Comparisons of the useable power characteristics of lithium batteries and supercapacitors for vehicle applications

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Abstract

In this paper the power capabilities of several lithium batteries and supercapacitors are determined and compared based on measurements of the resistance of the cells at UC Davis. The comparisons were made for pulse efficiencies of 80-95%. It was found that for a pulse efficiency of 95% the batteries had a power density of 500-600 W/kg and most of the supercapacitors had power densities of 1500-2000 W/kg. Hence for applications requiring high efficiency pulses, supercapacitors have higher power densities than lithium batteries by a factor of at least 3-4. The high power supercapacitors have higher power capability than high power lithium batteries for vehicle by a factor of 4-5.

The advantages of combining an energy battery (high energy density, low cost, modest power capability) with supercapacitors in plug-in hybrid vehicles PHEV like the Volt was investigated. Simulations of PHEVs with an all-electric range of up to 50 miles indicated that the combination of an energy battery and supercapacitors both decreased the energy use (Wh/mi)of the vehicle and greatly reduced the peak currents from the energy battery by a large factor compared to that in a power battery in the same vehicle.

1. Introduction

The confusion and uncertainty concerning the useful pulse power capability of lithium batteries and supercapacitors and their relative power capability persists as the performance of both technologies continues to improve. This situation persists for several reasons. (1) The power capability depends primarily on the DC resistance of the lithium battery and supercapacitor cells and information/data on the resistance is not readily available. When it is measured, there is uncertainty in the test procedure used. (2) The cell manufacturers often do not list the resistance on the spec sheets for the cells. Instead they list a maximum power value (W/kg) that in most cases overstates the power capability of the cell by a significant factor. (3) The useful pulse power of any cell depends on the application because the maximum power capability of the cell depends on the minimum pulse efficiency and the time length of the pulse that are appropriate for the application. The pulse efficiency for vehicle applications can vary between about 80% and 95%, and the time period can vary between a fraction of a second to 10-15 seconds. These variations in pulse characteristics can result in about an order of magnitude (factor of 10) difference in the useful power capability of battery and supercapacitor cells. The influence of these factors on the useful power of lithium battery and supercapacitor cells is discussed in detail in this paper.

2. General considerations

As discussed in [1], the pulse power capability of battery and supercapacitor cells can be calculated from the simple relationships shown below.

Battery cell $\quad P= EF\,(1-EF)\,V_{0C}^2/R_{DC}$ (1)

Supercapacitor $\quad P= 9/16\; EF\,(1-EF)\,V_0^2/R_{DC}$ (2)

In the case of the battery cell, the efficiency EF depends on the ohmic losses in the pulse.

$$EF= V_{pulse}/V_{OC}, \quad V_{pulse} = V_{OC} - I_{pulse} R_{DC}, \quad V_{OC} \text{ varies with cell SOC}$$

In the case of the supercapacitor, V_O is the rated voltage of capacitor and the 9/16 factor results from the pulse being initiated from ¾ V_O, which is the average voltage during the discharge of the capacitor from V_O to $V_O/2$. Hence the efficiency EF accounts for the Ohmic losses in both the battery and supercapacitor cells. The factor EF (1-EF) varies from .0475 for EF=.95 to .24 for EF=.6.

For battery cells, the USABC hybrid pulse power test procedure (see Fig.1) is often used to determine the resistance and useable power of the cell [2}. Note that the power measured corresponds to a cell voltage drop to a minimum cell voltage set by the manufacturer of the cell. The resultant power is the maximum that can be attained at a particular SOC and corresponds to a low efficiency of 50-60%. This power is seldom useful in vehicle applications. The resistance measured corresponds to pulse time of 30 sec for discharge and 10 sec for a charge pulse. Further discussion of determining the resistance of battery cells is given in Sec 3.1.

