Introduction to Energy Storage Application Metrics

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Energy Storage: Key Metrics

Metric	Units	Definition	Notes
Energy Density	Wh/L	Energy for a given volume	When volume is a concern
Specific Energy	Wh/kg	Energy for a given mass	When mass is a concern
Power Density	W/L	Power for a given volume	When volume is a concern
Specific Power	W/kg	Power for a given mass	When mass is a concern
Self Discharge	% / Yr	Self discharge over time	When floating is a concern
“Cost” - Power	$/W	Cost of each Watt delivered from a cell	Power applications
“Cost” - Energy	$/Wh	Cost of each Wh delivered from a cell	Energy applications
Ext. Temperature	°C	Service/operational temperature	Extended temp applications
Cycle Life	Cycles	Cycles before EOL* is reached	Temp, Rate, DOD etc..?
Shelf Life	Years	How long can the cell sit on a shelf before EOL*	Temp?
Calendar Life	Years	How long can the cell be on float/ 100% SOC before EOL*	Temp?
Safety	0-7	Per SAE Standards: 0=Safe, 7=Very Bad	Refer to SAEJ2464
Roundtrip Efficiency	%	The total efficiency of both charging and discharging	Very important for Peak Load Shift
Disposal	$	The cost to recycle and/or dispose	True EOL replacement cost?

*Typical EOL: Is reached when 80% of the batteries initial capacity is remaining.

Application Metrics: Grid Storage

<u>*Residential Energy Storage (RES) :*</u> *Med to Large Format Energy Cells*

- Cost is a major concern: $/Wh
- Reliability is a major concern
- Backup / Demand Response – Infrequent Cycling *
- Peak Load Shift – Frequent Cycling
- Renewables Integration – Frequent Cycling
- Extended Temperature Operation

Supplies power to select systems in the home

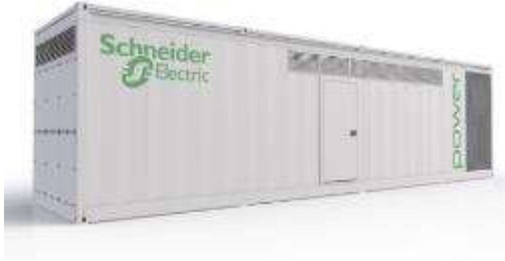
Peak Load Shift - Demand Response – Renewables Integration: Typical 2 – 6 hour run-times: C/2 – C/6

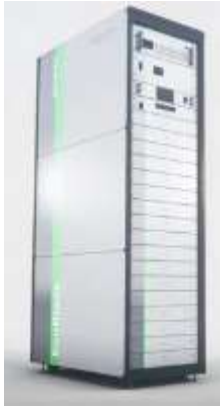
Metric	*Units*	Importance	Metric	*Units*	Importance
Energy Density	*Wh/L*	High	**Ext. Temperature**	*°C*	High
Specific Energy	*Wh/kg*	Med	**Cycle Life**	*Cycles*	High (Low*)
Power Density	*W/L*	Low	**Shelf Life**	*Years*	Med
Specific Power	*W/kg*	Low	**Calendar Life**	*Years*	Med (High*)
Self Discharge	*% / Yr*	Low	**Safety**	*0-7 (SAE)*	High
"Cost" – Energy	*$/Wh or Wh/$*	High	**Round Trip Efficiency**	*% (>90%)*	High (Low*)
"Cost" – Power	*$/W or W/$*	Med	**Disposal**	*$*	Med

Application Metrics: Grid Stabilization

<u>Frequency Regulation</u> : Med to Large Format Power Cells

- Limited space is a concern (shipping container)
- Cost is a major concern
- Reliability is a major concern
- Safety is a major concern
- Cycling events are very frequent





Metric	***Units***	**Importance**	**Metric**	***Units***	**Importance**
Energy Density	*Wh/L*	Med	**Temperature**	*°C*	Med
Specific Energy	*Wh/kg*	Med	**Cycle Life**	*Cycles*	**High** (Micro-Cycles)
Power Density	*W/L*	**High**	**Shelf Life**	*Years*	Med
Specific Power	*W/kg*	Low	**Calendar Life**	*Years*	Med
Self Discharge	*% / Yr*	Low	**Safety**	*0-7*	**High**
“Cost” – Energy	*$/Wh or Wh/$*	Med	**Round Trip Efficiency**	*% (>90%)*	Low
“Cost” – Power	*$/W or W/$*	**High**	**Disposal**	*$*	Med

Application Metrics: Grid Storage

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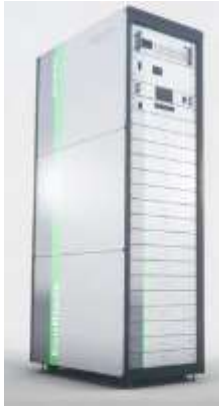
<u>Demand Response & Peak Load Shifting</u> : Med to Large Format Mid-Rate / Energy Cells

