

Analysis of Ultracapacitor-VRLA Energy Storage Systems for Mild Hybrids

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Content

- Background
- Motivation/Objectives
- Assumptions
- Analysis Approach
- Results
- Summary

Background

- FreedomCAR's Goals for mild hybrids are aggressive for batteries. Could ultracapacitors play a role?

FreedomCAR 42 V Energy Storage System End-of-Life Performance Goals (August 2002)

42 Volt Targets Rev. August 2002	Start-Stop		M-HEV		P-HEV	
Discharge Pulse Power (kW)	6	2 s	13	2 sec	18	10 sec
Regenerative Pulse Power (kW)	N/A		8	2 sec	18	2 s
Engine-Off Accessory Load (kW)	3	5 min	3	5 min	3	5 min
Available Energy (Wh @3 kW)	250		300		700	
Recharge Rate (kW)	2.4 kW		2.6 kW		4.5 kW	
Energy Efficiency on Load Profile (%)	90		90		90	
Cycle Life, Miles/Profiles (Engine Starts)	150k (450k)		150k (450k)		150k (450k)	
Cycle Life and Efficiency Load Profile	Zero Pwr Asst (ZPA)		Partial Pwr Asst (PPA)		Full Pwr Asst (FPA)	
Cold Cranking Power @ -30°C (kW)	8	21 V Min.	8	21 V Min.	8	21 V Min.
Calendar Life (Yrs)	15		15		15	
Maximum System Weight (kg)	10		25		35	
Maximum System Volume (Liters)	9		20		28	
Selling Price (\$/system @ 100k/yr)	150		260		360	
Maximum Open Circuit Voltage (Vdc) after 1 Sec.	48		48		48	
Minimum Operating Voltage (Vdc)	27		27		27	
Self Discharge (Wh/day)	<20		<20		<20	
Heat Rejection Coefficient (W/°C)	N/A		N/A		>30	
Maximum Cell-to-Cell Temperature Difference (°C)	N/A		N/A		<4	
Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52	
Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66	

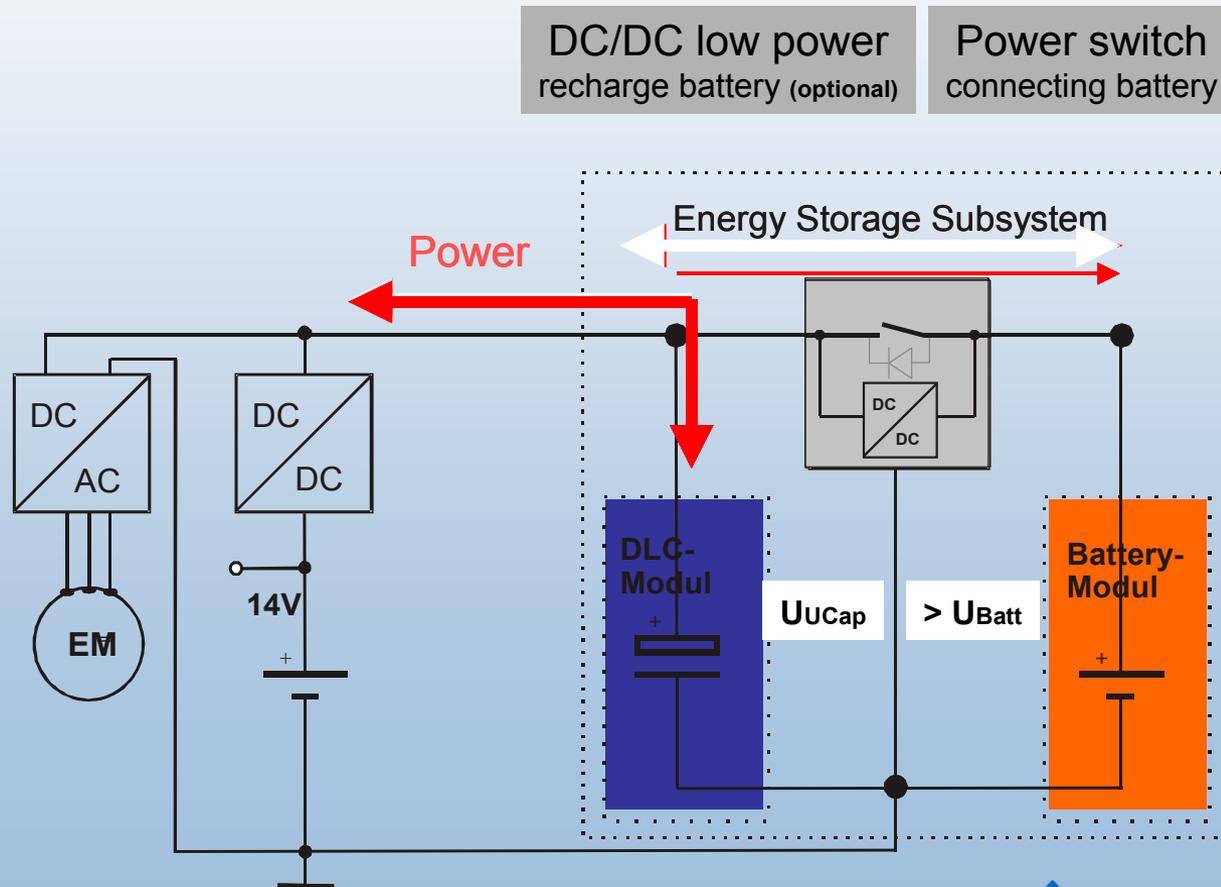
Background (cont.)