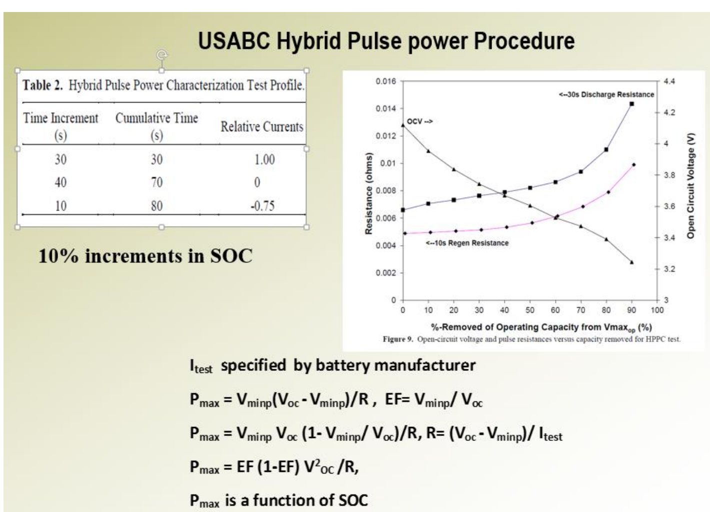


Fig. 1: The USABC hybrid pulse power test procedure

The USABC hybrid pulse power test procedure is not useful for determining the resistance of supercapacitors because the major fraction of the voltage change in a charging or discharging pulse of a supercapacitor is due to the capacitance of the cell and not its resistance. Test procedures for determining the resistance of supercapacitors are discussed in [1].

3. Determination of the Power capability of battery and supercapacitor cells

3.1 Lithium batteries

A general approach to determining the resistance of battery cells is to pulse the cells at constant current at various SOC. This is the approach used at UC Davis. The cells are charged to a specified voltage (V_{max}) and then discharged to a specified SOC (to a fraction of Ah capacity of the cell) and after a rest of 120 seconds, a constant current pulse of 10 or 15 seconds is initiated. The voltage during the pulse is measured and from that data the effective resistance during the pulse is calculated.

$$R_{DC} = (V_{OC} - V_{pulse})/I_{pulse}$$

This test yields values for the resistance as a function of I_{test}, SOC, and t for both charge and discharge pulses. The values of R_{DC} are then used in Eq (1) to calculate the useable power for particular values of EF.

Resistance data for the Nissan Leaf cell and the A123 $LiFePO_4$ cell are shown in Tables 1 and 2. For both cells, the variation of the resistance with the time (seconds) of the pulse is greater than the variation with SOC. The pulse resistance for the Lithium batteries is essentially the same for charge and discharge pulses. The test data indicated that the resistance does not vary significantly with the magnitude of the current of the pulse. The values of the resistances shown in Tables 1 and 2 are used to determine the power capabilities of the batteries in the next section of the paper.

Table 1: Pulse test results for the Leaf NCM 50 Ah cell

	V_0 (1)		**t=0**	**t=2 sec**	**t=5 sec**	**t=10 sec**			**t=0**	**t=2 sec**	**t=5 sec**
SOC 75%	3.8										
R mOhm		**Discharge pulse**	1	1.2	1.35	1.48		**Charge pulse**	1.1	1.28	1.41
SOC 50%	3.64										
R mOhm		**Discharge pulse**	1.02	1.2	1.31	1.5			1.08	1.29	1.42
SOC 25%	3.54										
R mOhm		**Discharge pulse**	1.05	1.24	1.37	1.46		**Charge pulse**	1.1	1.25	1.37

(1) Pulse currents of 75A and 140A with a discharge at 28A between pulse sequences and then rest for 2 minutes, cell weight .91 kg, 190 Wh/kg at C/3

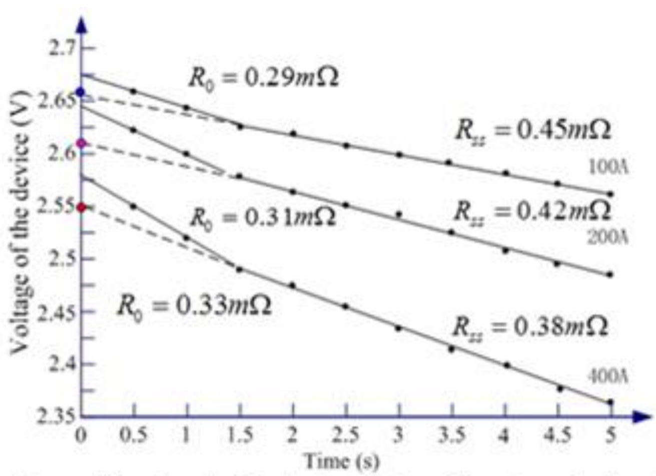
Table 2: 20A Pulse test results for the A123 2.5Ah LFP cell