- Limited space is a concern (shipping container)
- Backup / Demand Response – Infrequent Cycling *
- Cost is a major concern
- Reliability is a major concern
- Peak Load Shift – Frequent Cycling
- Round trip efficiency



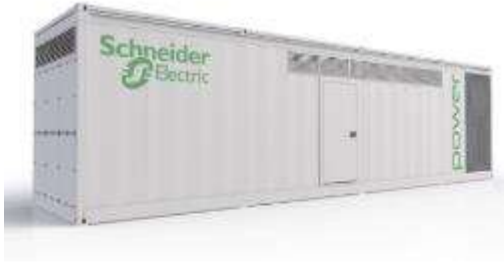
2 to 6 hour run-times: C/2 to C/6

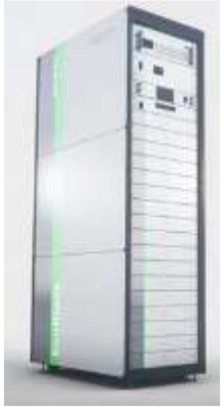
Metric	*Units*	Importance	Metric	*Units*	Importance
Energy Density	*Wh/L*	**High**	**Temperature**	*°C*	Med
Specific Energy	*Wh/kg*	Med	**Cycle Life**	*Cycles*	**High** (Low*)
Power Density	*W/L*	Med	**Shelf Life**	*Years*	Med
Specific Power	*W/kg*	Low	**Calendar Life**	*Years*	Med (**High***)
Self Discharge	*% / Yr*	Low	**Safety**	*0-7 (SAE)*	**High**
“Cost” – Energy	*$/Wh or Wh/$*	**High**	**Round Trip Efficiency**	*% (>90%)*	**High** (Low*)
“Cost” – Power	*$/W or W/$*	Med	**Disposal**	*$*	Med

Application Metrics: Grid Storage

<u>Large Scale Wind & Solar Energy Storage</u>: Medium to Large Format Mid-Rate *Cells*

- Limited space is a concern (shipping container)
- Cost is a major concern
- Reliability & Safety are major concerns
- Cycling events are frequent
- Round trip efficiency





Energy Storage Container System

Metric	*Units*	Importance	Metric	*Units*	Importance
Energy Density	*Wh/L*	**High**	**Temperature**	*°C*	Med
Specific Energy	*Wh/kg*	Low	**Cycle Life**	*Cycles*	**High**
Power Density	*W/L*	**High**	**Shelf Life**	*Years*	Med
Specific Power	*W/kg*	Low	**Calendar Life**	*Years*	Med
Self Discharge	*% / Yr*	Low	**Safety**	*0-7 (SAE)*	**High**
“Cost” – Energy	*$/Wh or Wh/$*	**High**	**Round Trip Efficiency**	*% (>90%)*	**High**
“Cost” – Power	*$/W or W/$*	**High**	**Disposal**	*$*	Med

Application Metrics: Primary Drivers

Energy Storage Application	Energy Density	Specific Energy	Power Density	Specific Power	Self Discharge	“Cost” Power	“Cost” Energy	Temperature	Cycle Life	Shelf Life	Calendar Life	Safety	Round Trip Eff.	Disposal
Stable Grid UPS	X		X			X						X		
Stable Grid UPS Adjacent Markets	X		X			X	X	X				X		
Unstable Grid UPS	X		X			X	X	X	X			X		
Stable Grid 3-Phase UPS			X			X						X		
Unstable Grid Storage: RES, Telco, ATM	X						X	X	X			X		
Grid Storage: RES	X						X	X	X		X*	X	X	
Grid Storage: Adjacent Markets RES	X						X	X	X			X	X	
Grid Stabilization: Frequency Regulation			X			X			X			X		
Grid Storage: Demand Response, Peak Load Shifting	X						X		X		X*	X	X	
Grid Storage: Large Wind & Solar Energy Storage	X		X			X	X		X			X	X	

Application Metrics: Secondary Drivers

Energy Storage Application	Energy Density	Specific Energy	Power Density	Specific Power	Self Discharge	“Cost” Power	“Cost” Energy	Temperature	Cycle Life	Shelf Life	Calendar Life	Safety	Round Trip Eff.	Disposal
Stable Grid UPS							X			X	X			X
Stable Grid UPS Adjacent Markets		X		X						X	X			X
Unstable Grid UPS		X		X						X	X			X
Stable Grid 3-Phase UPS	X	X		X			X			X	X			X
Unstable Grid Storage: RES, Telco, ATM		X				X				X	X		X	X
Grid Storage: RES		X				X				X	X			X
Grid Storage: Adjacent Markets RES		X				X				X	X			X
Grid Stabilization: Frequency Regulation	X	X						X		X	X			X
Grid Storage: Demand Response, Peak Load Shifting		X	X			X		X		X	X			X
Grid Storage: Large Wind & Solar Energy Storage		X						X		X	X			X

Questions?

