Cost Analysis of Fuel Cell Systems for Transportation

Compressed Hydrogen and PEM Fuel Cell System

Final Presentation to:
Fuel Cell Tech Team
FreedomCar
Detroit. MI

October 20, 2004

TIAX LLC
Acorn Park
Cambridge, Massachusetts
02140-2390

Ref D0006
SFAA No. DE-SCO2-98EE50526
Topic 1 Subtopic 1C

Agenda

1. Project Overview
2. Compressed Hydrogen Storage Cost
3. 2004 System Cost Update
4. Appendix

In our final year of the project, we assessed the cost of compressed hydrogen storage and updated the overall system cost projection.

Task 1: PEMFC System Technology Synopsis

- Develop baseline system specification
- Project technology developments
- Assess impact on system performance
- Identify manufacturing processes

Task 2: Develop Cost Model and Baseline Estimates

- Develop cost model
- Specify manufacturing processes and materials
- Develop production scenarios
- Baseline cost estimate

Task 3: Identify Opportunities for System Cost Reduction

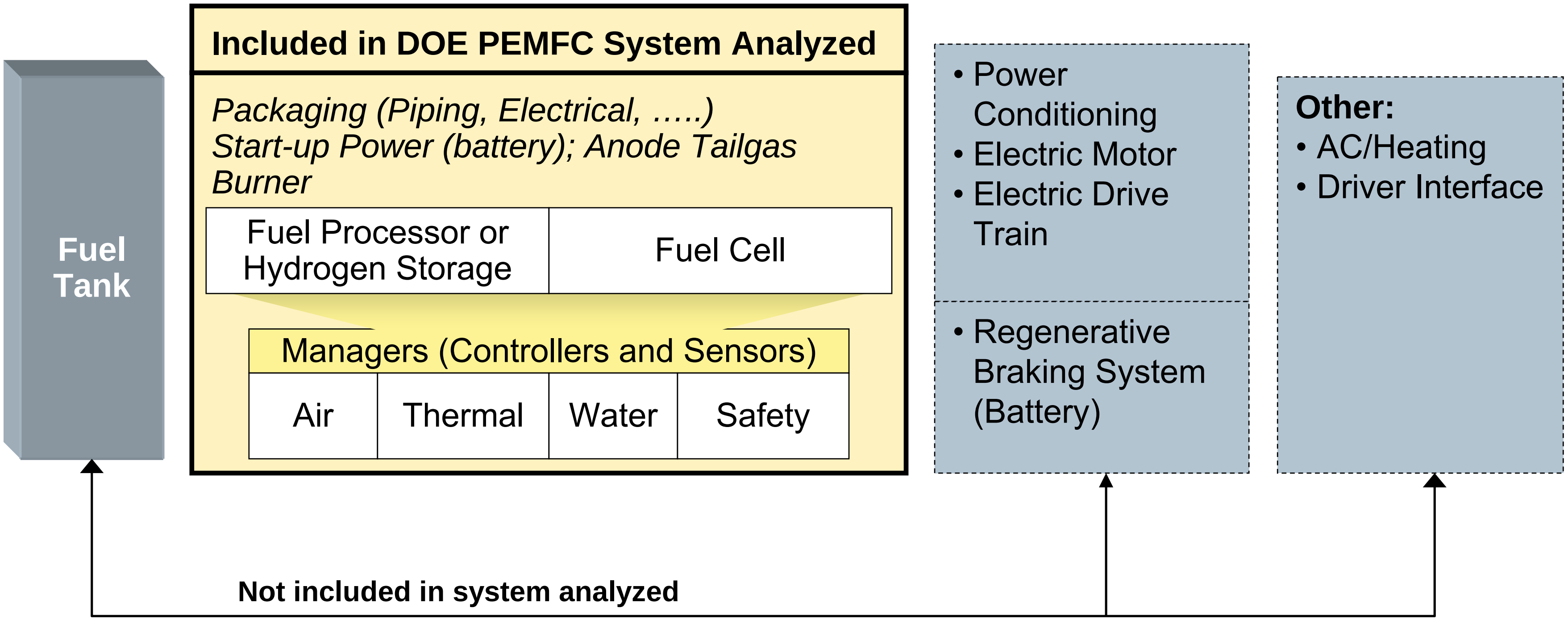
- Perform sensitivity analysis to key parameters
- Evaluate the impact of design parameters and potential technology breakthroughs on subsystem and overall system costs
- Identify and prioritize opportunities for cost reduction in transportation PEMFC systems
- Obtain industry feedback

Tasks 4, 5, 6 & 7: Annual Updates

- Assess technology evolution
- Update baseline cost estimate based on technology developments

Year 1 (1999)) — *Year 2 (2000)* — *Years 3, 4, and 5 Concluded 2004r*

A fuel cell vehicle would contain the PEMFC system modeled in this project along with additional electric drive train components. Components included in the analysis are based on PNGV/FreedomCar guidelines.



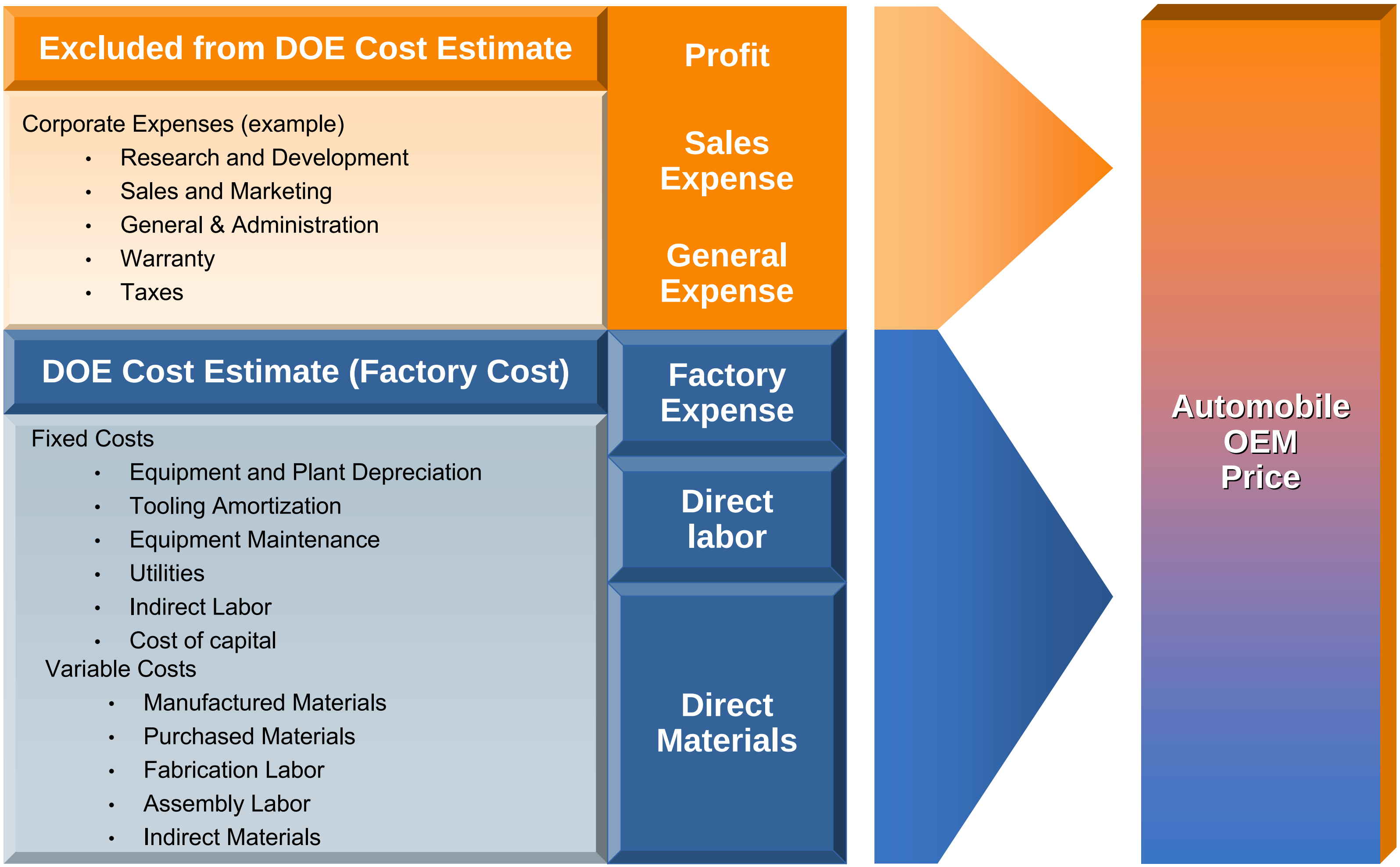
In the direct hydrogen system, the hydrogen storage subsystem replaces the fuel processor.

Individual components have been distributed between the major sub-systems as shown below for the Year 2000/2001 baseline system.

<table>
<tr><th colspan="2">Fuel Processor Sub-System</th><th>Fuel Cell Sub-System</th><th>Balance-of-Plant</th></tr>
<tr><td>◆ Reformate Generator
◆ ATR
◆ HTS
◆ Sulfur Removal
◆ LTS
◆ Steam Generator
◆ Air Preheater
◆ Steam Superheater
◆ Reformate Humidifier</td><td>◆ Fuel Supply
◆ Fuel Pump
◆ Fuel Vaporizer</td><td rowspan="3">◆ Fuel Cell Stack (Unit Cells)
◆ Stack Hardware
◆ Fuel Cell Heat Exchanger
◆ Compressor/Expander
◆ Anode Tailgas Burner
◆ Sensors & Control Valves</td><td rowspan="3">◆ Startup Battery
◆ System Controller
◆ System Packaging
◆ Electrical
◆ Safety</td></tr>
<tr><td>◆ Reformate Conditioner
◆ NH_3 Removal
◆ PROX
◆ Anode Gas Cooler
◆ Economizers (2)
◆ Anode Inlet Knockout Drum</td><td>◆ Water Supply
◆ Water Separators (2)
◆ Heat Exchanger
◆ Steam Drum
◆ Process Water Reservoir</td></tr>
<tr><td colspan="2">◆ Sensors & Control Valves for each section</td></tr>
</table>

Hydrogen storage replaces the fuel processor but still needs water and thermal management.

We have estimated the system cost up to and including factory costs for annual production volumes of 500,000.