	V_0 (1)		t=0	t=5 sec	t=10 sec			t=0	t=5 sec	t=10 sec
SOC 75%	3.37									
R mOhm		**Discharge pulse**	9	13	14		**Charge pulse**	9	13	13
SOC 40%	3.34									
R mOhm		**Discharge pulse**	8	12.5	14.5					
SOC 10%	3.32									
R mOhm		**Discharge pulse**	8.5	17	18.5		**Charge pulse**	6	13	13.5

(1) Discharge at 1.25A between pulse sequences and then rest for 2 minutes, cell weight 76 g, energy density 103 Wh/kg at 132 W/kg constant power

3.2 Carbon/carbon supercapacitors

A pulse test like that used for batteries can be used only to determine the resistance of the capacitor at t=0 because the primary voltage change during the pulse is due to the capacitance of the cell not its resistance. Another approach [1] used at UC Davis to determine the resistance is to plot voltage vs. time for constant current discharge data and extrapolate the linear voltage curve back to t=0 to get V(0) (see Fig. 2). The resistance of capacitor cell is given by $R_{DC} = (V_O - V(0))/I_{test}$. For most capacitor cells, the resistance R(t=0) is somewhat smaller than R_{DC}, which is the steady-state resistance R_{ss} after the micropores in the cell are fully operative. For vehicle application, R_{ss} is the most appropriate resistance to use to calculate the power capability of the capacitor using Eq. (2).



Method for determining the steady-state resistance by extrapolating the voltage trace to t=0 (Nesscap/2.7V/3000F)

Figure 2

The characteristics of many of the supercapcitors [3] developed around the world are summarized in Table 3. The resistances (R_{ss}) shown Table 3 for the cells were measured at UC Davis using the procedure discussed previously. The power capabilities are given in terms of that for 95% efficient pulse $(W/kg)_{95\%}$ and the matched impedance power ($P_{MI} = V_0^2/4\ R_{ss}$) which corresponds to EF = .5. In most applications, supercapacitors are used to store relatively small quantities of energy and the energy is transferred in and out of the capacitors to increase the efficiency of the system. Hence it is critical that the capacitors operate at a high efficiency of 95% or higher. Thus the P_{MI} value for supercapacitors is of little practical use. It is shown in Table 3 only because the power capability quoted for batteries is often close to the matched impedance value for the battery. In practice, the power capability $(W/kg)_{95\%}$ will be exceeded because the capacitor will be operating at a voltage greater than ¾ V_0. If the voltage of the capacitor is less than $3/4V_0$, its power capability will be less than the $(W/kg)_{95\%}$ value.

Table 3: Summary of the Characteristics of supercapacitors

Device	V rate	C (F)	R (mOhm) (3)	RC sec	Wh/kg (1)	W/kg (95%) (2)	W/kg Match. Imped. (4)	Wgt (kg)	Vol. lit.
Maxwell	2.7	2885	.375	1.1	4.2	994	8836	.55	.414
Ioxus	2.85	3095	.33	1.0	5.0	1355	12065	.51	.41
Skeleton Technol.	2.85	3450	.13	.45	5.4	3353	29809	.52	.39
Skeleton Technol.	3.4	3200	.48	1.5	8.9	1730	15400	.40	.096
Skeleton Technol	3.0	3320	.25	.83	5.6	1878	17310	.54	.39
Skeleton Technol	3.0	1900	.52	.98	4.9	1430	13520	.34	.22
Skeleton Technol	2.85	4100	.22	.90	6.3	1956	19230	.53	.39
Yunasko*	2.75	1275	.11	.13	4.55	8791	78125	.22	.15
Yunasko*	2.7	7200	1.4	10	26	1230	10947	.119	.065
Yunasko*	2.7	3200	1.5	7.8	30	3395	30200	.068	.038
Ness Maxwell	3.0	3650	.27	.98	6.5	1875	16666	.50	.394
Ness (cyl.)	2.7	3160	.4	1.3	4.4	982	8728	.522	.379
DAE-China	2.7	440	2.3	1.0	5.5	1536	13662	.058	
JSR Micro	3.8	1100 2300 3225	1.15 .77 1.0	1.21 1.6 3.2	10 7.6 11	2450 1366 1167	21880 12200 10374	.144 .387 .348	.077 .214 .213
DAE-China	3.8	850	4.7	3.5	12.4	993	8828	.087	

