed H2 (@ 10K psi)	Liquid Carrier	H[illegible]: Compressed H2 (@ 2640 psi)	Compressed H2 (@ 5K psi)	Compressed H2 (@ 10K psi)	Liquid Carrier		Goals Score
1	Factor of Safety	5	4	3	5	5	4	3	[illegible]		[illegible]
2	Factor of Toxicity of Fuels, Byproducts, Materials	5	5	5	3	5	5	5	3		[illegible]
3	System Availability	3	3	3	3	3	3	3	3		0.779
4	Efficiency (% H2 Energy Conserved)	5	5	4	4	5	4	4	4		0.736
5	H2 Cost ($ / Kg H2 or $ / GGE)	0	0	0	0	3	4	5	1		0.683
6	Green House Gas Emissions (ppm)	0	0	0	0	0	0	0	0		0.534
7	Pollutants (ppm)	0	0	0	0	0	0	0	0		0.534
8	Volumetric Density (Kg / L)	5	2	3	5	1	2	3	5		0.529
9	Storage Capacity (Kg of H2 Total)	5	2	3	5	1	2	3	5		0.522
10	Delivery System Capacity (Kg H2 / day)	0	0	0	0	1	2	4	5		0.473
11	System Capital Cost	3	4	3	2	3	4	3	2		0.468
12	Refueling Rate (Kg of H2 / Min)	3	5	5	5	5	4	3	5		0.403
13	System Maintenance Cost	4	4	3	1	5	4	3	1		0.367
14	Technical Readiness Level	4	5	4	1	5	3	1	1		0.296
15	% of H2 by Weight	3	2	2	3	3	4	4	2		0.236
16	Energy Density (KWH / L)	5	2	3	5	1	2	3	5		0.21
16	Cycle Life (Cycles 1/4 tank to full)	3	5	5	3	5	5	5	3		0.191
	System Score	1.00	0.89	0.83	0.86	1.00	1.00	1.00	0.98		

Relative Goal Ranking	
0	N/A
1	Poor
2	Fair
3	Satisfactory
4	Good
5	Excellent

The Goals Score ranking the goals was carried forward from earlier goals analysis activities. This was used as a weighing to establish the raw score and the system score which is normalized version of the raw score. The raw score is the Sum of (Relative Goal Rank * Goals Score) . The System Score is the Raw Score divided by the Max Value of the scores.

Market Introduction
Business Strategy

Market Predictions

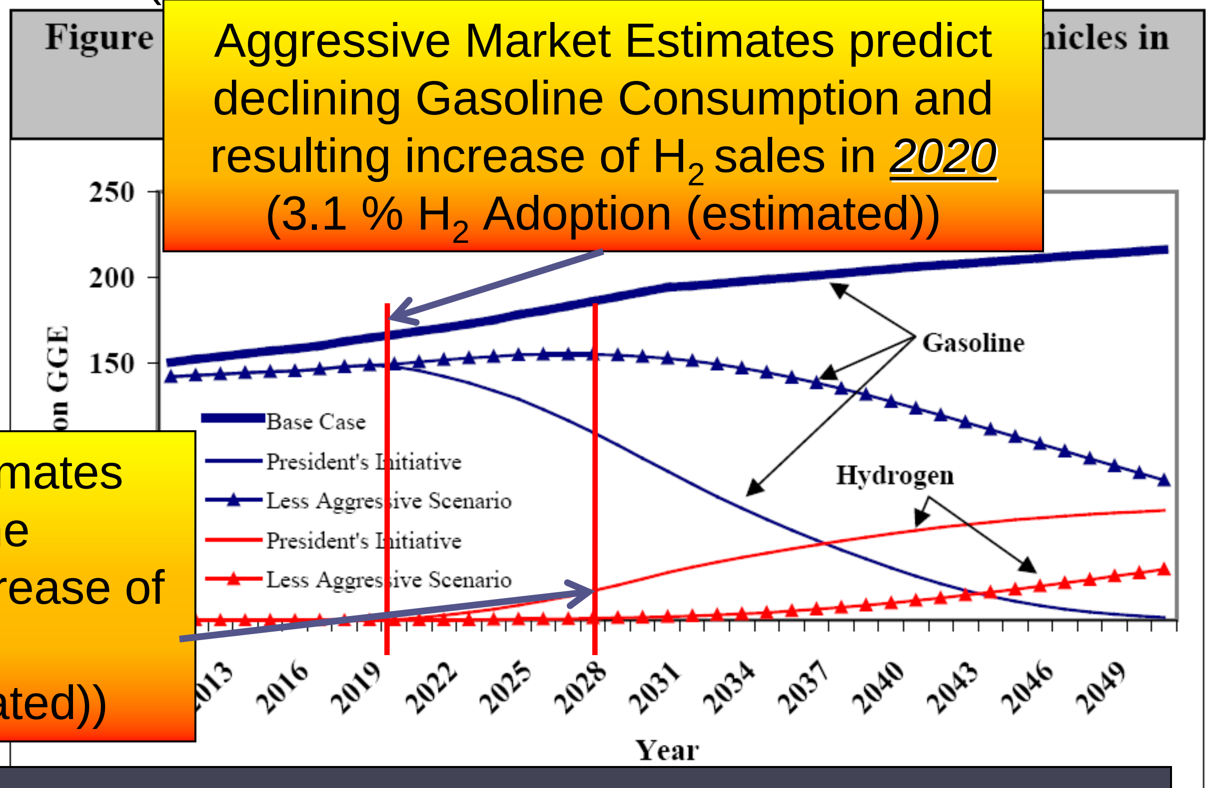
President's Hydrogen Fuel Initiative (HFI) Market Prediction is the most aggressive development case based around the HFI scenario.