- FreedomCAR's goals for ultracapacitors are also aggressive. Could VRLAs play a role?

System Attributes	12V Start-Stop (TSS)		42V Start-Stop (FSS)		42V Transient Power Assist (TPA)	
Discharge Pulse	4.2 kW	2s	6 kW	2s	13 kW	2s
Regenerative Pulse	N/A		N/A		8 kW	2s
Cold Cranking Pulse @ -30°C	4.2 kW	7 V Min.	8 kW	21 V Min.	8 kW	21 V Min.
Available Energy (CP @1kW)	15 Wh		30 Wh		60 Wh	
Recharge Rate (kW)	0.4 kW		2.4 kW		2.6 kW	
Cycle Life / Equiv. Road Miles	750k / 150,000 miles		750k / 150,000 miles		750k / 150,000 miles	
Cycle Life and Efficiency Load Profile	UC10		UC10		UC10	
Calendar Life (Yrs)	15		15		15	
Energy Efficiency on UC10 Load Profile (%)	95		95%		95%	
Self Discharge (72hr from Max. V)	<4%		<4%		<4%	
Maximum Operating Voltage (Vdc)	17		48		48	
Minimum Operating Voltage (Vdc)	9		27		27	
Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52	
Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66	
Maximum System Weight (kg)	5		10		20	
Maximum System Volume (Liters)	4		8		16	
Selling Price (\$/system @ 100k/yr)	40		80		130	

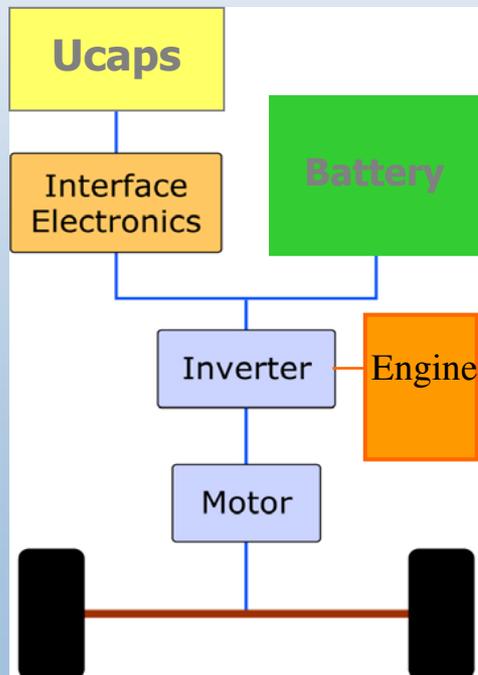
Background (concl.)

- In AABC-2004, Continental Temic presented a concept on combining lead acid batteries and ultracapacitors through DC/DC converters to meet the targets of mild hybrids. How does this concept compares with battery alone solutions in meeting targets?



Motivation for this Study

- There is some believe that all the performance, life, and cost goals set for energy storage system in mild 42V hybrids could not be met with advanced batteries.
- What is the potential of dual energy storage systems such as combining valve regulated lead acid (VRLA) and ultracapacitors in meeting the targets?



