Energy Storage with Batteries and Supercapacitors in vehicle applications

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Battery requirements in electrified vehicles

- **Battery must meet the power (kW) of the electric motor**
- **Battery must be able to accept the regeneration braking energy**
- **Battery must be able to provide accessory loads when the vehicle is stopped**
- **Battery must be able to start the engine in a HEV**
- **Battery must be able to meet the all-electric range in a PHEV**
- **Battery must have long cycle life and reasonable cost**

In some cases to meet all these requirements, the best solution can be to combine supercapacitors with the battery

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Mid-size passenger car- EV and PHEV

PHEV range (1)	Wh/mi (2)	Storage battery kWh (3)	Supercapacitor Wh (4)
20 mile	282	7	220
40 mile	282	15	220
60 mile	282	23	220
EV-100	282	37	
EV-200	282	75	
EV-300	282	112	

(1) All-electric range and maximum power 120kW

(2) Wh/mi is the average of the value 225 Wh/mi of the FUDS and 340 Wh/mi on the US06

(3) 75% of the energy stored in the battery is used

(4) Energy available from the supercapacitor to ½ rated voltage (32 kg of cells)

Long haul truck (39500 kg)

PHEV range (1)	kWh/mi (2)	Storage battery kWh (3)	Supercapacitor Wh (4)
10 mile	2.4	32	900
20 mile	2.4	64	900
40 mile	2.4	128	900
EV-100	2.4	320	
EV-200	2.4	640	
EV-300	2.4	960	

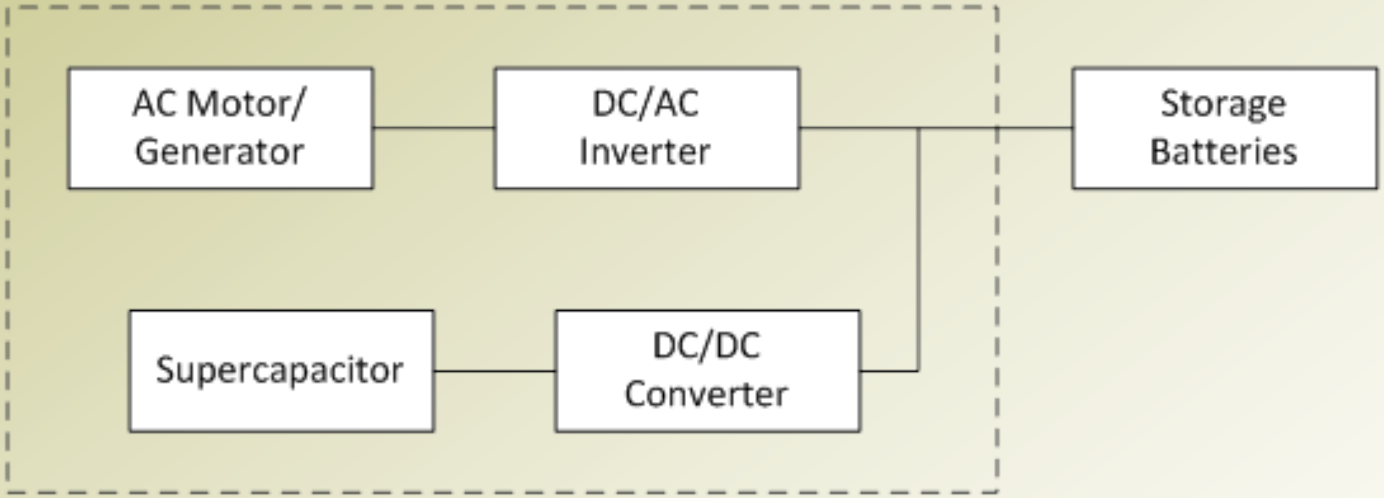
(1) All-electric range and maximum power 320 kW

(2) Wh/mi is the average of the value 2.4 kWh/mi for mix of city and highway driving

(3) 75% of the energy stored in the battery is used

(4) Energy available from the supercapacitor to ½ rated voltage (90 kg of cells)

Electric drive with supercapacitors



If the supercapacitors are combined with the electric drive package rather than with the batteries, the supercaps can be used with different battery packs and not considered to be part of the battery pack. In this case, the decision whether to use supercaps is made by the electric drive designer, not the battery manufacturer.