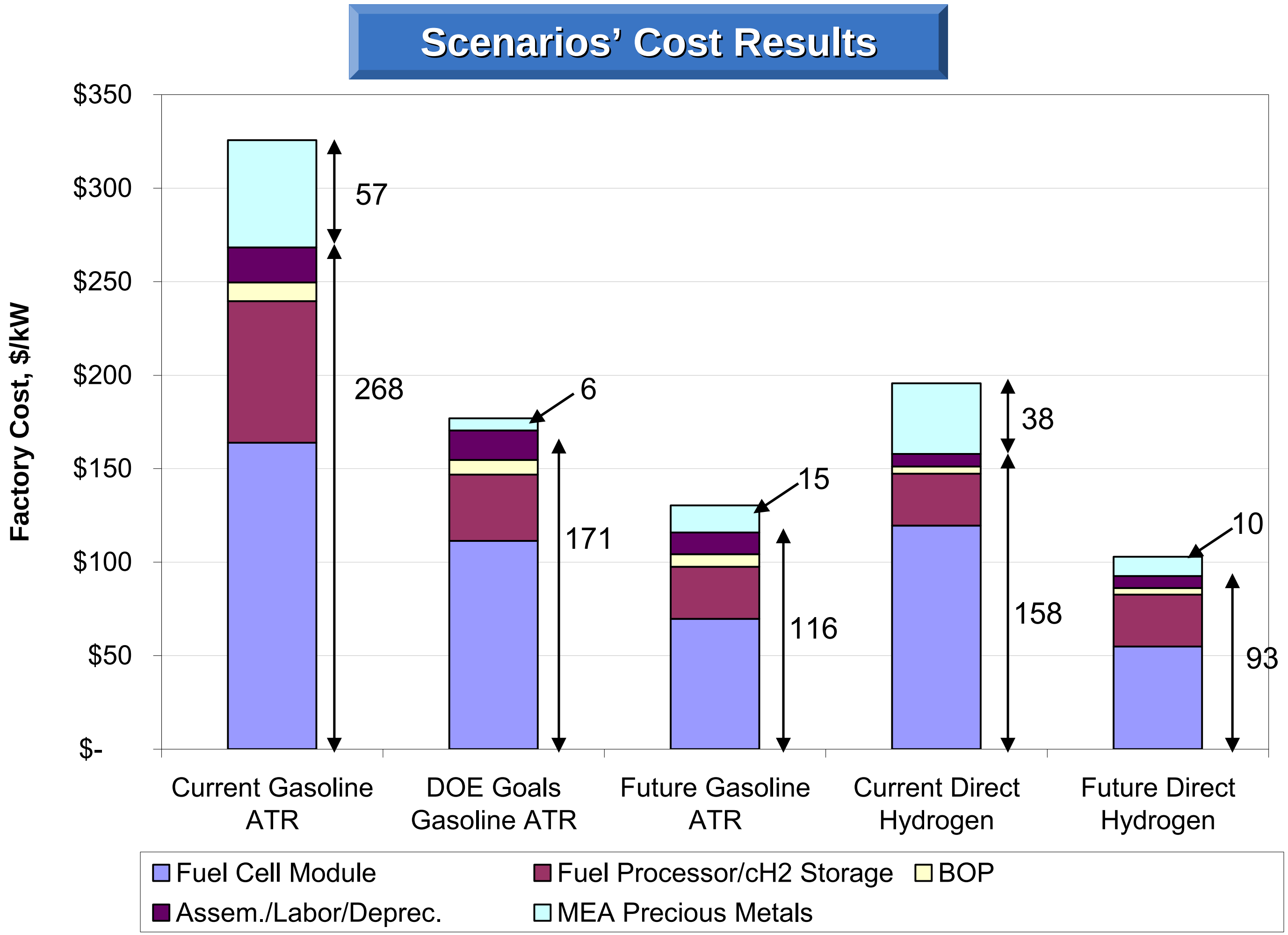


Our early estimates for reformate systems were around $300/kW (2000/2001 technology at large production volumes).

Sub-System	Factory Cost Estimate *			Driver
	2000 Baseline ($/kW)	2001 Baseline ($/kW)	% Change	
Fuel Cell	177	221	+25	Electrode and membrane material cost basis revised resulting in net increase
Fuel Processor	86	76	-12	Catalyst bed calculation basis revised
BOP	10	10	0	No changes to 2000 Baseline
System Assembly	21	17	-19	Reduction in assumed welding times
Total	**294**	**324**	**+10**	Overall increase due to fuel cell subsystem cost increase

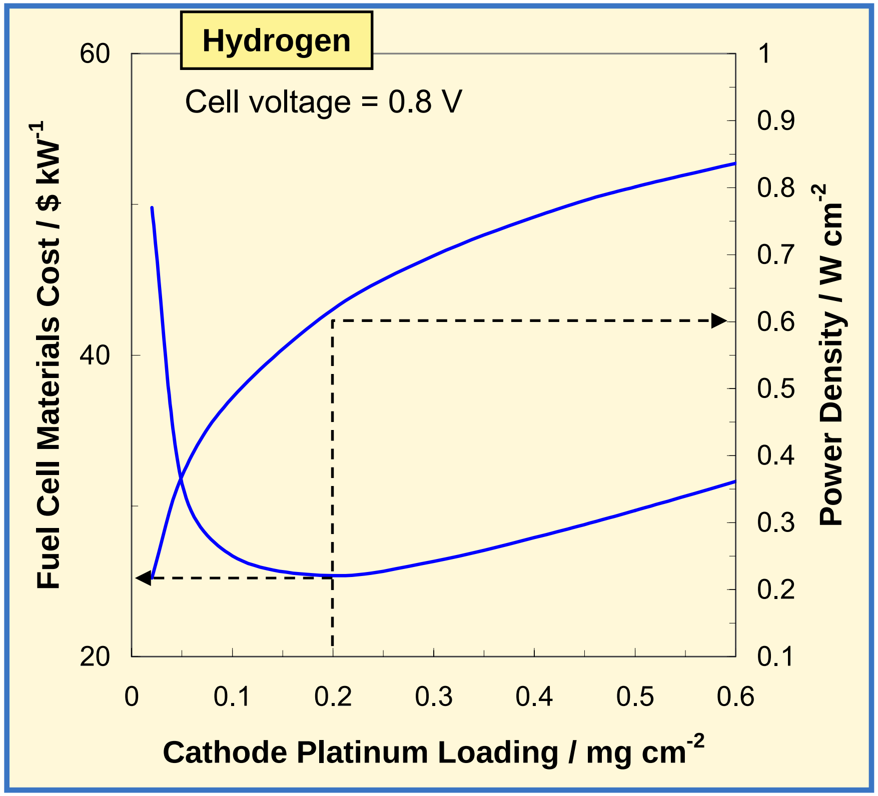
*Basis: 50 kWe net, 500,000 units/yr. Not complete without assumptions.

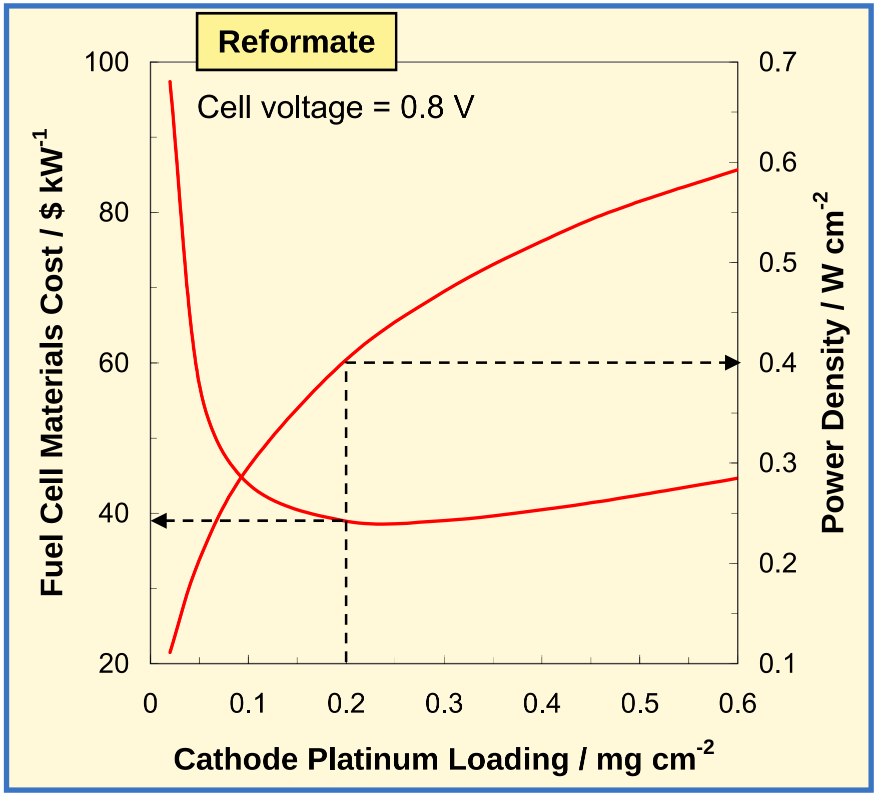
In 2002 projected improvements in performance and operation on hydrogen led to an estimate of approximately $100/kW for the system cost.



See Appendix pages 30 – 32 for assumptions.

In both reformate and direct hydrogen cases, the minimum in stack material costs occurs around cathode platinum loadings of 0.2 mg/cm².



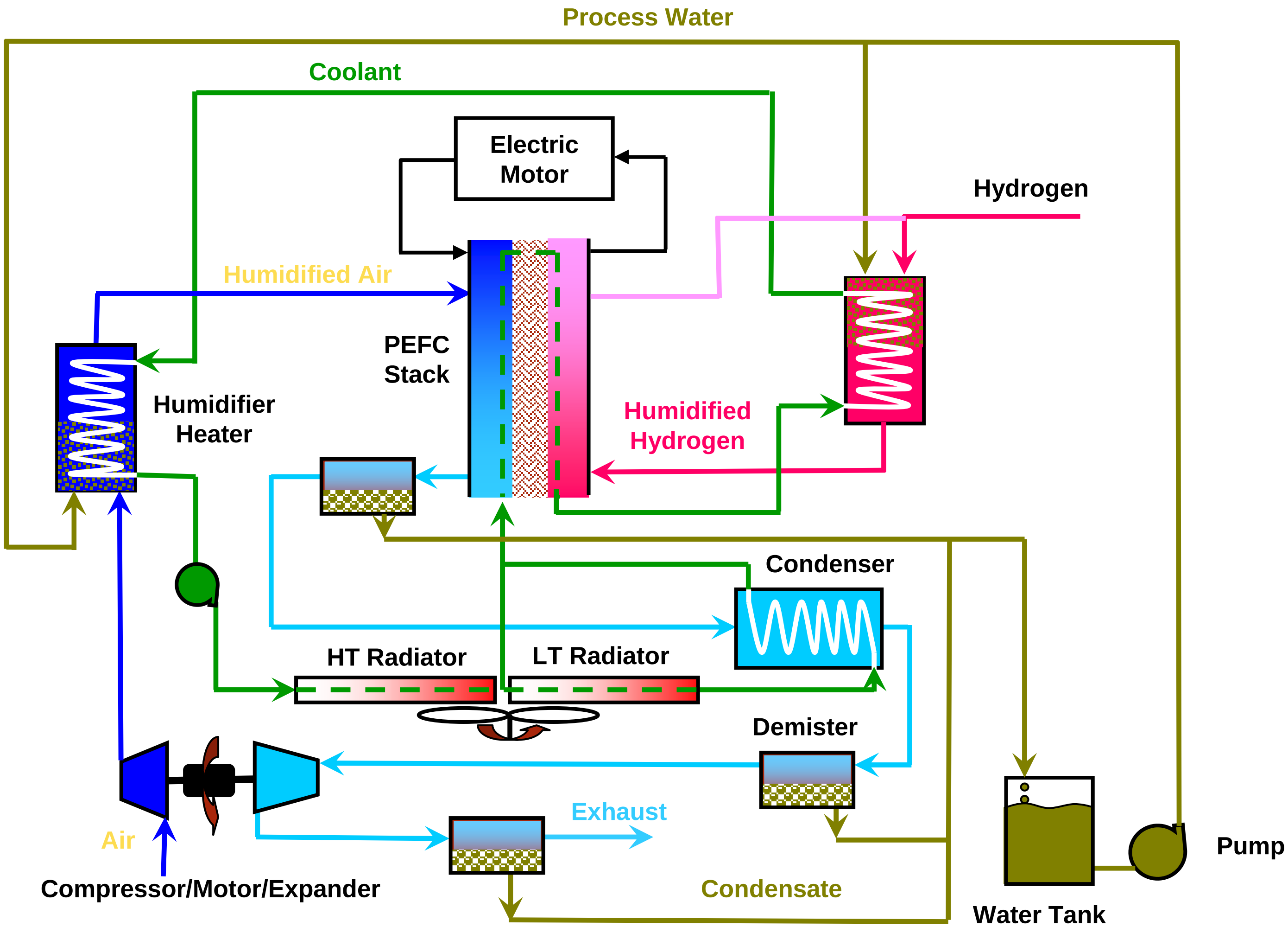


Assumptions	Hydrogen	Reformate
Anode overpotential (mV)	0	30
Membrane Resistance (mΩ cm²)	50	50
Electronic Reisistance (mΩ cm²)	20	20

Operating Conditions:
0.8 V, 3 atm, 160 C, 3.5 nm Particles, 2x Pt activity

1	Project Overview
2	**Compressed Hydrogen Storage Cost**
3	2004 System Cost Update
4	Appendix

We worked with Argonne National Laboratories (ANL) to define the overall system and hydrogen requirements for a mid-size vehicle.