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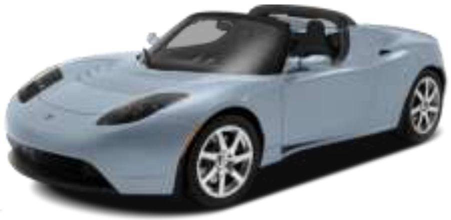
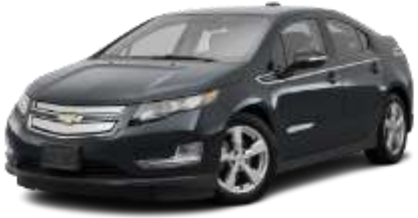
Automotive Industry Drives the Energy Storage Industry (for now)

EV > PHEV > HEV for Total Energy = Battery Pack Size and Weight



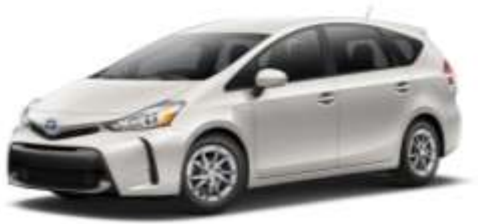
Electric Vehicle (EV) = "Low-Rate or Energy Pack"

•Key Metric: Energy Density, Specific Energy, Temperature
•Shallow DOD Low-Rate Cycles (Rarely 100% DOD): Low Cycle Life
•Decent Charge Acceptance
•Good Low-Rate Roundtrip Efficiency



Plug-in Hybrid Electric Vehicle (PHEV) = "Mid-Rate Pack"

•Key Metric: Energy & Power Density, Specific Energy & Power, Cycle Life, Temperature
•Varying DOD Mid-Rate Cycles (often 100% DOD): High Cycle Life
•Very Good Charge Acceptance
•Excellent Mid-Rate Roundtrip Efficiency



Hybrid Electric Vehicle (HEV) = "High-Rate or Power Pack"

•Key Metric: Power Density, Specific Power, Cycle Life, Temperature
•Many Varying DOD High Rate Cycles (Often 100% DOD): Very High Cycle Life
•Excellent Charge Acceptance
•Excellent High-Rate Roundtrip Efficiency

Popular Li-ion Chemistries in Production

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Cathode and Anode

Chemistry	Chemical Formula	Full Chemical Name	Voltage
LCO	LiCoO2	Lithium Cobalt Oxide	3.6
LCO (LMO)	LiCoO2 (LiMn2O4)	Lithium Cobalt Oxide (Lithium Manganese Oxide)	3.6-3.7
LFP	LiFePO4	Lithium Iron Phosphate	3.2
LMFP	LiMn.71Fe.29PO4	Lithium Manganese Iron Phosphate	3.2
LMO	LiMn2O4	Lithium Manganese Oxide: *Spinel*	*3.7*
LMO (LNO)	LiMn2O4 (LiNiCoAIO2)	Lithium Manganese Oxide (Lithium Nickel Aluminum Oxide)	3.6-3.7
LMO (NMC)	LiMn2O4 (LiNiMnCoO2)	Lithium Manganese Oxide (Lithium Nickel Manganese Cobalt Oxide)	*3.6-3.9*
LMO (NCA)	LiMn2O4 (LiNiCoAlO2)	Lithium Manganese Oxide (Lithium Nickel Cobalt Aluminum Oxide)	3.6-3.7
LNO	LiNiO2	Lithium Nickel Oxide	3.6
LTO	Li4Ti5O12	Lithium Titanate (Anode)	*2.2-2.5*
NCA	LiNiCoAlO2	Lithium Nickel Cobalt Aluminum Oxide	3.6-3.7
NMC	LiNiMnCoO2	Lithium Nickel Manganese Cobalt Oxide	3.7

Realities of Li-ion

Cost of Li-ion portrayed often that of energy, not power cells

- Example below shows to Li-ion cells that are physically the same size, but have vastly different performance characteristics and costs.

Same Physical Dimensions of Cells A & B

Cell A

ENERGY CELL
50Ah
1C Rate
NMC Cathode
Graphite Anode
3.7V

>1hr Runtimes

Energy Cell
Max Cont. Rate: 50A
Max Cont. Power: 165W
Energy: 165Wh
$/Wh is the Driver!

Cell B

POWER CELL
25Ah
6C Rate
NMC Cathode
Graphite Anode
3.7V

<30min Runtimes

Power Cell
Max Cont. Rate: 150A
Max Cont. Power: 495W
Energy: 82.5Wh
$/W is the Driver!

Key Attributes: Power Cell vs. Energy Cell
- Lower internal AC & DC impedance
- Better Roundtrip Efficiency
- Requires less cooling @ same rates
- Much greater cycle life
- Less Active Material – Thin Electrodes
- More complex to manufacture
- Greater costs to manufacture
- Lower Energy Densities
- Lower Specific Energy
- Higher Power Densities
- Higher Specific Power