42 Volt Targets Rev. August 2002	M-HEV	
Discharge Pulse Power (kW)	13	2 sec
Regenerative Pulse Power (kW)	8	2 sec
Engine-Off Accessory Load (kW)	3	5 min
Available Energy (Wh @3 kW)	300	
Recharge Rate (kW)	2.6 kW	
Energy Efficiency on Load Profile (%)	90	
Cycle Life, Miles/Profiles (Engine Starts)	150k (450k)	
Cycle Life and Efficiency Load Profile	Partial Pwr Asst (PPA)	
Cold Cranking Power @ -30°C (kW)	8	21 V Min.
Calendar Life (Yrs)	15	
Maximum System Weight (kg)	25	
Maximum System Volume (Liters)	20	
Selling Price (\$/system @ 100k/yr)	260	
Maximum Open Circuit Voltage (Vdc) after 1 Sec.	48	
Minimum Operating Voltage (Vdc)	27	
Self Discharge (Wh/day)	<20	
Heat Rejection Coefficient (W/°C)	N/A	
Maximum Cell-to-Cell Temperature Difference (°C)	N/A	
Operating Temperature Range (°C)	-30 to +52	
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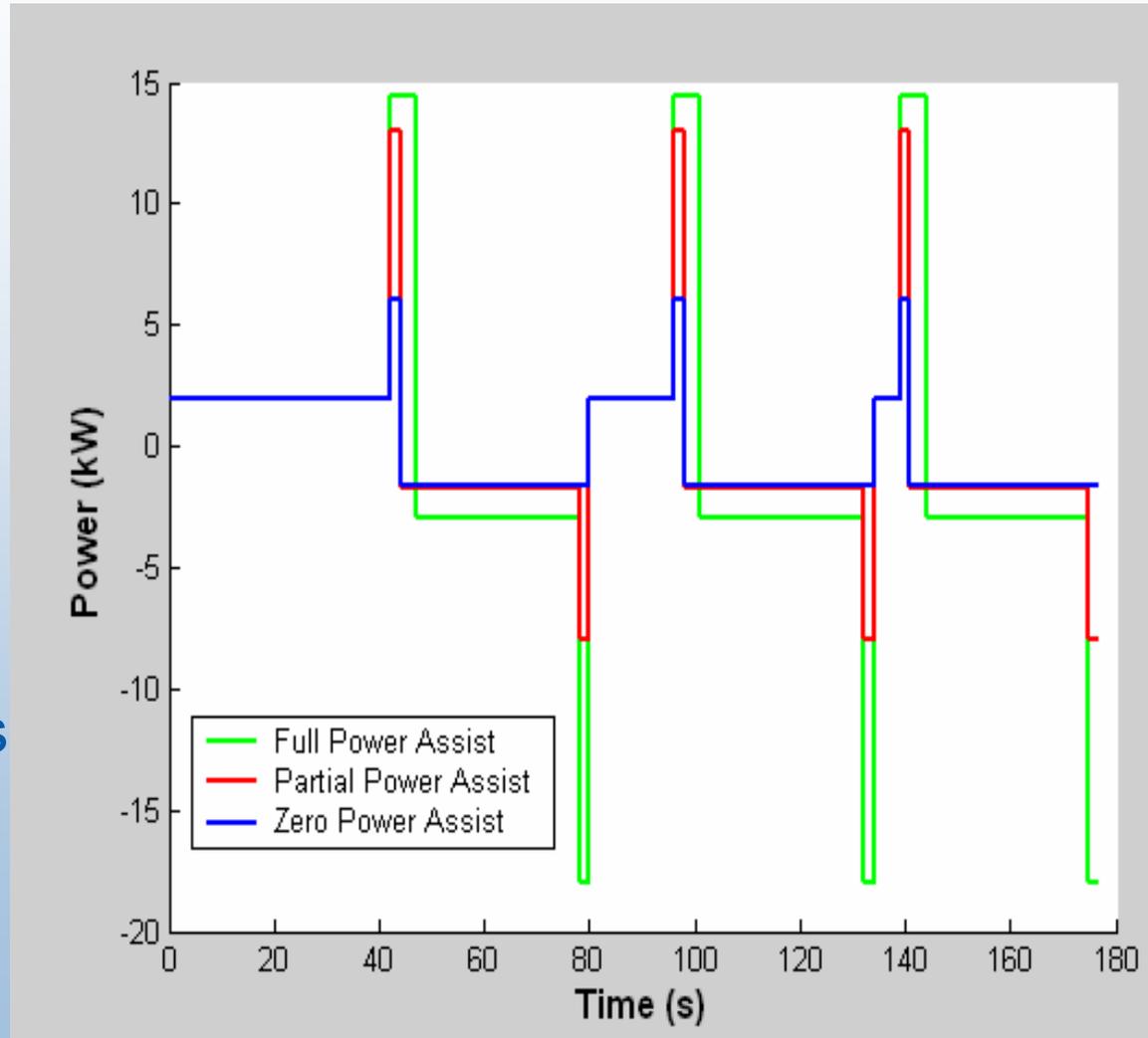
Objectives

- Develop strategies in analyzing dual volt energy storage systems
 - Dynamic analysis – equivalent circuit modeling (in Matlab)
 - Vehicle simulations (ADVISOR™)
- Analyze a combined VRLA and Ucap system in meeting 42V mild hybrid targets
- Compare VRLA+Ucap with advanced batteries