Source: Dr. Rajesh Ahluwalia of ANL

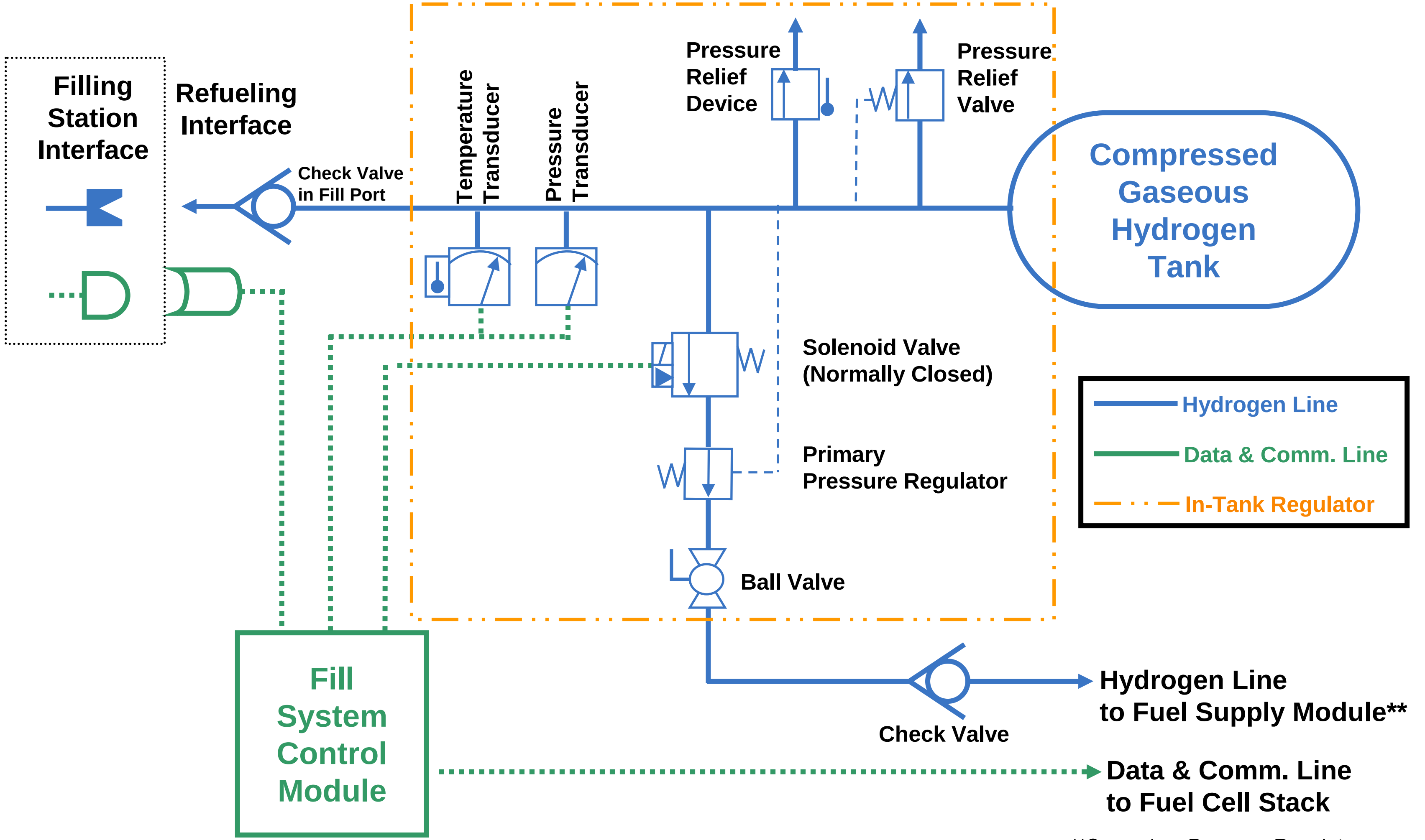
Several hybridization scenarios were considered before choosing an 80kW fuel cell with a "40kW" battery requiring 5.6 kg hydrogen storage.

ANL Results	ICEV 120 kW	FC EV 120 kW	FC HEV 100 kW	FC HEV 80 kW	FC HEV 60 kW
Engine/Fuel Cell Power, kW peak	114	120	100	80	60
Battery Power, kW peak	0	0	20	40	55
Fuel Economy, mpeg	23	59	65	68	69
Hydrogen Required	NA	6.3	5.9	5.6	5.6

References: 1.) Ahluwalia, R.K. and Wang, X., "Direct Hydrogen Fuel Cell Systems for Hybrid Vehicles," Journal of Power Sources, In print, 2004; 2.) Ahluwalia, R.K., Wang, X. and Rousseau, A., "Fuel Economy of Hybrid Fuel Cell Vehicles," 2004 Fuel Cell Seminar, San Antonio, TX, Nov. 2-5, 2004.

The analysis was conducted for a mid-size vehicle with a 370 mile range on a combined urban/highway drive cycle.

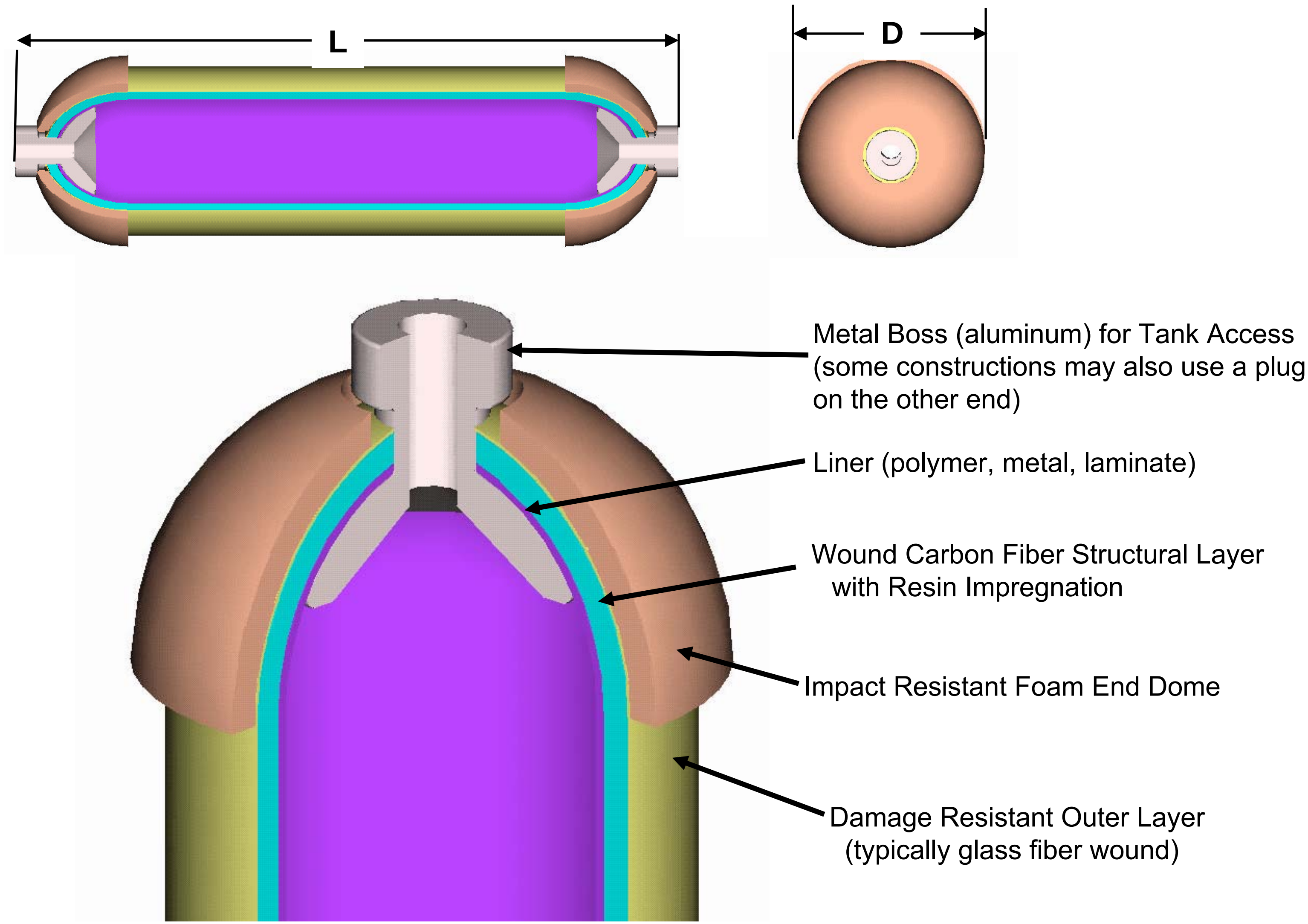
We used the hydrogen storage system schematic below as a basis for the cost assessment.*