- Market Share: 3.1 % (2020), 59.6% (2035), 96% (2050)

A less aggressive model was developed,

- Market Share: 0.5 % (2020), 7.5% (2035), 38.2% (2050)

Base Case is where Hydrogen has a minimal role in the economy



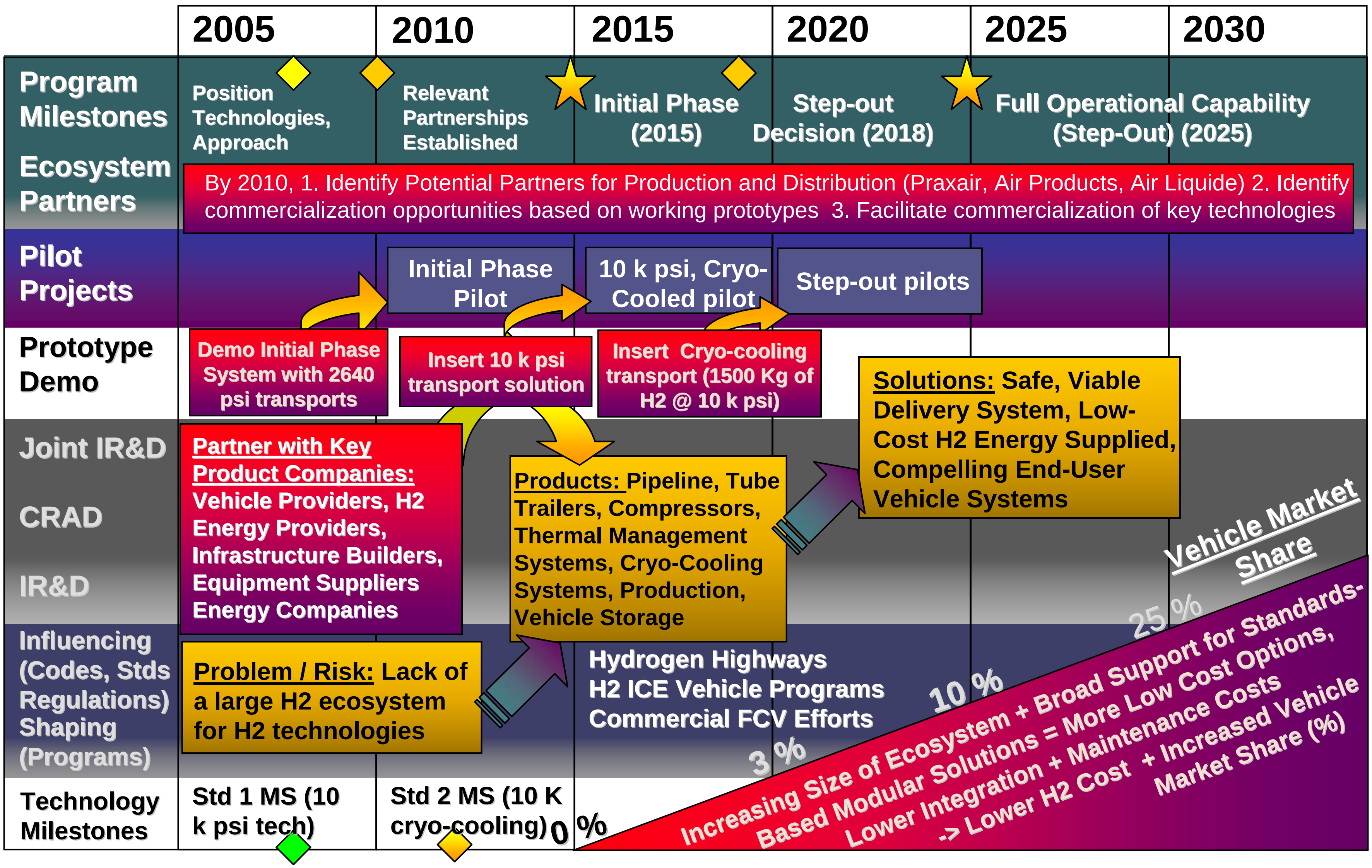
Aggressive Market Estimates predict declining Gasoline Consumption and resulting increase of H_2 sales in ***2020*** (3.1 % H_2 Adoption (estimated))

Less Aggressive Market Estimates predict declining Gasoline Consumption and resulting increase of H_2 sales in ***2028*** (3 - 4 % H_2 Adoption (estimated))

Sales in H_2 will be required to compensate for loss of revenue from declining sales in current gasoline product offerings.

http://www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf, pp. 19 - 22, July 2008