Key characteristics/advantages of supercapacitors

- High power capability permitting energy to be charged/discharged at very high efficiency
- Very long cycle life for high power, deep discharge cycles
- Ability to accept very high charge power/high rates
- Good power capability at low temperatures
- Minimal thermal management problems

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Present - 48V 40 Wh NessCap module (18 x 3000F 2.7Vcells)

Future - 54V 60 Wh NessCap module (18 x 3600F 3V cells)

Photographs of the JSR Micro 1100F and 2300F devices

Positive- activated carbon, negative- lithiated graphitic carbon

Characteristics of the JSR Micro 1100F cell

Constant Current discharge 3.8V – 2.2V

Current (A)	Time (sec)	C(F)	Resistance (mOhm) **
20	86.4	1096	
40	41.9	1078	
60	27.2	1067	
75	21.4	1063	1.2
100	15.7	1057	1.15
150	10.1	1056	1.1

** Resistance is steady-state value from linear V vs. time discharge curve

Constant Power discharges 3.8V – 2.2V

Power (W)	W/kg	Time(sec)	Wh	Wh/kg *	Wh/L *
50	347	106.7	1.47	10.2	19.1
83	576	61.9	1.43	9.9	18.6
122	847	40.1	1.36	9.4	17.7
180	1250	26.2	1.31	9.1	17.0
240	1667	19.1	1.27	8.8	16.5

* based on the measured weight and volume of the cell as tested
Laminated pouch cell weight 144 gm, 77 cm3, 1.87 g/cm^3

Peak pulse power at 95% efficiency R=1.15 mOhm

P= 9/16*.05* $(3.8)^2$ /.00115 = 353 W, 2452 W/kg

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Considerations in selecting a battery for use with supercapacitors

- **Battery can be selected primarily to meet the energy storage requirement with much reduced consideration of its power capability**
- **Result will be a battery with higher energy density, longer cycle life, and lower cost for the same energy storage (kWh)**
- **Battery will experience much reduced dynamic high currents which should further increase its cycle life**
- **High regeneration braking currents will be accepted by the supercaps and not the battery**
- **Greater fraction of total energy stored in the battery can be used in most application than would be the case without supercaps**

Do not use the same battery with/without supercaps

Use EV batteries in PHEVs

Variation of battery unit cost ($/kWh) between energy and power batteries

Table 2. Projected pack-level direct manufacturing costs for MY2025 by vehicle type and range ($/kWh, 2015$)

	PHEV20	PHEV40	BEV75	BEV100	BEV200
P2W Class 1	371-388	250-258	205-223	173-185	145-151
P2W Class 2	352-365	242-251	193-211	165-177	137-144
P2W Class 3	337-361	237-247	186-205	159-172	133-140
P2W Class 4	319-346	232-246	176-204	155-165	126-134
P2W Class 5	277-309	227-241	160-189	146-155	115-124

Taken from EVS 30 presentation by M.J. Safoutin, U.S. EPA, October 2017, Stuttgart, Germany

Battery Pack Manufacturing Cost in 2025, $/kWh

Type	BEV 200 mi[22]	BEV 100 mi	PHEV 40 mi.
Standard car	142	171	251
Small SUV	132	159	246
PU Truck	123	148	228

Taken from "Technical assessment of CO2 Emission reductions for passenger cars in the post-2025 timeframe", T. Cackette and R. Rykowski, February 2017

EV energy batteries are lower cost than PHEV power batteries

Light-duty Vehicle Application

My poster deals with the light-duty case in detail

Comparisons of the weight, volume, and costs of the energy storage systems with/without supercapacitors