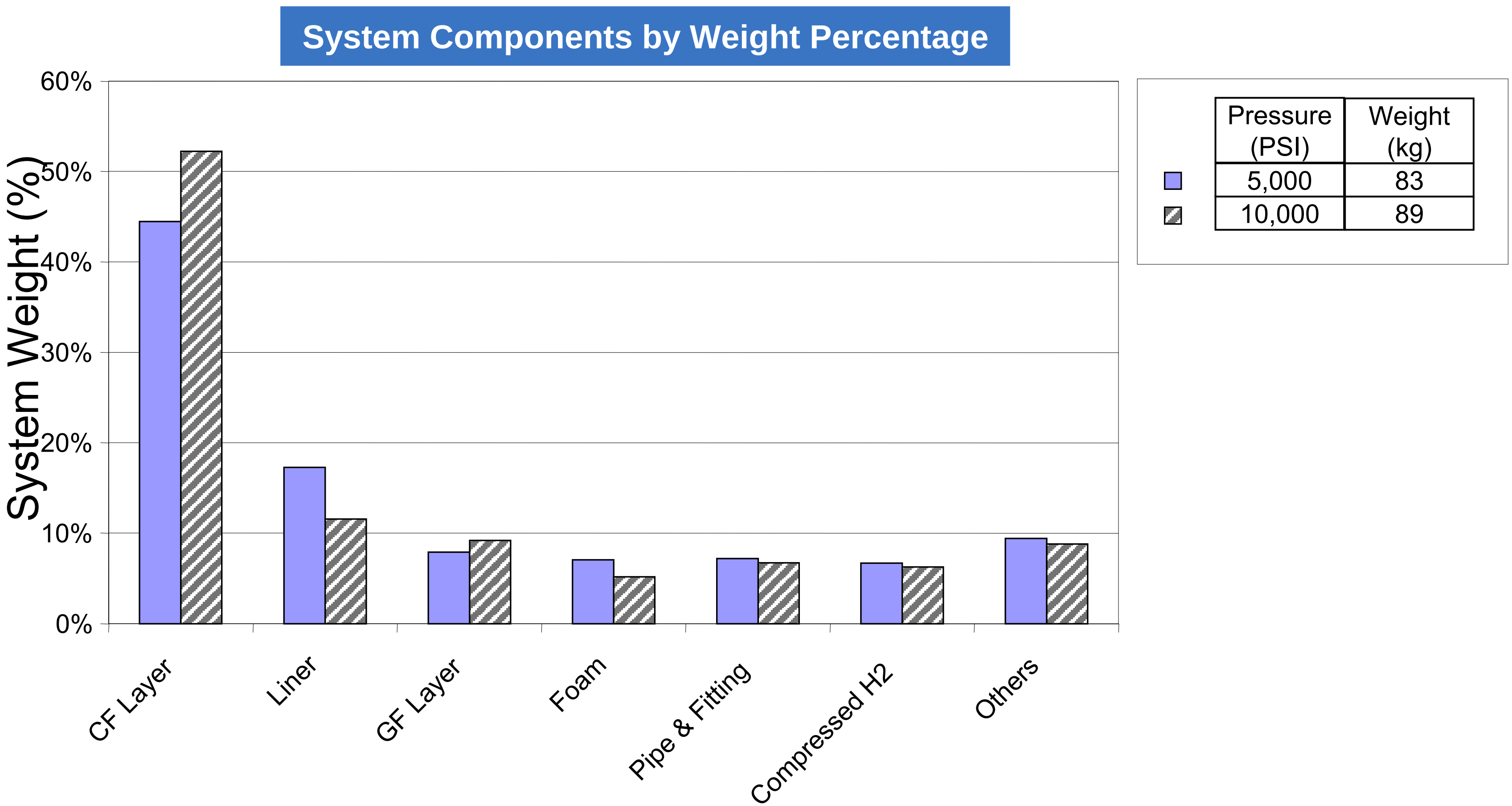
*Schematic based on both the requirements defined in the draft European regulation for "Hydrogen Vehicles: On-board Storage Systems" and US Patent 6,041,762.

**Secondary Pressure Regulator located in Fuel Control Module.

We used a typical Type III or Type IV tank as the basis for our costing effort.

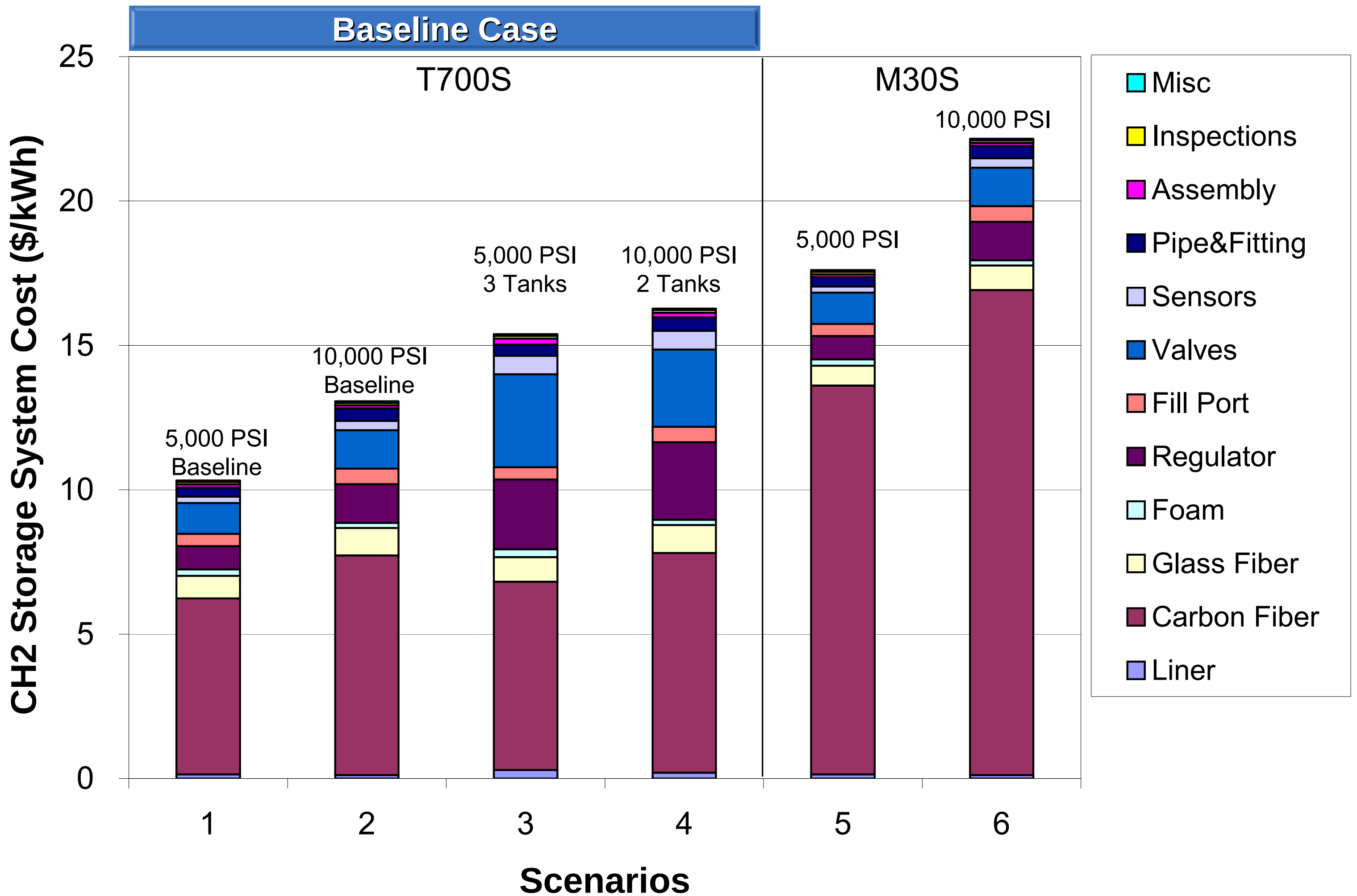


The 5,000 and 10,000 psi Baseline systems have similar weight distributions with the carbon fiber layer being the largest contributor.

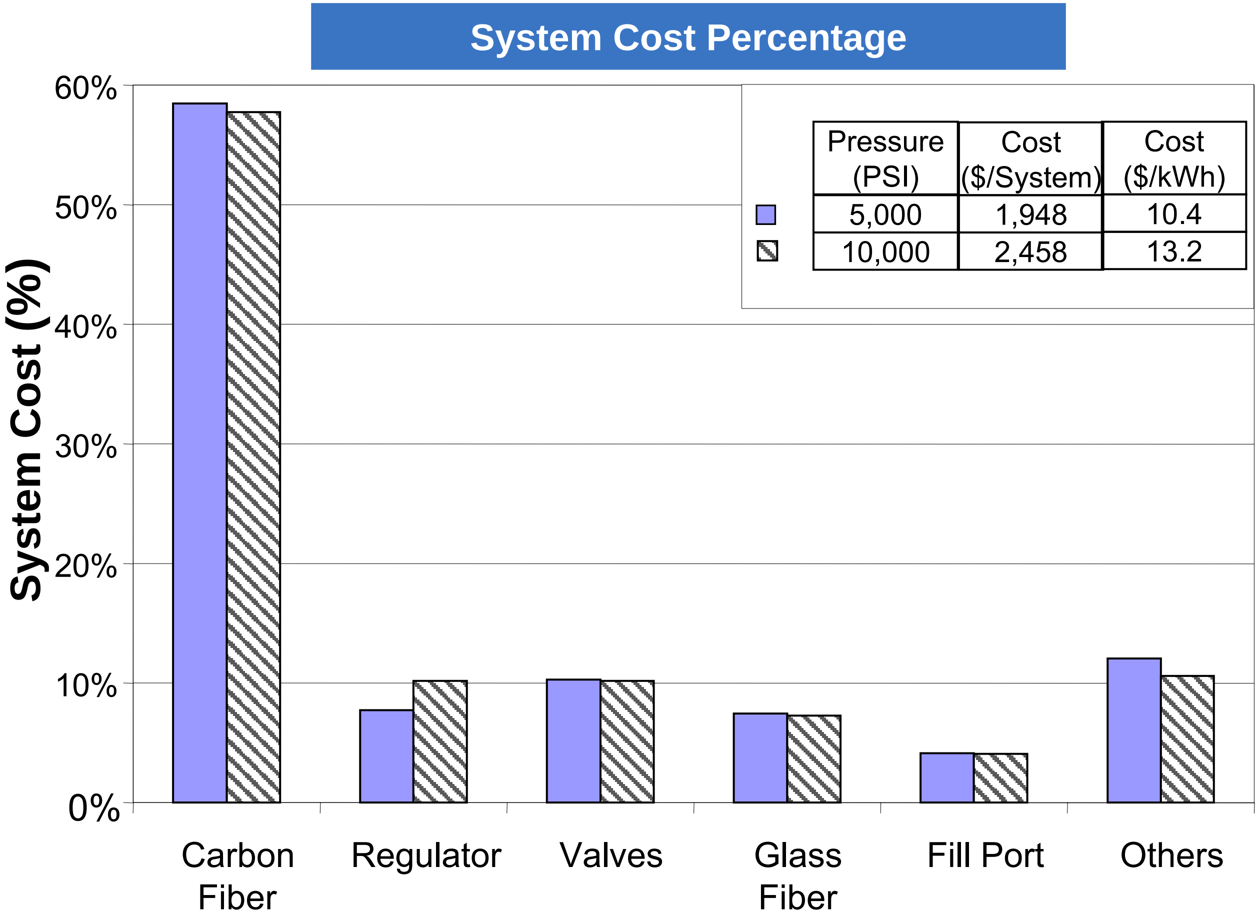


Other components (including regulator, fill port, sensors, valves, bosses, and packaging), each contribute less than 3%.

Storage system costs start at 10-15 $/kWh and increase with the use of multiple tanks to improve the form factor and the use of higher strength carbon fiber for weight reduction.