(1) Energy density at 400 W/kg constant power, Vrated - 1/2 Vrated
(2) Power based on $P=9/16*(1-EF)*V_o{}^2/R$, EF=efficiency of discharge
(3) Steady-state resistance including pore resistance
(4) Matched impedance power based on $P= V_{oc}^2/4R_{DC}$
*** All devices except those with * are packaged in metal/plastic containers: those with * are laminated pouched packaged**

4. Comparisons of the power capability of lithium batteries and supercapacitors

In this section of the paper, the power capability of the lithium battery cells and the supercapacitors will be compared for the same pulse characteristics. In both cases, the power capability depends on the cell resistance and the efficiency of the pulse. The power capability (W/kg) of the battery cells for the lithium NCM and $FePO_4$ chemistries are shown in Table 4. The results are given for pulse times of 2, 5, 10 seconds and pulse efficiencies of 95% and 80%. The power density for matched impedance power is also given in the table. The power capabilities shown apply both to discharge and charge pulses. It is clear from Table 4 that the power capability of the lithium batteries vary over a wide range depending on the efficiency requirement of the application and the time of the pulse. When a maximum power density of 2000-3000 W/kg is claimed for a cell by the battery manufacturer, it is for a pulse of low efficiency, short time and likely not applicable for most vehicle applications.

Table 4: Battery power characteristics for different pulse efficiencies

Battery Chemistry	Efficiency EF	Pulse time 2 sec	5 sec	10 sec
		W/kg		
Leaf LiNMC	95%	676	563	451
	80%	2279	1899	1519
	Matched Impedance	3560	2967	2374
A123 $LiFePO_4$	95%		536	498
	80%		1806	1677
	Matched Impedance		2839	2636

The resistance and power capability of a large number of supercapacitors are shown in Table 3. It is clear from the table that the power characteristics of the available capacitors vary over a wide range. In order to clarify the power situation for the supercapacitors, the characteristics of selected commercially available cells are shown in Table 5. All the cells except those for JSR Micro are carbon/carbon devices. Most of the supercapacitors have a $(W/kg)_{95\%}$ value of 1000-2000 and energy density of 5-7 Wh/kg. It is clear from Table 5 that much higher power devices have been developed by Skeleton Technologies and Yunasko without sacrificing energy density. It seems only reasonable to compare the power densities of the lithium batteries and supercapcitors for applications requiring an efficiency of 95% or higher. In those cases, most of the capacitors have power densities about 3-4 times that of the batteries and some capacitors have power densities that are 6-16 times higher. Only for applications that can accept considerably lower efficiencies than 90% are the power densities of lithium batteries and supercapacitors comparable.

Table 5: Characteristics of commercially available supercapacitors

Device	V rate	C (F)	R (mOhm) (3)	RC sec	Wh/kg (1)	W/kg (95%) (2)	W/kg Match. Imped. (4)	Wgt (kg)	Vol. lit.
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5. Supercapacitors in combination with Lithium batteries