Business / Technology Roadmap

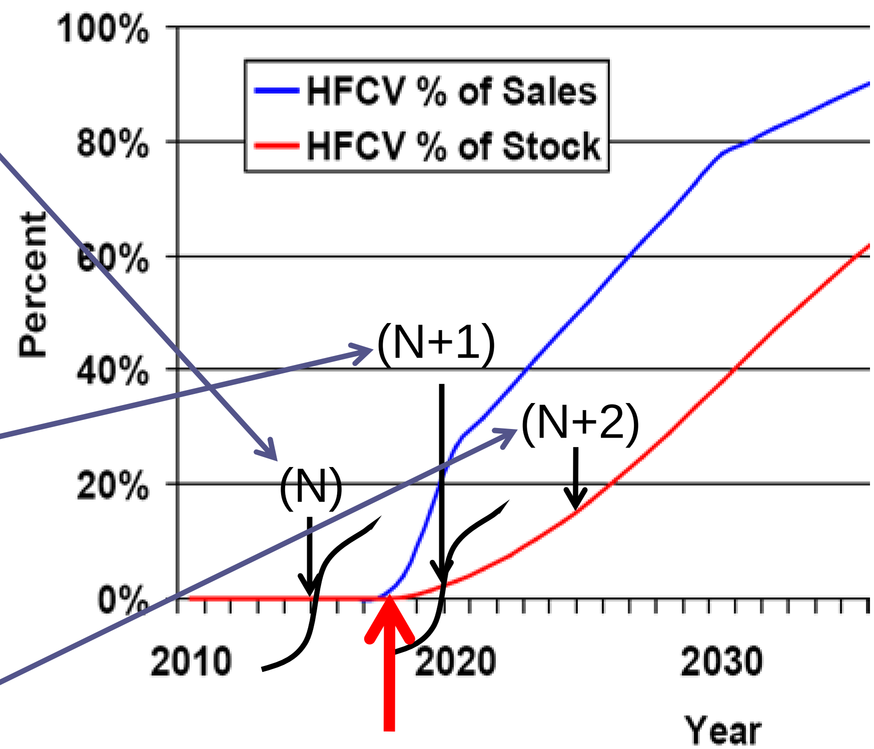


Technology Insertion Points

(N) - Initial Phase System
(Full Operational Capability (2015))
10 K psi Compressed Hydrogen
Tube Transports, Compressors
(Large, Small)

(N+1) - Tech Insertion
(Operational - 2020)
10 K psi Cryo-cooled H2

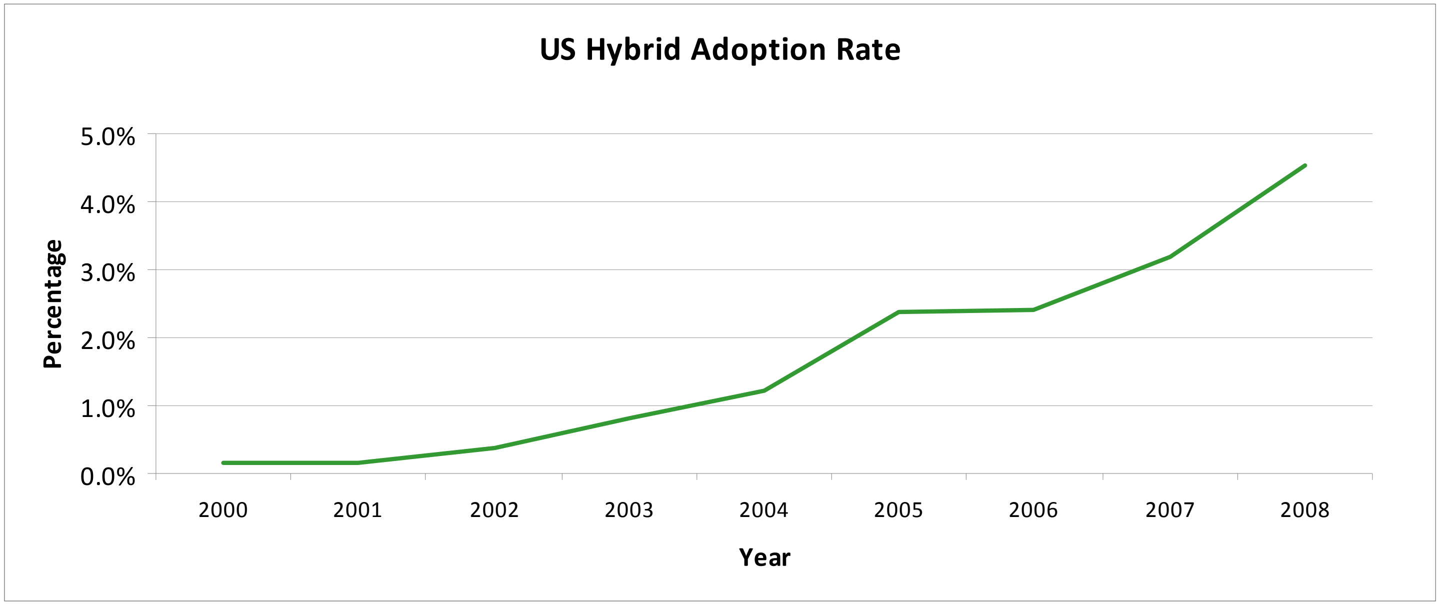
(N+2) - Step-Out Phase System
(Full Operational Capability (2025))
w/ Highway Pipeline Distribution
(Hydrogen Highways)



Step-Out
Decision Point
(2018)