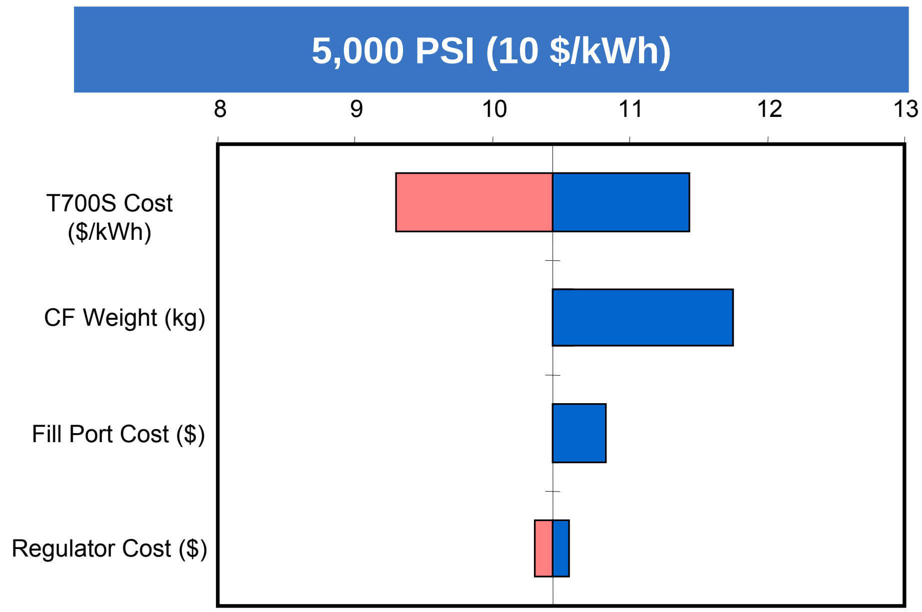


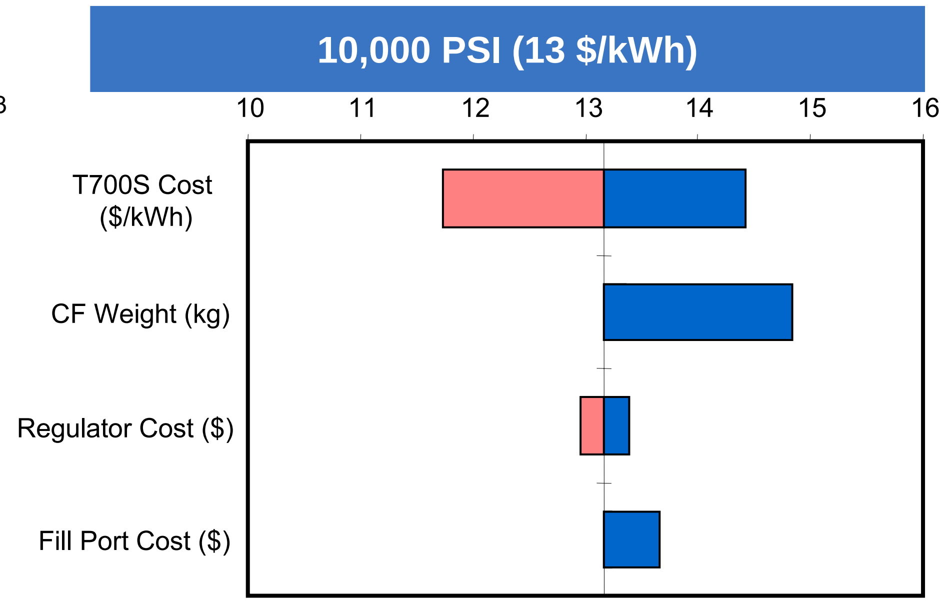
The 5,000 and 10,000 PSI Baseline systems have a similar distribution of cost. Carbon fiber is the dominant cost contributor by a large margin.



Other components, including the liner, foam, sensors, and bosses contribute less than 3% each to the total.

Overall system cost is dominated by the carbon fiber cost and weight. The other factors have much less impact on cost.





Factors	5,000 PSI / T700S			10,000 PSI / T700S		
	Baseline	Min	Max	Baseline	Min	Max
Carbon Fiber Cost ($/lb)	10.00	7.50	12.00	10.00	7.50	12.00
Carbon Fiber Weight (kg)	25.23*	25.23	31.54	31.69*	31.69	39.61
Regulator Cost ($)	150	120	180	250	200	300
Fill Port Cost ($)	80	80	160	100	100	200

* Assumes 100% property translation

Our results indicate that compressed hydrogen will be 2-3 times more costly than the DOE near-term target.

System Metric	DOE Targets			Model Results	
	2005	2010	2015	5,000 psi	10,000 psi
Cost ($/kWh)	6	4	2	9 - 13	12 - 16
Specific Energy (kWh/kg)	1.5	2	3	2.2	2.1
Energy Density (kWh/liter)	1.2	1.5	2.7	0.6*	0.9*
Specific Energy (Wt%)	4.5	6	9	6.7	6.3

* Tank only volume

On a volumetric basis, our model results for both 5,000 and 10,000 psi tanks projected volumes do not meet the DOE targets.

Our findings indicate that it will be difficult to achieve the DOE targets for compressed hydrogen storage due to the required amount and cost of carbon fiber.

- Carbon Fiber Issues
  - Aerospace grade carbon fibers must be used to achieve reliability, safety, and life
    - Commercial grade fibers will not provide the mechanical properties or reliability required for this application
  - Aerospace fibers are currently made in high volume and we do not anticipate much further cost reduction
- The system modeled in this assessment will meet mid-term specific energy target and will not be able to satisfy even the near-term volumetric energy density target.

1	Project Overview
2	Compressed Hydrogen Storage Cost
3	**2004 System Cost Update**
4	Appendix

Our 2004 estimate of a cH_2 fuel cell system with today's performance produced at high volume is \$175/kW.

Preliminary Results

50 kW Fuel Cell System - Current Technology	2001 Estimate		2004	2004
	Baseline Refomate ($/kW)	Direct CH2 ($/kW)	Direct CH2 ($/kW)	80 kW Direct CH2 ($/kW)
Fuel Cell	$221	$155	$104	$97
Fuel Supply	$76	$29	$58	$38
Balance of Plant	$10	$4	$5	$4
Assembly & Indirect	$17	$7	$8	$6
Total ($/kW)	$324	$195	$176	$145
Total ($)	$16,200	$9,750	$8,800	$11,600

- The 2004 cost estimate has a lower fuel cell subsystem cost but higher fuel supply (i.e., cH_2 storage system) cost driven primarily by higher stack power density
- The 80 kW system reduces $/kW cost due to "economies of scale", but the absolute cost is higher
  - Note that the cH_2 storage system is assumed to be the same size and cost
  - A complete powertrain cost analysis is needed to determine the net benefits

The 2004 cost estimate had a lower stack cost due to higher power density and reduced membrane and Pt cost assumptions.

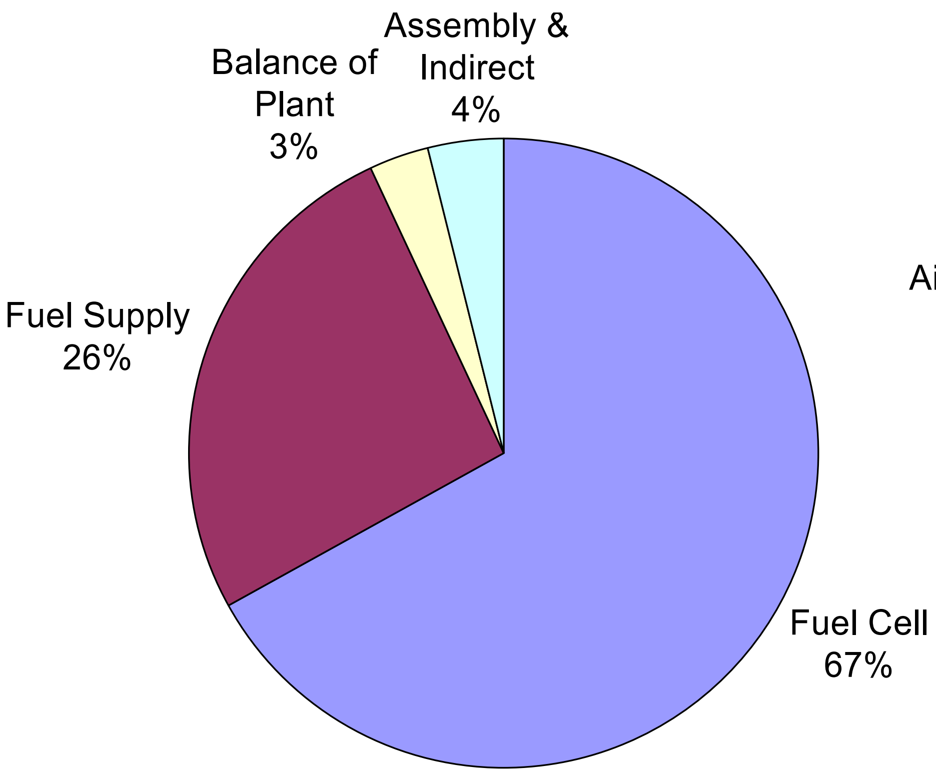
Preliminary Results

50 kW Fuel Cell Subsystem - Current Technology	2001 Estimate Baseline Refomate ($/kW)	2001 Estimate Direct CH2 ($/kW)	2004 Direct CH2 ($/kW)	2004 80 kW Direct CH2 ($/kW)
Fuel Cell Stack	$181	$123	$73	$72
Tailgas Burner	$7	$6	$0	$0
Air Supply	$20	$15	$20	$13
Cooling System	$12	$10	$11	$12
Total ($/kW)	$220	$155	$104	$97
Total ($)	$10,988	$7,737	$5,215	$7,729

- Higher power density is based on lower cell voltage operation despite having a reduced Pt loading compared to 2001
- Note that a tailgas burner was not part of the ANL fuel cell system design in 2004

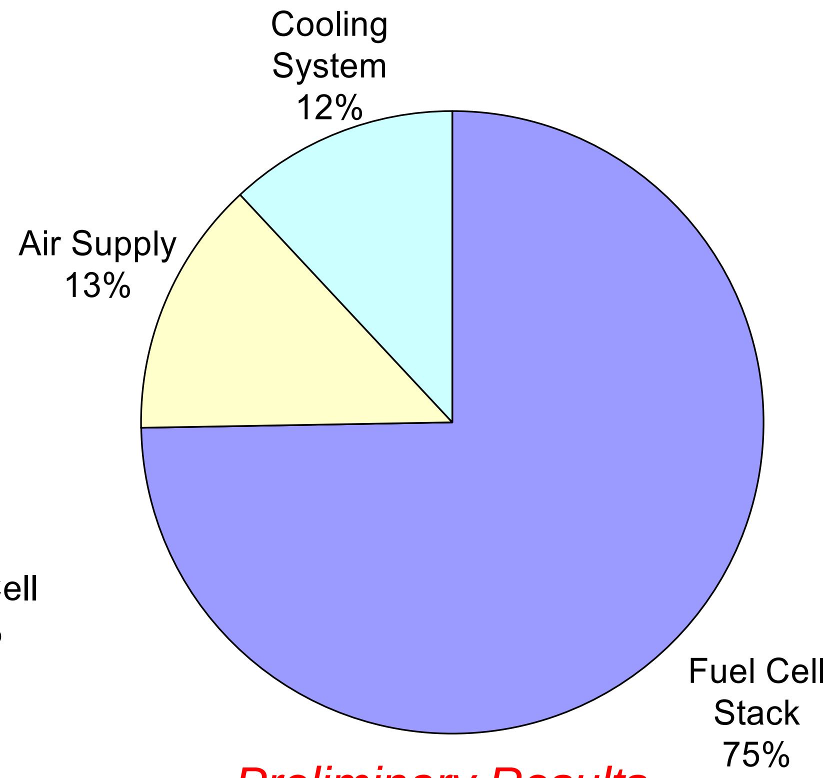
The fuel cell stack makes up a majority of the total cost for the 80 kW Direct Hydrogen Fuel Cell System.