5.1 Background

In any vehicle application, the energy storage system must meet both the energy (kWh) and power kW) requirements of the vehicle. This can be done with lithium batteries alone, but in some applications, it requires that the energy density of the battery be significantly sacrificed in order to meet the power requirement. A good example of this is the plug-in hybrid vehicle which has a relatively small battery to meet a 50 mile or less all-electric range and the same electric drive power (kW) as an electric vehicle. The energy storage or range requirement for the battery can be decoupled from the power requirement by combining a lithium battery and a supercapacitor. This permits the use of an **energy battery** in all electric drive applications. An **energy battery** is a battery which has been optimized for the energy density with little attention to power. These batteries are used in electric vehicles like the Bolt and are produced in large quantities and sell at a low price. The Leaf NCM battery is an energy battery. Its energy density is high (about 225 Wh/kg) and its power density is modest, but high enough to meet the power demand of the Leaf because the battery in the Leaf is large (30 kWh). If the P/E ratio of the maximum power (kW) of the electric drive to the energy stored in the battery (kWh) is greater than about 4, it is reasonable to consider combining supercapacitors with an energy battery in the vehicle. Consider the examples of the Volt which has a 120 kW drive system and an 18 kWh battery: P/E=120/18 = 6.7 and the Bolt which has a 150 kW electric drive and a 60 kWh battery: P/E= 150/60 = 2.5. Hence the Volt would be a good candidate for combining a lithium battery and capacitor and the Bolt would not.

Test data for the 3400F Skeleton Technology cell is given in Table 6. Note that for this supercapacitor, the capacitance and energy discharged (Wh) is nearly constant for complete discharges of 100-10 seconds. For the 12 second discharge, the efficiency is about 95%. Hence for this high power supercapacitor, the total energy stored can be used at the 95% efficiency power of the device. This results in a P/E ratio for the Skeleton cell of 580 compared to a pulse P/E ratio for the Leaf NCM cell of only 3.4.

Table 6: Test data for the Skeleton 2.85V device

Device characteristics:
Packaged weight 524 gm
Packaged volume 390 cm^3

Constant current discharge data

Current A	Time sec	Capacitance F	Steady-state R_{ss} mOhm	R_0 mOhm
60	84.1	3541		
85	58.6	3495		
130	38.2	3473		
200	24.4	3461		
300	16.3	3469	.14	.067
400	12.0	3357	.125	.0875
500	9.6	3357	.13	.074

Discharge 2.85V to 1.425V
Resistance calculated from extrapolation of the voltage to t=0
Capacitance calculated from C= I*t disch/ delta from Vt=0

Constant power discharge data

Power W	W/kg	Time sec	Wh	Wh/kg	Wh/L
100	191	104.6	2.91	5.55	7.45
200	382	51.7	2.87	5.48	7.36
400	763	25.4	2.82	5.39	7.24
500	954	20.4	2.83	5.40	7.26
600	1145	16.8	2.80	5.34	7.18
700	1336	14.4	2.80	5.34	7.18
800	1527	12.5	2.78	5.31	7.13

Pulse power at 95% efficiency
$P = 9/16\ (1-\text{eff})\ V_R^2/R_{ss}$,, R_{ss}= .13 mOhm, $(W/kg)_{95\%} = 3353$, $(W/L)_{95\%} = 4505$
Matched impedance power
$P = V_R^2/4\ R_{ss}$, (W/kg) = 29809

5.2 Systems aspects of combining lithium batteries and supercapacitors

A schematic of supercapacitors combined with a battery for energy storage [4, 5, 6] in an electric drive system for a vehicle is shown in Figure 3. A key component in the schematic is the DC/DC converter which is needed to control the discharge current of the supercapacitor and to match its voltage to that of the battery. The control strategy for the battery/supercapacitor combination involves the battery being load leveled by the supercapacitor and the battery recharging the capacitor to maintain it between V_0 and $V_0/2$. All the regenerative braking energy recovered is stored in the supercapacitor.