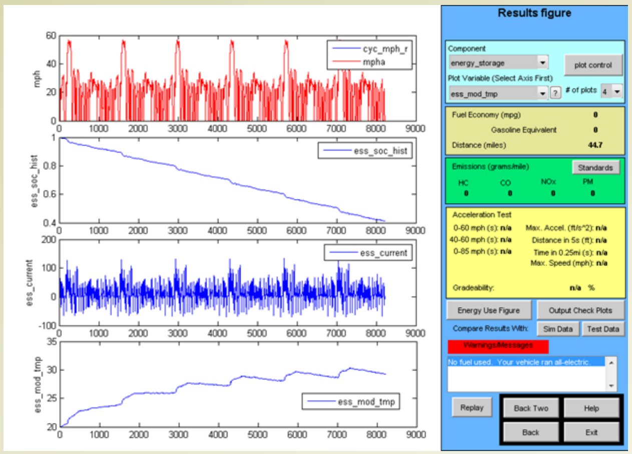
PHEV range	Power battery kWh	Energy battery kWh	Capacitor Wh	weight. kg Vol. L of the battery plus capac.	weight. kg Vol. L of the power battery	Cost ($) of the battery plus the capac. (1)	Cost ($) of the power battery (2)
20 mile	7	7	220	66 kg 33 L	58 kg 27 L	$1600	$1575
40 mile	15	15	220	115 kg 55 L	125 kg 57 L	$2800	$3375
60 mile	23	23	220	163 kg 77 L	192 Kg 87 L	$4000	$5175

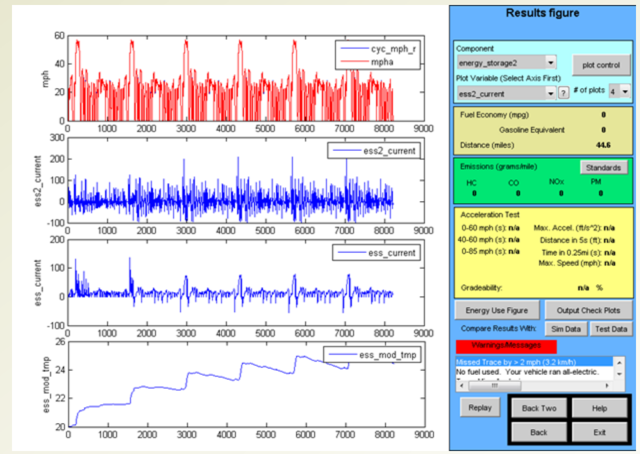
The supercapacitor cost was taken as .25 cents per Farad which is $2.5/Wh

The battery costs were $150/kWh for the energy battery and $225/kWh for the power battery

Economic advantage of using supercaps greater with longer all-electric range

80 kg Energy battery with and without caps, 6 FUDS cycles





Energy battery alone

Energy battery with 24 kg Skeleton Caps

Heavy-duty vehicle application

HEV and PHEV long haul truck (39500 kg)

Summary of Advisor simulation results for a heavy-duty truck using supercaps in a PHEV

Long haul truck powertrain	Fuel economy mpgD 55 mph average	Fuel economy mpgD City stop-go
Diesel engine 324 kW	6.9	3.3
PHEV 320 kW as HEV-Battery with 900 Wh Capacitors		
12 kWh	7.3	4.2
25 kWh	7.3	4.3
54 kWh	7.4	4.3

Conclusions regarding the use of batteries and supercapacitors in vehicles of various sizes

- Supercapacitors can be used with an energy (EV) battery
- The supercap reduces the peak currents and stress on the battery by at least a factor of two
- PHEV applications in mid-size cars will require about 220 Wh of energy storage in the supercap
- Long haul truck applications will require about 1 kWh of energy storage in the supercap
- The cost of the supercap/battery system will be attractive due to the lower cost of the energy battery compared to a power battery
- The cost of supercaps will continue to decrease as their volume of production increases. I have assumed $2.5/Wh in this study.

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