Total System Cost – 80 kW Direct Hydrogen



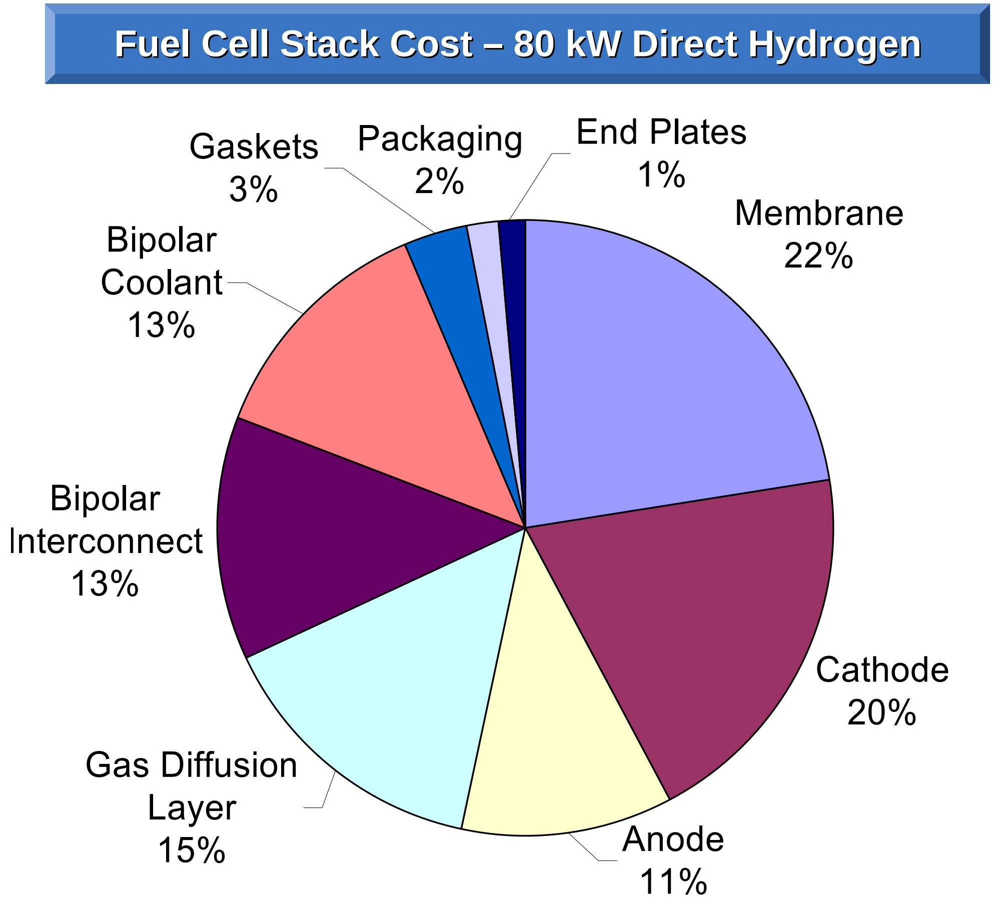
Preliminary Results

Fuel Cell Subsystem – 80 kW Direct Hydrogen



Preliminary Results

The membrane and electrodes make up over half of the $72/kW fuel cell stack cost.



Preliminary Results

- The 80 kW system cost projection includes assumptions more representative of a vehicle, including
  - a mid-size vehicle platform and a hybrid powertrain
  - Uses drive cycle analysis and a 370 mile range to calculate efficiency and hydrogen requirements rather than calculating efficiency at rated power
- Cost is still significantly higher than DOE targets
  - Need to clarify basis of cost comparison with targets and ICE powertrains
  - Powertrain cost in dollars ($11,600) for a mid-size hybrid vehicle provides unambiguous metric
  - Stack cost still represents 50% of the system cost

1	Project Overview
2	Compressed Hydrogen Storage Cost
3	2004 System Cost Update
4	**Appendix**

In the initial tasks of the project, Argonne National Laboratory provided modeling support.

Program Manager: Nancy Garland
ANL Technical Advisor: Robert Sutton

TIAX Team

Primary Contact: Eric J. Carlson

Core Team:
Dr. Suresh Sriramulu
Stephen Lasher
Yong Yang
Jason Targoff

Argonne National Laboratory
System Modeling

Primary Contacts: Dr. Romesh Kumar
Dr. Rajesh Ahluwalia

Technical Targets

System	Efficiency	Cost ($/kW)	
		2010	2015
Direct Hydrogen Fuel Cell Power System (including hydrogen storage)	**60%**	**45**	**30**
Reformer-based Fuel Cell Power System • clean hydrocarbon or alcohol based fuel • 30 second start-up • satisfies emissions standards	**45%**		

Barriers

N. Cost (Fuel-Flexible Fuel Processor)
O. Stack Material and Manufacturing Cost

Technical Targets			2005	2010	2015
Direct Hydrogen Fuel Cell Power System					
System Level	Efficiency	%	60%		
	Cost	$/kW		**45**	**30**
H_2 Storage	Specific Energy Density	kWh/kg	1.5	2	3
		%	4.5	6	9
	Energy Density	kWh/L	1.2	1.5	2.7
	Cost	$/kWh	**6**	**4**	**2**
	Refueling Rate	kgH_2/min	0.5	1.5	2
	H_2 Losses	(g/hr)/kg H_2	1.0	0.1	0.05
	Min Flow Rate	g/sec/kW	0.02	0.02	0.02

Source: FreedomCAR Technical Targets: On-Board Hydrogen Storage Systems

The future reformate scenario replaces the ATR and LTS catalysts with more costly but more effective catalysts.

Precious Metal Content and GHSV	Current Reformate	DOE Goals Reformate	Future Reformate
ATR Platinum, g	6.3	1.7	0
ATR Rhodium, g	0	0	1.5
ATR GHSV, hr^{-1}	80,000	200,000	1 MM
LTS Platinum, g	0	0	6.3
LTS GHSV, hr^{-1}	5,000	30,000	80,000
PrOX Platinum, g	7.1	1	NA
PrOX GHSV, hr^{-1}	10,000	150,000	NA

* Pt = $15/g, Rh = $30/g, Ru = $1.60/g.
GHSV = gas hourly space velocity, calculated at standard temperature and pressure of the products.

The platinum content for the DOE Goals scenario is much lower than the other cases due to its very aggressive cathode loading assumption.

MEA Precious Metal Calculation	2001 Reformate	DOE Goals Reformate	Future Reformate	2001 Hydrogen	Future Hydrogen
Current Density	310	400	500	405	750
Cathode Pt Loading, mg/cm^2	0.4	0.05	0.2	0.4	0.2
Anode Pt Loading, mg/cm^2	0.4	0.025	0.1	0.4	0.1
Power Density, mW/cm^2	248	320	400	372	600
Gross System Power, kW	56	56	53	56	53
Cathode Pt, g	90	8.8	26	60	18
Anode Pt, g	90	4.4	13	60	8.8
Anode Ru, g	45	2.2	6.6	0	0
Total Precious Metals, g	225	15	46	120	27

* Pt = $15/g, Rh = $30/g, Ru = $1.60/g.

Only the future hydrogen scenario was able to meet the mid-term DOE cost targets outlined in the recent RFP.

Characteristic	Units	Mid- term PNGV Target	DOE Goals Reformate	Future Reformate	Long-term PNGV Target	Current Hydrogen	Future Hydrogen
Overall System Cost[1]	$/kW	125	179	154	45	196	118
Overall System Specific Power[1]	W/kg	250	181	291	325	165	365
Stack Cost[2]	$/kW	100	120	108	35	157	81
Stack Specific Power[2]	W/kg	400	287	510	550	213	658
Fuel Processor Cost[3]	$/kW	25	35	28	10	NA	NA
Fuel Processor Specific Power[3]	W/kg	700	694	1,250	800	NA	NA

* Targets are based on DOE's Nov. 21, 2000 SFAA No. DE-RP04-01AL67057.

[1] Includes fuel processor or compressed hydrogen tank, stack, auxiliaries and startup devices; excludes fuel, gasoline tank, and vehicle traction electronics.

[2] Includes fuel cell ancillaries: heat, water, air management systems; excludes fuel processing/delivery system.

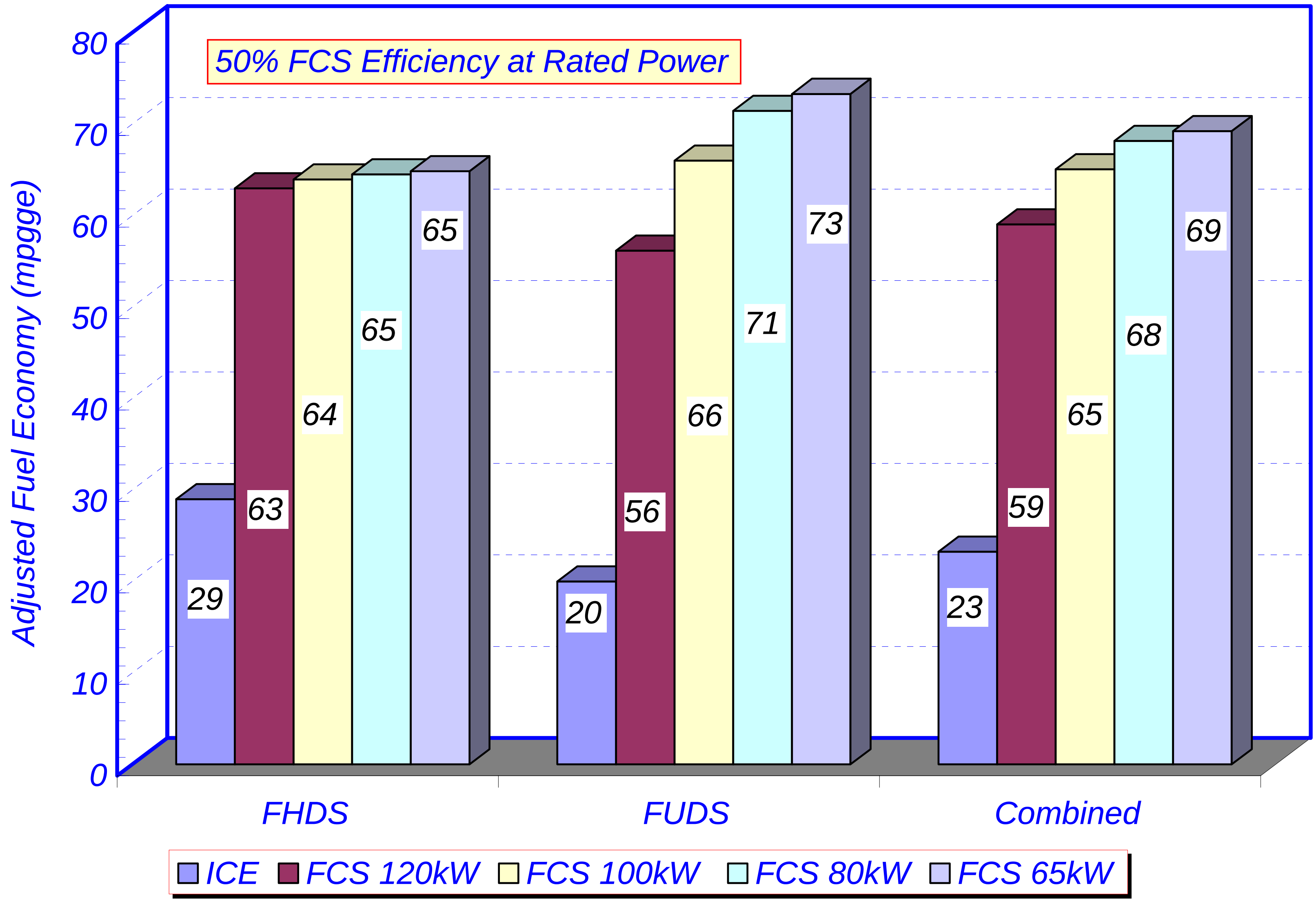
[3] Excludes fuel storage; includes controls, shift reactors, CO cleanup, and heat exchanges.