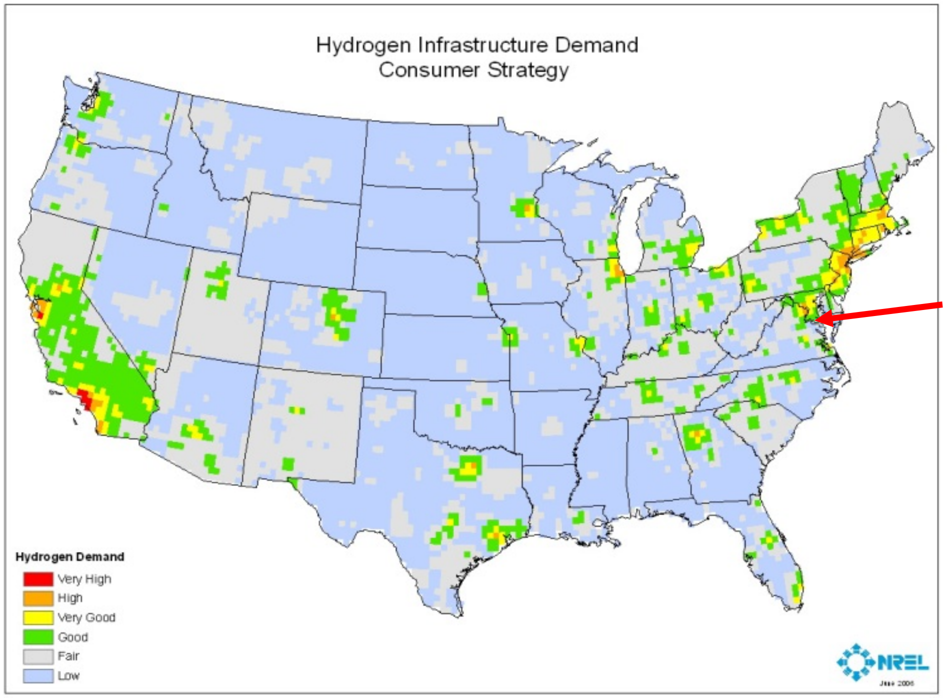
Market Analysis

- The Toyota Prius gasoline-electric hybrid vehicle was launched in the U.S. in 2000 and has taken off with record sales due to its high fuel economy.
- Several other hybrid vehicles have been developed since the Prius and currently the Prius has a 40% market share.
- It can be assumed that a hydrogen car will have the same market penetration as hybrids which is characterized by the hybrid sales growth rate.



Hydrogen Demand

- If hydrogen vehicles were available in the Washington metropolitan area there would be a high demand for hydrogen.
- There would be a significant amount of vehicles requiring hydrogen due to the demand for hydrogen in combination with a 0.5% - 1% adoption rate



Business Strategy: Location Analysis

Analysis

- Needs:
  - >70% of retail cost is due to the delivery infrastructure
  - Need an ability to determine where and when to invest

- Problem:
  - For a given area, how many stations should be converted to H2? In what locations, and at what times?

- Our model is scaled to Fairfax County for feasibility & analyst familiarity

Problem Scope

Parameters:
- Station capital cost
- User preference costs for proximity
- Retail fuel costs
- Vehicle efficiencies

Inputs:
- Architecture Alternatives
- US Census Data on population, vehicles per household, commute times
- Distances between zip codes
- Technology strategies and cost

Hydrogen Station Analysis

Outputs:
- # of stations per zip code
- Amount from stations in a zip from customers in various zips

Constraints:
- Forecourt Supply must be > Demand
- Regulatory constraints on trailer tube pressures (volume)
- Regulatory constraints on storage pressures

Approach

1. Identify all the zips in the given metro area (these are the nodes)
2. Define the distance between each zip (using zip-code radius finder, above) in a node-node adjacency matrix.
3. Find those within 5 miles, giving the list of accessible zips for the cij matrix
4. Determine the demand Dj. Use commute time from the US Census as a proxy for demand, and come up with a factor based on vehicle efficiency and a rough translation of commute time to mileage to estimate the amount of kg of H2 consumed per time period. Apply an assumption about the adoption level of H2 vehicles in the population.
5. Solve the mixed integer and linear program.
6. Solve the dual and perform sensitivity analysis.
7. Consider several scenarios with different adoption levels

Model

- Decision Variables
  - Where should supply be built (to service demand)?
  - When should transitions be made? How many?
- Objective
  - Maximize profit
- Constraints
  - Cover all demand
  - Demand in any year must not exceed station capacity
  - Continuity – stations that exist one year must exist the next

Assumptions

- Constant demand throughout the year
- Future years will not choose not to have a station already built
- Each “station” offers the same capacity
- Consumers will demand only near their home
  - This can be relaxed with more data on work locations and travel patterns
- Customers will choose equally among accessible stations
- Competition is considered in the demand assumptions applied, based on the market analysis
- Capital and operating costs are the same for each station
- Initial scope of a metro area will scale up

Location Study Results

- Not profitable with base case (existing trailer tech)
- Can be profitable with next best trailer (5k psi)

- Locations chosen / per year:

Total Stations Required, by Year and Location											
	Year										
Zip Codes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
20170	1	1	1	1	1	2	2	2	3	4	**4**
22030	1	1	1	1	1	1	1	2	2	3	**3**
22151	1	1	1	1	1	1	1	1	2	2	**2**
22308	1	1	1	1	1	2	2	2	3	4	**4**
Total	**4**	**4**	**4**	**4**	**4**	**6**	**6**	**7**	**10**	**13**	

Scenarios

- # Stations built for each scenario (initial year):