Selected 42V Power Profiles for Analysis

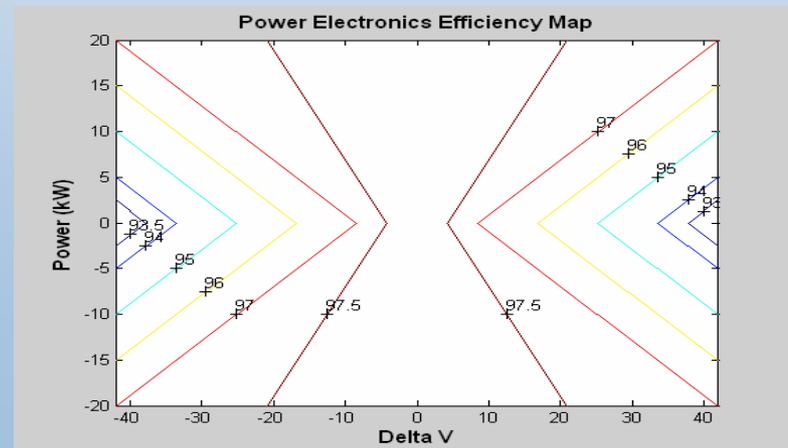
(FreedomCAR 42V Battery Test Manual, *DOE/ID-11070*, April 2003)

- Zero Power Assist includes no regen capture
- Full Power Assist includes 10s discharge for acceleration
- Drive cycle analysis of various profiles and vehicle testing experience indicates regen events are typically longer than 2s
 - More likely 4-5s



Input Parameters

- ESS Model inputs
 - VRLA: Hawker Genesis 25 Ah
 - SOC Limits: 0.6-0.9
 - Voltage Limits: 9.5V-16.5V
 - Mass: 11 kg/module
 - Ultracap: Maxwell 2500F
 - SOC Limits: 0.5-1.0
 - Voltage Limits: 1.25V-2.7V
 - Mass: 0.71 kg/module
- Power electronics inputs
 - Mass: 1 kg/kW
 - Efficiency: $f(\text{Power}, V1/V2)$
- Other ESS technologies
 - Li-ion: Saft 6Ah
 - SOC Limits: 0.6-0.9
 - Voltage Limits: 2.0V-4.1V
 - Mass: 0.37 kg/module
 - NiMH: Panasonic Prismatic 6Ah
 - SOC Limits: 0.6-0.9
 - Voltage Limits: 6V-9V
 - Mass: 1 kg/module



Power Split Strategies between VRLA & Ucap in Combined ES System

- Ucap protects battery from high power transients
- Peak power ratings for each system individually result in base power split set-point for both charge and discharge events
- Rate term forces greater portion of power request towards the Ucap during transients
- SOC term modifies request to maintain SOC of both storage devices
- Low power charge and discharge events (below 1 kW) are handled entirely by battery
- Rate term = 5 kW/s
 - Transient power requests above this value will be pushed toward the Ucap
 - Below this, value are proportionally split between the two sources

Example of Control Strategy for VRLA+Ucap

	Battery low	Battery mid	Battery high
Always accept regen up to limits. Always bring ucap up to mid point first, then battery.			
Ucap low	Bat: Don't discharge unless needed for power, wait for regen Ucap: Don't discharge unless needed for power, wait for regen	Bat: discharge to bring ucap up to mid point Ucap: don't discharge, take charge from battery	Bat: discharge to bring ucap up to mid point Ucap: take charge from bat
Ucap mid	Bat: do nothing Ucap: do nothing unless needed for power	Bat: do nothing unless needed for power or eff op of engine Ucap: do nothing unless needed for power or efficient operation of engine	Bat: provide power for propulsion Ucap do nothing unless needed to supplement bat power
Ucap high	Bat: take charge energy from ucap Ucap: discharge to bat	Bat: do nothing Ucap: provide power for propulsion	Bat: provide power for propulsion Ucap: use for power propulsion

Evaluating Response of ES System (attributes considered)

- Total Mass (minimize)
 - Sum of module masses + power electronics mass
- Total Cost (minimize)
 - Sum of module costs + power electronics cost
- Total Regen (maximize)
 - Percentage of regen available that is captured
- Total Loss (minimize)
 - Combination of ESS and PE losses over the cycle
- Time in Red Zone (minimize)
 - Sum of time battery is within 5% of voltage limits, a condition that reduces life
- Other Responses
 - Cumulative Trace Misses
 - Integral of difference between requested and achieved power outputs
 - Peak Trace Misses
 - Greatest difference between requested and achieved power outputs
 - Average Voltage Ratio
 - Min/Max Battery Power

Case Study Summaries

Initial Results for Meeting 42V M-HEV Profile

Case	Description	ESS1_Num	ESS2_Num	Mass	Energy Loss	Regen	RedZone Time
		#	#	Kg	Wh	--	Sec
1	Baseline UC – matched voltage	20	3	77.2	100.6	0.986	38
2	Reduced UC	7	3	48.5	138.7	0.967	53
3	Lead acid only	0	3	33	153.3	0.839	171
4	UC Only	20	0	44.2	83.7	0.948	0
5	Optimum. PbA and UC	10.2	5	77.6	110.7	0.996	9
6	Optimum PbA, UC, and	6.4	5	69.2	110.9	0.991	1
7	Optimum UC only	72	0	159.1	73.7	1	0
8	Optimum PbA only	0	7	77	110	1	0
9	Li-ion only	0	30	11.3	50.3	0.995	103
10	NiMH only	0	16	16	68.6	0.994	94