ANL performed vehicle drive cycle analyses based on a mid-sized family sedan with various degrees of hybridization.

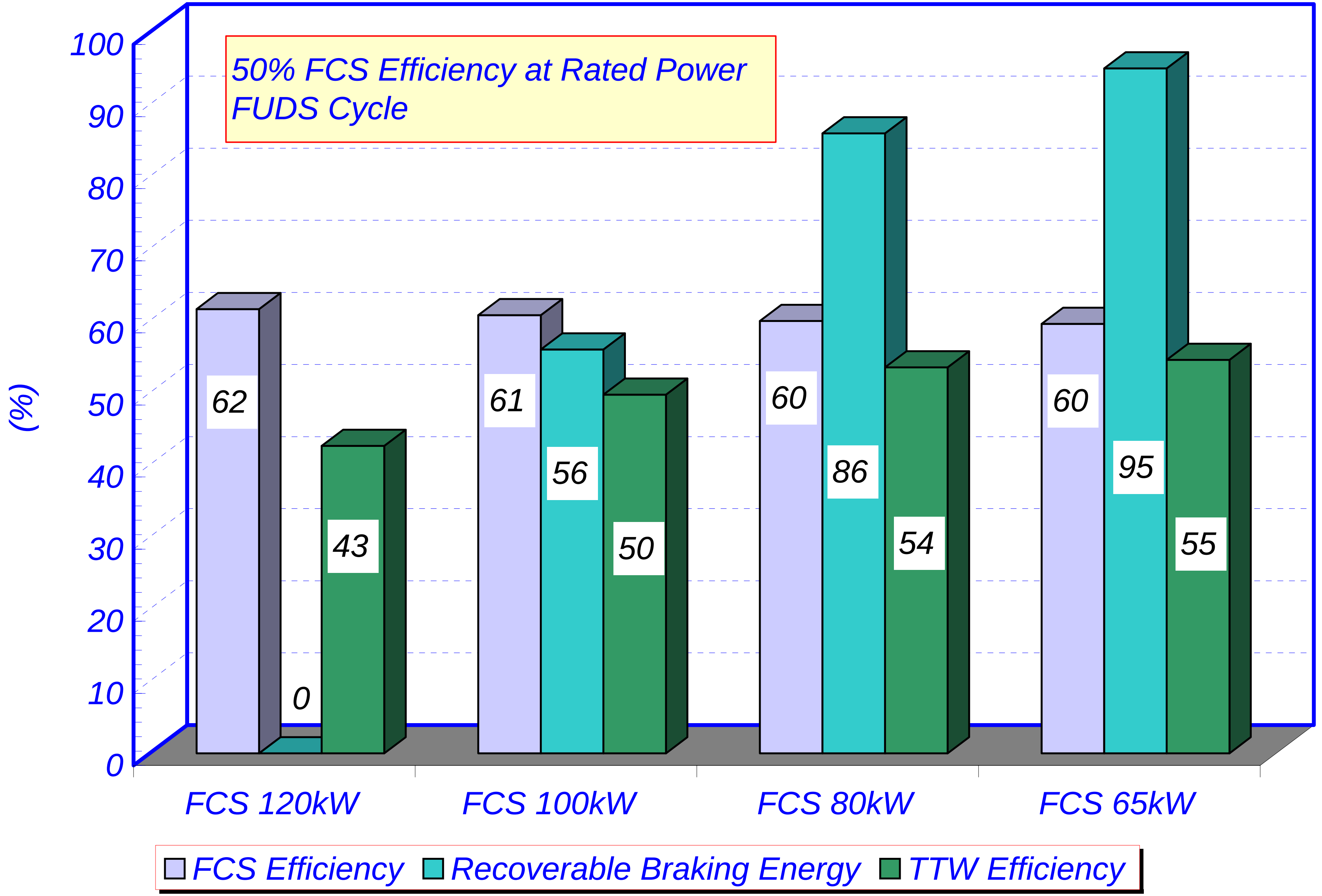
- **Vehicle Specifications**
  - Type — Mid-sized sedan (e.g., Taurus)
  - Drag coefficient — 0.33
  - Frontal area — 2 m^2
  - Rolling resistance coefficient — 0.009
  - Vehicle mass (conventional) — 1557 kg
  - Engine power (conventional) — 114 kW (155 hp)
  - Engine type (conventional) — 3L V6 - OHC
  - Transmission type (conventional) — Automatic (2.7 / 1.5 / 1.0 / 0.7)
- **Performance Specifications**
  - Range — 370 miles on combined drive cycle
  - Top speed (sustained) — 100 mph
  - Response time — 0-60 mph in 10 sec (with battery)
  - Hill climb — 55 mph at 6.5% grade for 20 min

The ANL analyses sized the fuel cell, hydrogen, and battery systems to meet vehicle performance specifications.

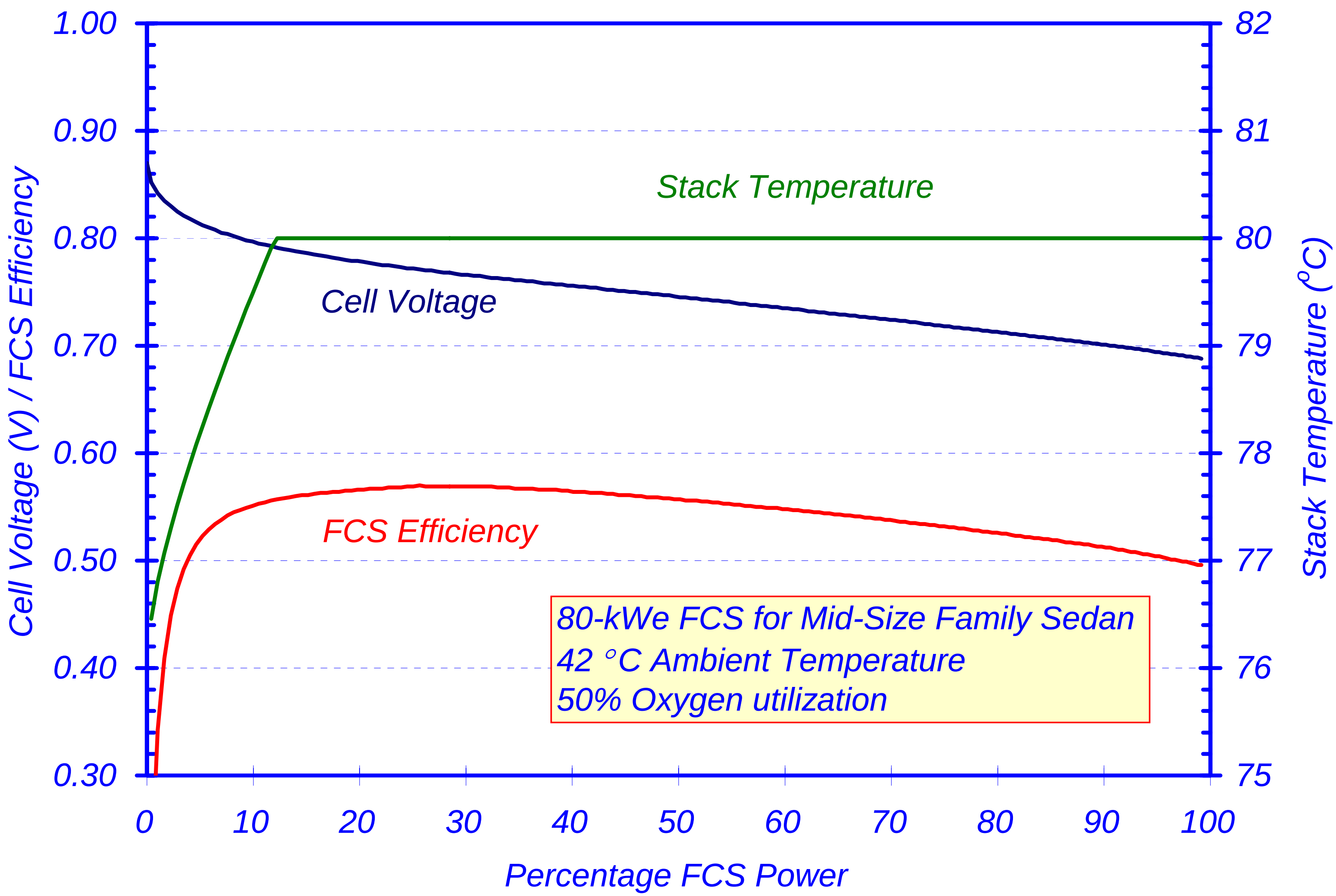
- **Fuel Cell System Specifications**
  - Power rating — to meet top speed and hill climb spec.
  - Efficiency — 50% LHV at rated power (DOE spec.)
  - Cathode utilization — 50% (sustained)
  - Transient response — 1 sec for 10 to 90% power
  - Start-up — max power in 15 sec at 20˚C
  - Cold start — max power in 30 sec at -20˚C
  - Water balance — water self-sufficient up to 42˚C
- **Hydrogen Storage Specifications**
  - Capacity — sized to meet vehicle range spec.
  - Pressure — 350 and 700 bar (5,000/10,000 psi)


50% FCS Efficiency at Rated Power
Adjusted Fuel Economy (mpgge)
80
70
60
50
40
30
20
10
0
29
63
64
65
65
20
56
66
71
73
23
59
65
68
69
FHDS
FUDS
Combined
ICE
FCS 120kW
FCS 100kW
FCS 80kW
FCS 65kW

Source: ANL


100
90
80
70
60
50
40
30
20
10
0
(%)
50% FCS Efficiency at Rated Power
FUDS Cycle
62
0
43
61
56
50
60
86
54
60
95
55
FCS 120kW
FCS 100kW
FCS 80kW
FCS 65kW
FCS Efficiency
Recoverable Braking Energy
TTW Efficiency

Source: ANL


1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
Cell Voltage (V) / FCS Efficiency
82
81
80
79
78
77
76
75
Stack Temperature (^{o}C)
Stack Temperature
Cell Voltage
FCS Efficiency
80-kWe FCS for Mid-Size Family Sedan
42 °C Ambient Temperature
50% Oxygen utilization
0
10
20
30
40
50
60
70
80
90
100
Percentage FCS Power

Source: ANL

For the baseline cases, we used a Toray T700S like carbon fiber and S-glass for the impact resistant outer layer.