	Scen #1	Scen #2	Scen #3	Scen #4	Scen #5	Scen #6	Scen #7	Scen #8	Scen #9	Scen #10	Scen #11	Scen #12	
Price	lo	lo	lo	lo	lo	med	med	med	hi	hi	hi	hi	
Demand	lo	lo	lo	med	med	med	med	med	med	hi	hi	hi	
Op Cost	0.60	1.63	3.21	1.63	1.63	0.60	1.63	3.21	1.63	0.60	1.63	3.21	
Zip Code													**Total**
20120									3	11	11	11	**11**
20170	3	3	3	4	4	4	4	4	3	7	7	7	**7**
20194										4	4	4	**4**
22030				3	3	3	3	3	3	7	7	7	**7**
22039										6	6	6	**6**
22042										2	2	2	**2**
22044										7	7	7	**7**
22066									2	4	4	4	**4**
22124										4	4	4	**4**
22151						2	2	2					**0**
22152										4	4	4	**4**
22181									2				**0**
22307	3	3	3						3	10	10	10	**10**
22308				4	4	4	4	4					**0**
Total	**3**	**3**	**3**	**4**	**4**	**4**	**4**	**4**	**3**	**11**	**11**	**11**	**11**

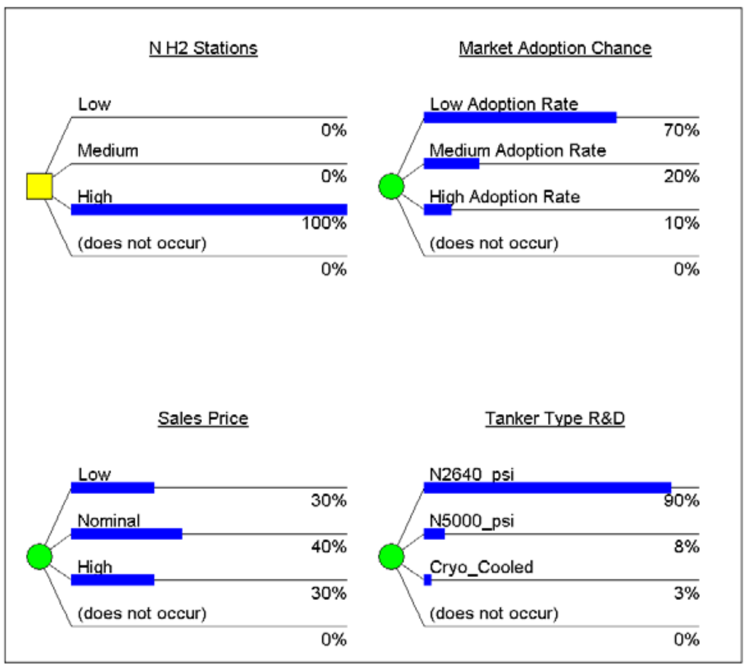
- Results:
  - Retail price and technology have high variation on NPV, but little effect on locations and transition decisions

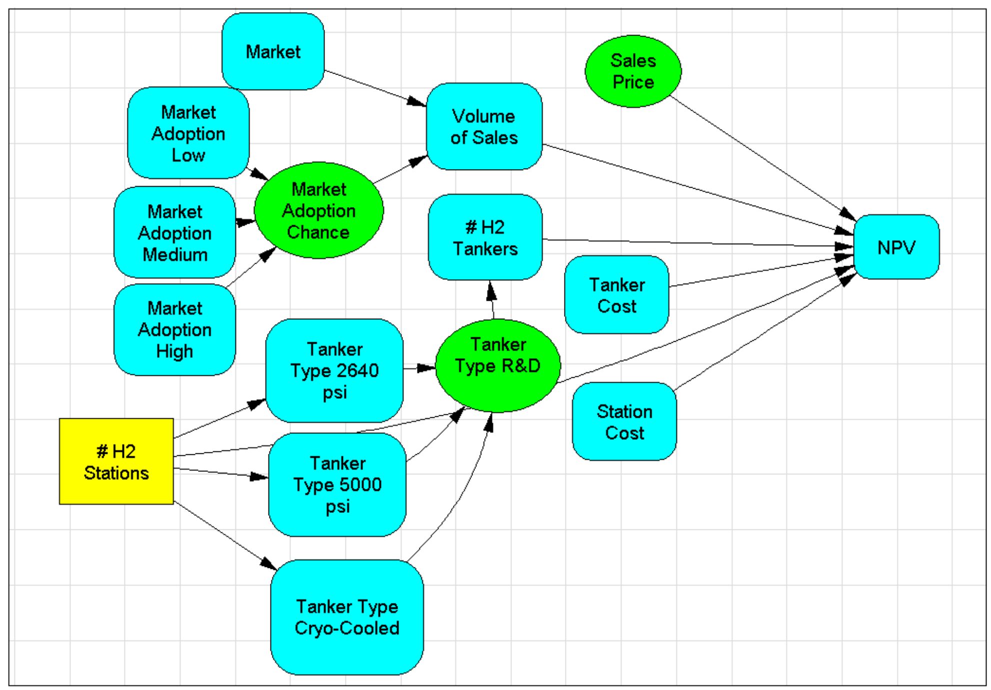
Cost Analysis

- Compressed Hydrogen Fuel Station
  - Loading / Storage Compressor
  - Land Costs
  - Station Conversion to Hydrogen Costs
  - Operating Costs
- Compressed Hydrogen Tanker
  - Tractor
  - Tube Tank Trailer
  - Operating Costs

System Influence

- Hydrogen Tankers and Stations have the most possible variance
- The auto market size and market adoption have little room for varying values