Initial Results: Case Study Summaries For 42V Hybrid

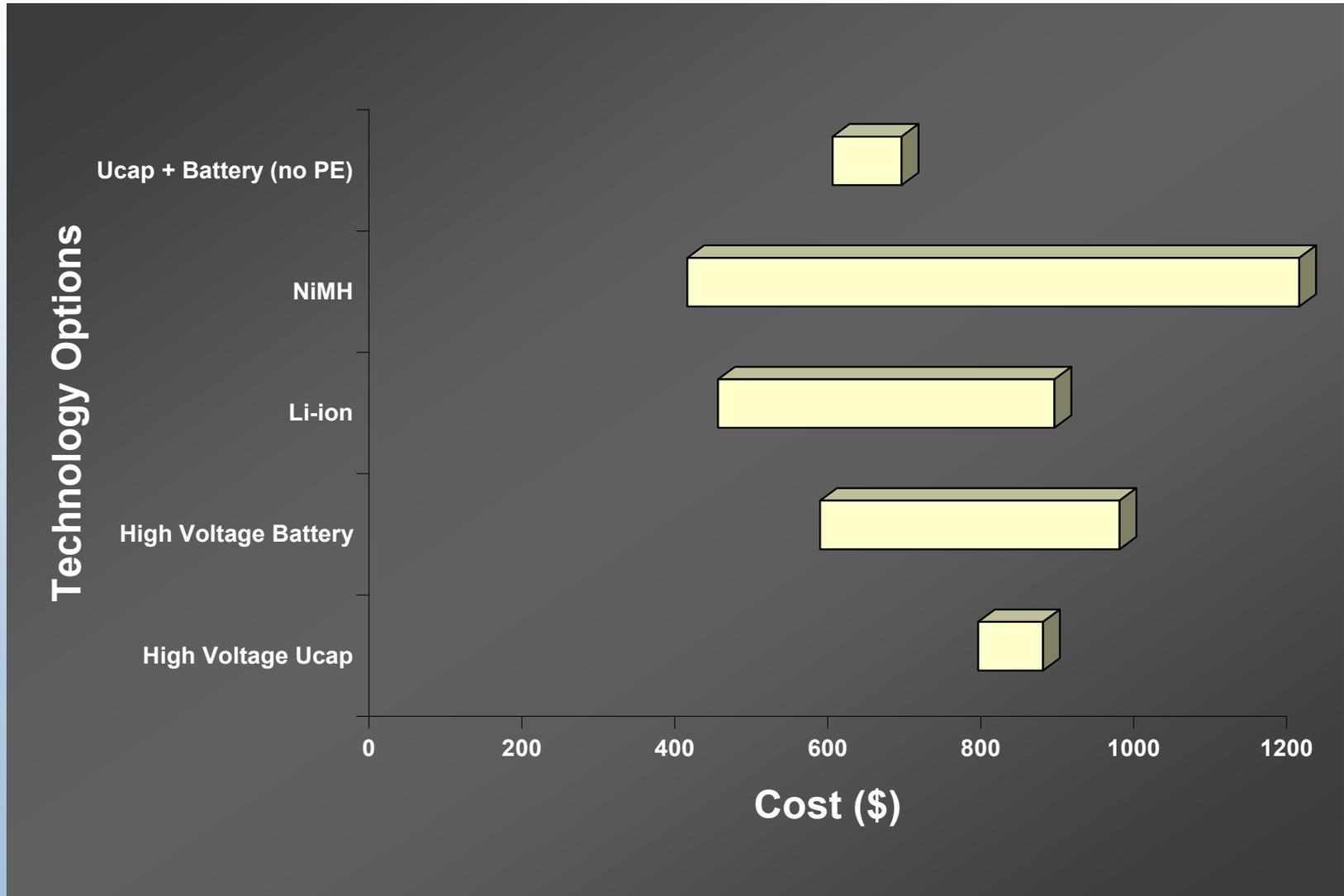
Case	Description	ESS1_Num #	ESS2_Num #	Mass kg	Loss Wh	Regen --	RedZone Time s	ESS2 Min Pwr kW	ESS2 Max Pwr kW	Cum Trace Miss Wh	Peak Trace Miss kW	DeltaSOC1 --	DeltaSOC2 --	Obj --
1	Baseline - matched voltages	20	3	77.2	100.6	0.98626	38	-8091.43	6370.43	6.17	3.35	-0.0357151	-0.0643018	2.94
2	Reduced UC	7	3	48.5	138.7	0.966742	53	-8220.42	7323.59	30.11	8.32	0.049704	-0.0900061	3.14
3	Lead acid only	0	3	33	153.3	0.838809	171	-8609.95	7306.19	89.58	7.65	0	-0.172421	5.93
4	UC only	20	0	44.2	83.7	0.947857	0.0	0	0	82.79	11.73	0.192294	0	3.94
5	Opt. PbA and UC	10.2	5	77.6	110.7	0.995727	9	-12956.4	8395.89	6	3.40	0.00807023	-0.0383088	1.96
6	Opt. PbA, UC, and fixed split ratio	6.4	5	69.2	110.9	0.989705	1	-9480.71	10037.9	20.2	3.27	0.206621	-0.0381189	1.78
7	Opt. UC only	72	0	159.1	73.7	1.00634	0	0	0	5.58	0.36	0.0229676	0	6.07
8	Opt. PbA only	0	7	77	110	1	0	-13157.9	13931.2	2.86E-13	7.28E-15	0	-0.0375241	0.85
9	Li-ion only	0	30	11.3	50.3	0.991295	103	-13157.9	13931.2	3.37	3.68	0	-0.0250984	0.86
10	NiMH only	0	16	16	68.6	0.994244	94	-13157.9	13931.2	2.23	3.77	0	-0.098452	0.30