Parameters	5,000 PSI Baseline	10,000 PSI Baseline
Production Volume (System /Year):	500,000	
Working Pressure (PSI)	5,000	10,000
Total H_2 storage Weight (kg)*	5.89	5.96
Tank Volume (liter)	255	155
Tank Weight (kg)	64	70
Liner Thickness & Material	0.25 Inch HDPE or 0.090 Inch Aluminum	
Carbon Fiber Type	T700S	
Glass Fiber Type	S-Glass	
Fiber / Epoxy Ratio (wt ratio)	68 / 32	
Fiber Process	Filament Winding	
Regulator Type	In Tank	
Safety Factor	2.25	

*@5,000 PSI tank, including H_2 that can not pass through the regulator at 200 PSI.
@10,000 PSI tank, including H_2 that can not pass through the regulator at 400 PSI

We used netting analysis to calculate the carbon fiber requirements. The higher strength fiber (M30S) reduced weight by 8-9%.

Pres-sure	Vol.	Fiber	Liner Type	Tank Component Weight (kg)				
				Liner	Carbon Fiber Composite	Glass Fiber Composite	Foam	Tank Total
5,000 PSI	255 Liter	M30S	HDPE	14.4	33.0	5.8	5.9	59
			AL	14.8				
		T700S	HDPE	14.4	37.1	6.6	5.9	64
			AL	14.8				
10,000 PSI	155 Liter	M30S	HDPE	10.3	41.3	7.3	4.7	64
			AL	10.3				
		T700S	HDPE	10.3	46.6	8.2	4.7	70
			AL	10.3				

Carbon Fiber/ Glass Factor= 0.85; Carbon Fiber Weight% = 68; HDPE thickness= 0.25”;
Al thickness= 0.09”, Tank weight without bosses and regulator

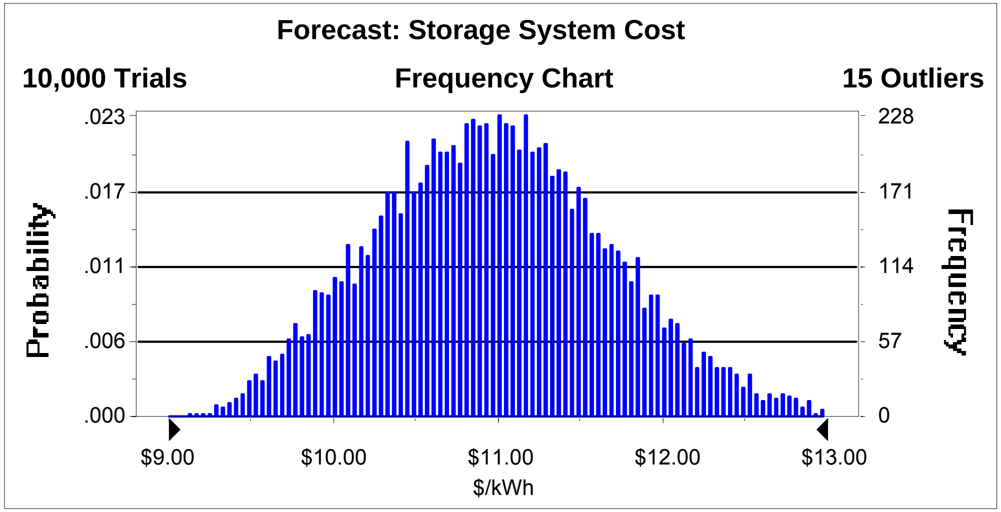
For the assumed liner thicknesses, the liner choice does not effect weight.

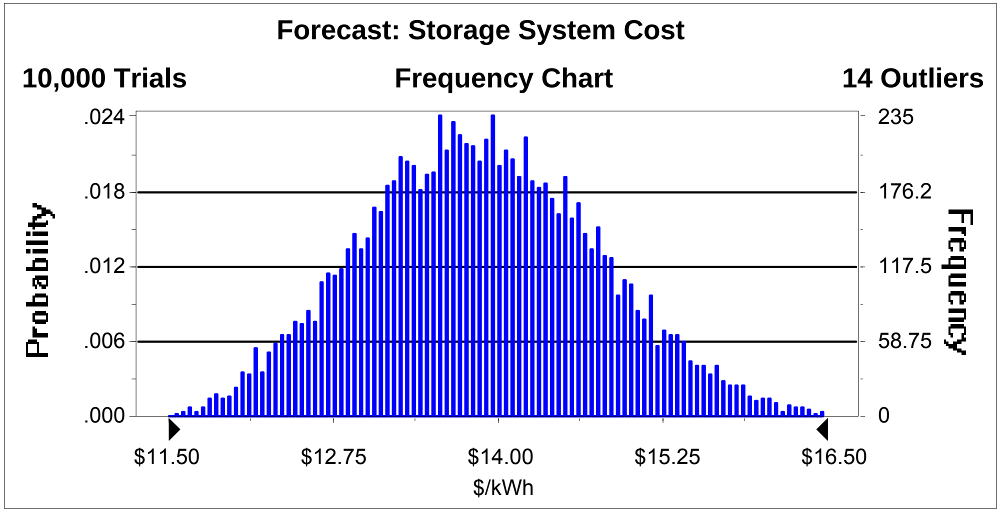
We believe aerospace grade properties and certifications will be required for composite compressed H_2 (cH_2) tank structures, consequently this sets the cost per pound in the $10-30 per lb range.

PAN Fiber Types					
Grade Designation	**Commodity**	**Standard Modulus**	**High Strength (HS)**	**HS Intermediate Modulus**	**High Modulus**
Use Class	Commercial	Commercial, Industrial			Aerospace
PAN Precusor	Textile grade	HQ Industrial grade			Aerospace grade
Typical Tow Count, K	48, 160, 320	24, 48			12, 24
Tensile Strength, Ksi	550	550			700
Tensile Modulus, Msi	33	33			55
Cost Range, $/lb ($/kg)	5–7 (11-15)	7–9 (15-20)			>30 (>66)
Applications	Sporting goods, Automotive	Sporting goods, Industrial			Aerospace
Suppliers	Zoltec	Fortafil, Grafil, SGL, Aldila			Toray, TohoTenax, Cytec, Hexcel

Monte Carlo simulation for the two pressures still leads to costs that are double the 2005 target for compressed hydrogen storage of $6/kWh.

5,000 PSI Case





10,000 PSI

The direct hydrogen system cost estimate we shared with DOE in 2001 was based on developer's projections for the cost of cH2 storage.

Model Changes	Comments
Increased cost of Hydrogen Storage System from $12,00 to $1,950 (\$272 to \$348/kg H_2)	◆ Using activities-based cost analysis of the cH_2 storage system ◆ Previous estimate was based on discussions with component developers - assuming high production volumes, 2010 technology, including the whole storage system (a detailed analysis was not performed) ◆ Amount of usable hydrogen stored changed from 4.4 kg to 5.6 kg
Eliminated Fuel Processor Components	◆ Reformate generator, reformate conditioner, fuel processor water supply
Eliminated Tailgas Burner Components	◆ Burner, fuel vaporizer, warm-up steam generator
Increased Net Parasitic Power from 6.1 to 8 kW	◆ Consistent with ANL modeling of 80 kW cH_2 fuel cell system ◆ Note that operating pressure was reduced from 3 to 2.5 atm
Increased CEM Cost from \$630 to \$900	◆ Based on recent discussions with CEM developers
Modified Heat Exchanger Designs and Cost	◆ Based on new LMTD and heat loads from ANL modeling of 80 kW cH2 fuel cell system ◆ Condenser increased in size significantly (minimal cost impact)
Eliminated Start-up Batteries	◆ Assumes start-up time using stored hydrogen is nearly instantaneous ◆ Equipment required for start-up under extreme conditions (e.g., sub-zero) were outside of this scope of work

The cost of cH_2 storage at 5,000 psi was found to be ~30% higher on a per kg hydrogen basis using activities-based cost analysis.

The latest direct hydrogen fuel cell stack performance and cost parameters also differ from the direct hydrogen estimate we prepared for DOE in 2001.

Model Changes	Comments
Increased Design Power Rating from 50 to 80 kW	◆ Consistent with ANL drive-cycle modeling of a cH_2 fuel cell vehicle with moderate battery hybridization
Decreased Electrolyte Cost from 100 to 40 $/m²$	◆ Based on recent discussions with fuel cell and membrane developers
Increased Fuel Utilization from 95% to 100% (effective)	◆ Consistent with current stack operation on pure hydrogen (i.e., no tailgas burner)
Decreased Pt loading from 0.4/0.4 to 0.2/0.1 mg/cm^2 (Cathode/Anode sides)	◆ Based on previous TIAX analysis that indicated a decrease in cathode catalyst loading beyond 0.2 mg/cm^2 does not reduce overall stack costs ◆ Assume anode loading is half that of the cathode based on the observation that hydrogen oxidation rate is higher than oxygen reduction rate
Decreased Design Cell Voltage from 0.8 to 0.69 V	◆ Consistent with ANL modeling of 50% efficient cH2 fuel cell system at rated power – resulting drive-cycle fuel economy is 68 mpg
Increased Current Density[1] from 465 to 500 mA/cm^2	◆ Assumption based on improvement in current density due to lower cell voltage (0.69 vs 0.8) that is somewhat offset by a reduction in Pt loading (0.8 vs 0.3 mg/cm^2) - net result is an increase in current density by <10% ◆ Needs to be vetted by industry

[1] New current density at 100% excess air, 2.5 atm operating pressure (3 atm previously), and other conditions stated above.

This table summarizes many of the performance and cost assumptions used in sizing and pricing the stack.

Parameters	2000 Reformate	2001 Reformate	2001 Direct H_2	Future Direct H_2	2004 Direct H_2
Technology	2000	2001	2001	Future	2004
Stack Gross Power (kW)	56	56	56	56	88
Stack Power Density (mW/cm^2)	248	248	372	600	345*
Cell Current Density (mA/cm^2)	310	310	465	750	500
Membrane Cost ($\$/m^2$)	50	100	100	50	40
Pt Loading (Cathode/Anode mg/cm^2))	0.4/0.4	0.4/0.4	0.4/0.4	0.2/0.1	0.2/0.1
Pt Cost ($/kg)	15,000	15,000	15,000	15,000	15,000
GDL Cost ($\$/m^2$ /Layer)	9	14	16	16	16
Bipolar Plate Cost ($\$/m^2$)	23	24	24	24	28
CEM ($/unit)	630	630	630	500	900

*@ 0.69 V, all others at 0.8V

The table below summarizes the component costs in the fuel cell subsystem.

Parameters	2001 50 kW Reformate ($/kW)	2001 50 kW Direct H_2 ($/kW)	Future Direct H_2 ($/kW)	2004 50 kW Direct H_2 ($/kW)	2004 80 kW Direct H_2 ($/kW)
Fuel Cell Stack	181	123	47	73	72
Tailgas Burner	7	6	5	0	0
Air Supply	20	15	12	20	13
Cooling System	12	10	3	11	12
Total	220	155	67	104	97