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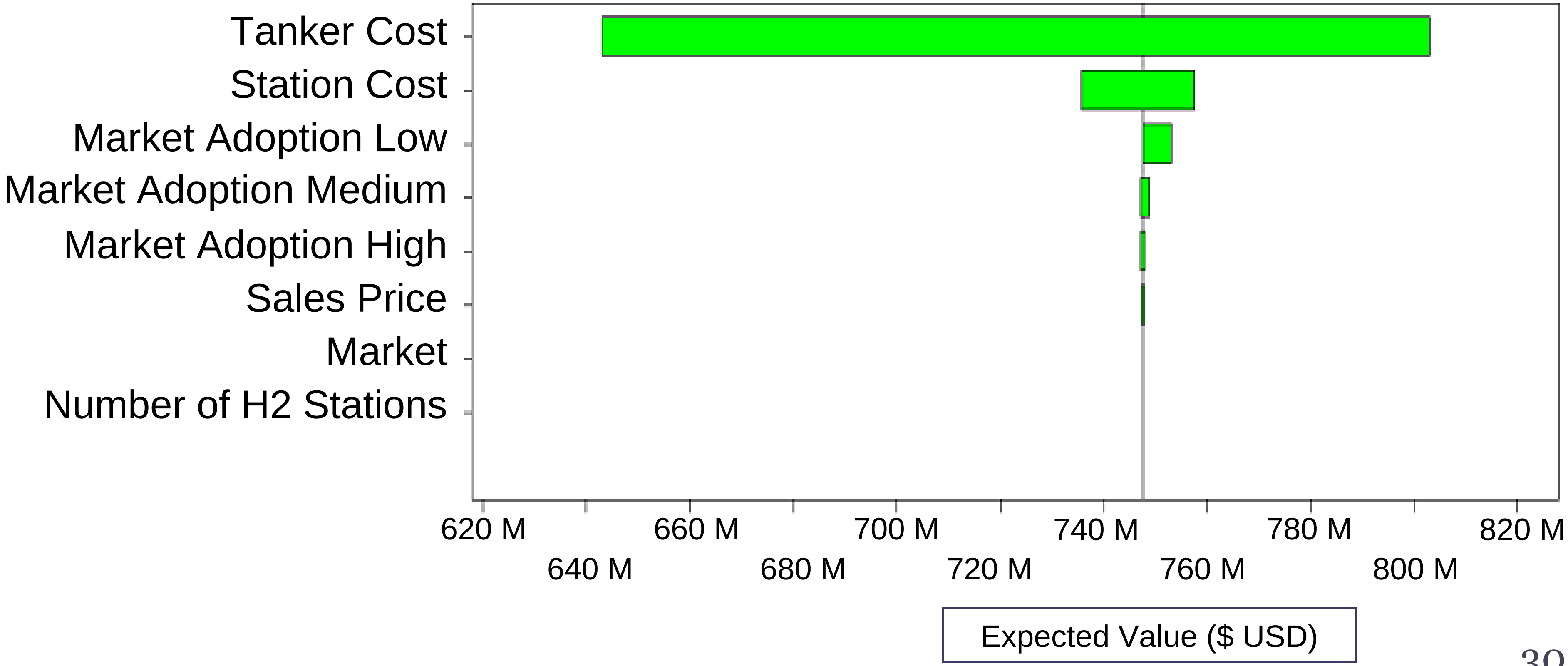
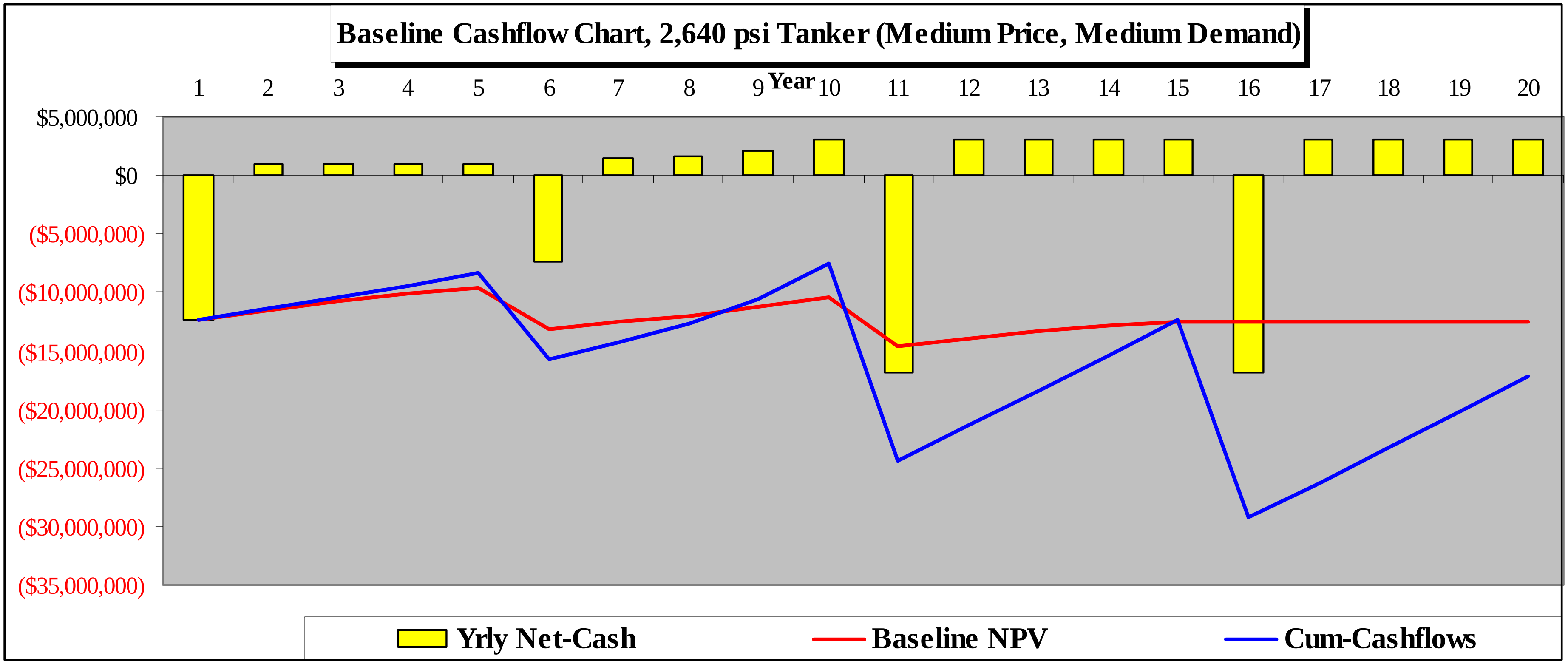