- Case 5 and 6 push Ucap-PbA design toward less Ucaps/
more battery to improve cost and reduce red time
- NiMH only case is not the worst or best in any one category
but provides a good overall option
- Lightest most efficient system is Li-ion only

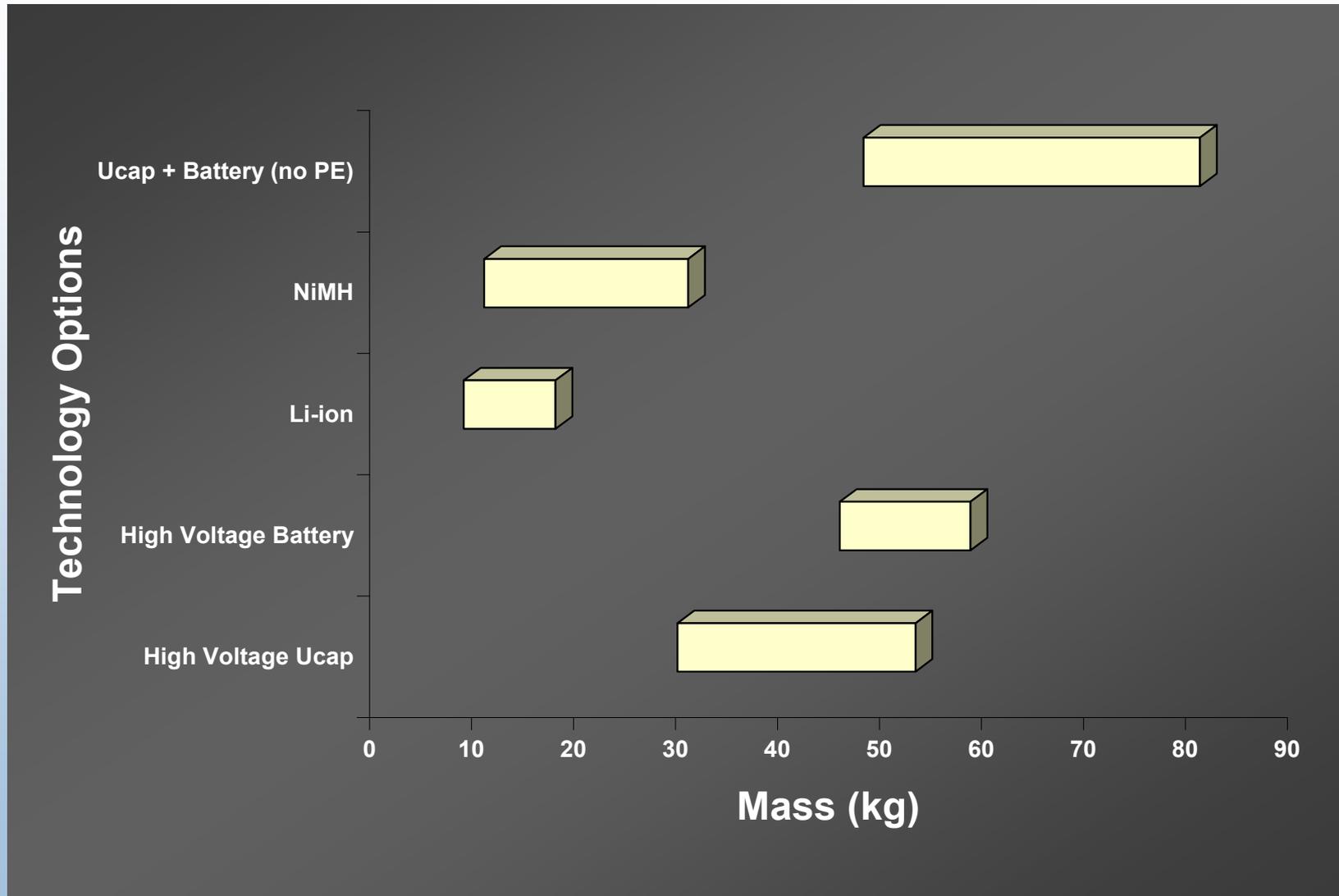
Comparing Dual ESS Options (Existing Technologies)

- High voltage Battery
 - Cost =
 $\$90 + \$250 + PE_var + UC = \$340 + \dots$
 - Mass =
 $33 + 3.75 + PE_var + UC = 36.75 + \dots$
 - Volume =
 $11.6 + 4.1 + PE_var + UC = 15.7 + \dots$
- High voltage UCap
 - Cost =
 $\$500 + \$250 + PE_var + Bat = \$750 + \dots$
 - Maybe $\$250 + \$250 + PE_var + Bat = \$500 + \dots$
 - Mass =
 $14.2 + 3.75 + PE_var + Bat = 18 + \dots$
 - Volume =
 $12.2 + 4.1 + PE_var + Bat = 16.3 + \dots$
- Other technologies
 - Li-ion
 - Cost = \$440-\$880
 - Mass = 8-17 kg
 - Volume = 7-13 L
 - NiMH
 - Cost = \$400-\$1200
 - Mass = 10-30 kg
 - Volume = 9-26 L

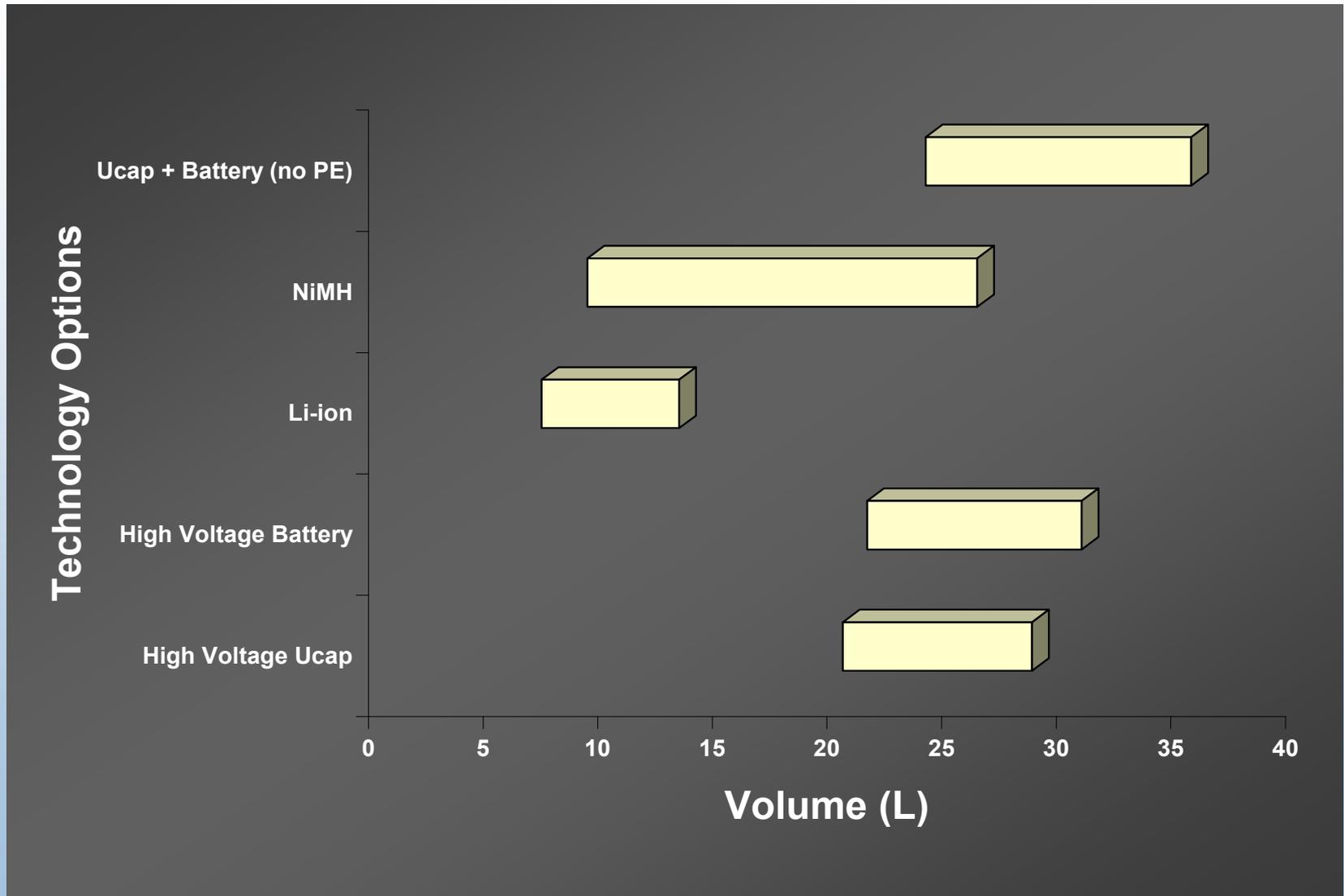
Cost Comparison



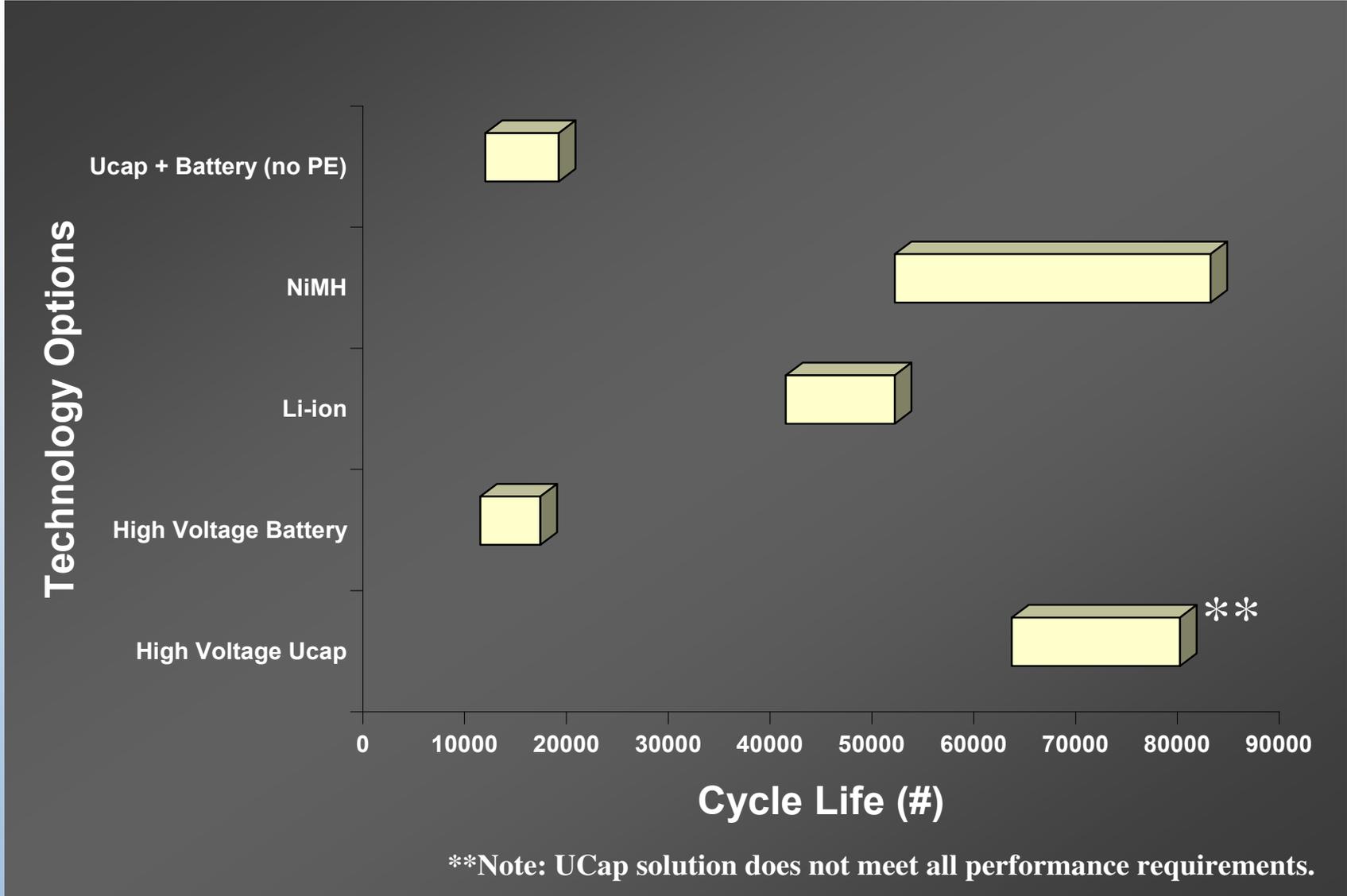
Mass Comparison



Volume Comparison



Cycle Life Comparison



Observations and Summary

- Having a high voltage UCap based system seems to have less potential for minimizing the system cost. The fixed base part of the cost is large and the variable part is small.
- The fixed attributes of either PbA+UCap approach make them less attractive than other advanced energy storage technologies.
- If power electronics base costs can be cut in half and UCap costs go to 0.5 cents/F then these systems maybe competitive based on cost, less so on mass and volume.
- Incremental mass of PbA+UCap system is ~25kg and will result in ~1% decrease in fuel economy with all other things being equal.
- Operating efficiency of UCap and other technologies fairly similar. PbA significantly lower. Therefore, PbA+UCap system slightly less efficient than other technologies.
- Future work to include drive cycle analysis for particular vehicles

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