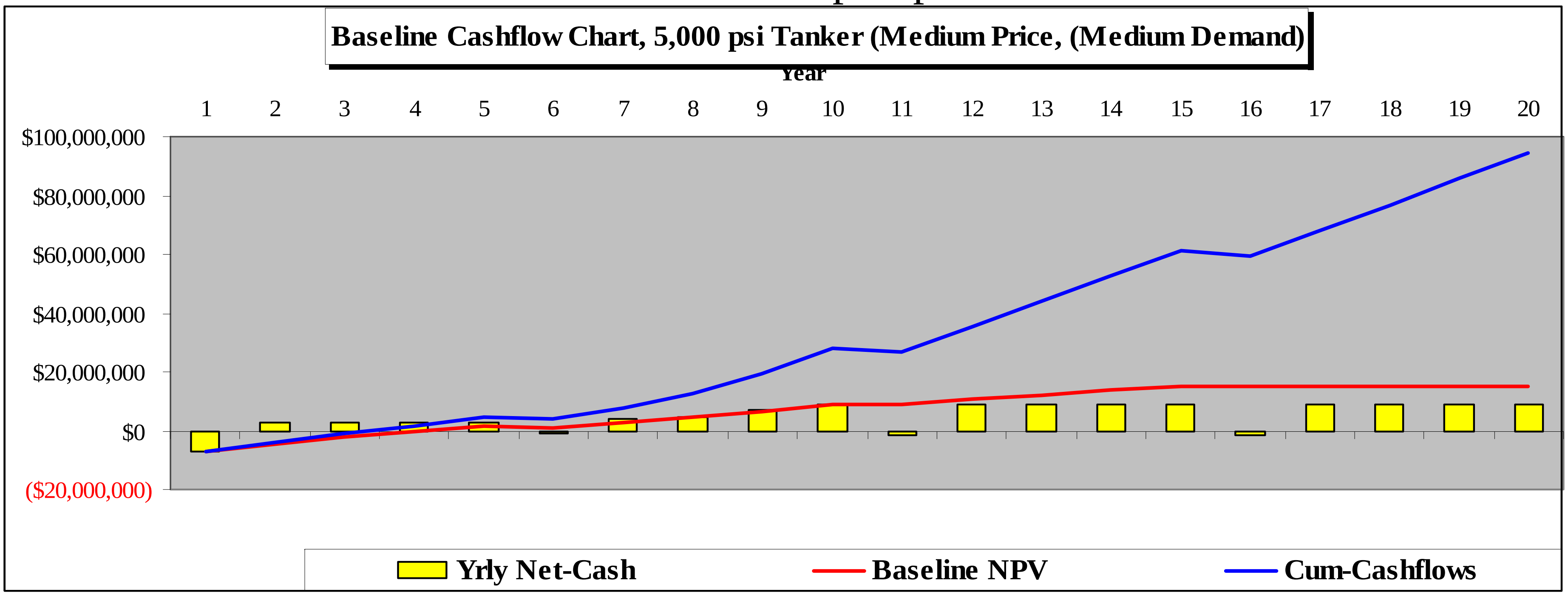
Net Present Value

- The current hydrogen technologies do not result in a positive net present value do to high costs to convert fueling stations and high hydrogen delivery costs



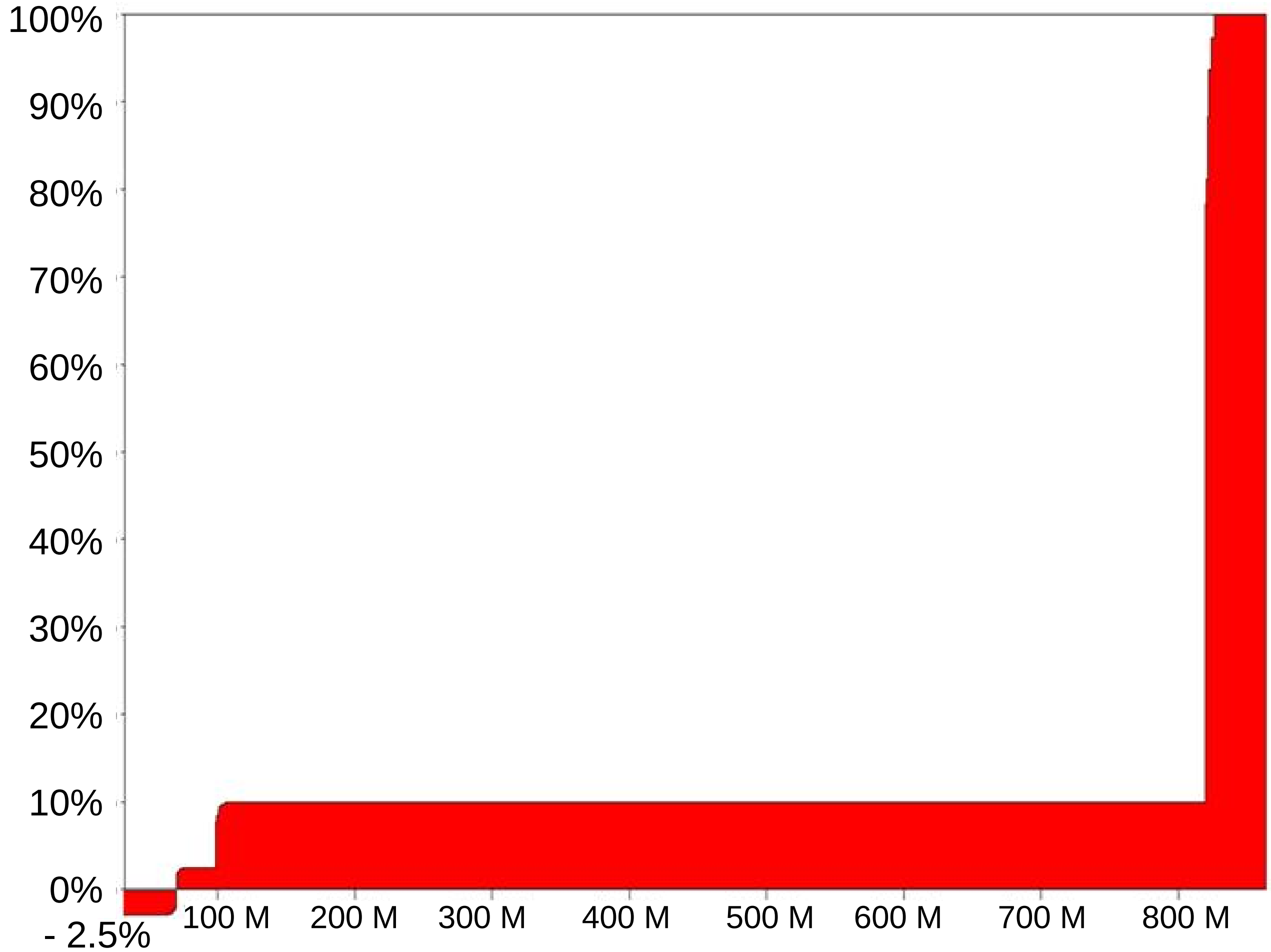
Cost Drivers

- To achieve a positive net present value the price of hydrogen at the pump would exceed $7 / kg
- The current tanker technology allows for the delivery of 280 kg per tanker which incurs a high cost to transport a small amount of hydrogen
- Tankers are being developed which will be able to deliver 550, and 1500 kg which will dramatically reduce the cost to deliver hydrogen to the stations and will reduce the cost at the pump



Net Present Value

- There is less than a 2.5% chance of a negative NPV when including possibilities such as low and high market adoption rates, low and high prices, and three different types of hydrogen tankers



Business Strategy Conclusions

Cost Analysis Summary				
NPV	Break Even Point	Kg / Tanker	Demand	Price
$ (35,172,921)	-	280	Low	Low
$ (54,467,791)	-	280	Medium	Medium
$ (115,748,744)	-	280	High	High
$ 53,319,147	Year 3	550	Low	Low
$ 72,194,467	Year 3	550	Medium	Medium
$ 167,684,392	Year 2	550	High	High
$ 107,281,753	Year 2	1500	Low	Low
$ 159,106,580	Year 2	1500	Medium	Medium
$ 353,103,052	Year 2	1500	High	High

- 10k psi (1500kg) trailers offer the best business case
  - However, technology not production ready
  - Need updates to DOT regulations before deploy
- Still, only a 2.5% probability for negative NPV.

Conclusions, Recommendations

- The Cost and Capacity of Tankers are the primary cost drivers.
- The most profitable, efficient approach in this environment is to deploy 10 k psi tankers with capacities of over 1500 Kg and apply technologies such as cryo-cooling (NPV of $353 M), though there are lower pressure / capacity scenarios where we will still be profitable (e.g. 5 k psi with an NPV of $53 M).
- Recommendations, Way-Forward:
  - Invest in the initial phase delivery system ($67 M for first five years)
  - Begin partnering discussions with Hydrogen Energy Providers.
  - Expand the Initial Phase business case to a nationwide deployment
  - Start developing the business case for the Step-Out phase

Declines in retail gasoline sales in the U.S. will occur between 2020 - 2028. Sales in H_2 will be required to compensate for loss of revenue from declining sales of current fuel product offerings. We must invest in a Hydrogen Delivery System now in order to meet this emerging challenge to the oil business.

Key References

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