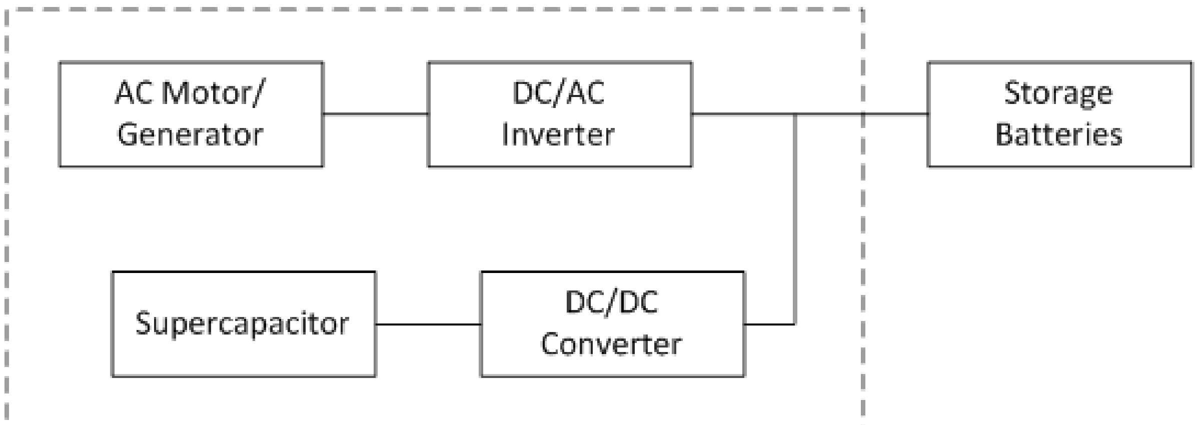


Figure 3: Schematic of supercapacitors combined with a battery for energy storage

The storage battery to be combined with the supercapacitors will be an **energy battery** not the power battery usually used in PHEVs or HEVs. The design parameters shown in Table 7 indicate the difference in the characteristics of **energy and power batteries.** The differences in the energy density and cost of the two batteries are particularly significant. These differences allow the weight and cost of the battery/supercapacitor system to be equal to or less than that of the power battery system as shown in Table 8.

Table 7: Design parameters for the energy storage components in the electric driveline system

Component	Wh/kg	kg/L	$(W/kg)_{95\%}$	$/kWh	$/Wh
Power battery	120	2.2	950	225	
Energy battery	165	2.2	490	150	
supercapacitor	6	1.4	3400		2.9
XALT Energy					
Power battery 40Ah / NMC	153	2.3	580		
Energy battery 65Ah / NMC	223	2.1	255		

Table 8: 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 capacitors.	weight. kg Vol. L of the power battery	Cost ($) of the battery plus the capacitors (1)	(1) Cost ($) of the power battery (2)
20 mile	7	7	150	66 kg 33 L	58 kg 27 L	$1985	$1575
40 mile	15	15	150	115 kg 55 L	125 kg 57 L	$3185	$3375
60 mile	23	23	150	163 kg 77 L	192 Kg 87 L	$4385	$5175

(1) The supercapacitor cost was taken as .25 cents per Farad which is $2.9/Wh

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

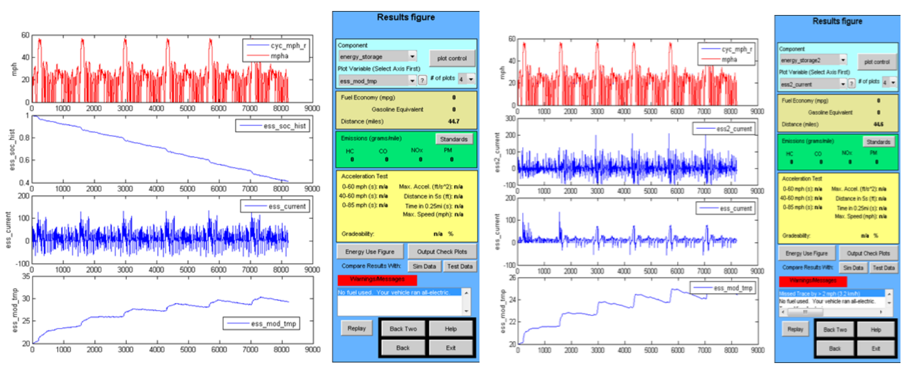
(3) $500 ($5/kW) for the DC/DC converter

The PHEV with the batteries alone and with the energy battery and Skeleton supercapacitors were simulated using the UC Davis Advisor program. The results of the simulations for a Volt size PHEV are shown in Figure 4 and Table 9. The simulation results show that the vehicle energy use Wh/mi is less with the energy battery and the supercapacitors than with the power battery alone. In addition, the maximum currents of the energy battery are relatively low and much lower than that of the power battery without the capacitors. The battery losses are significantly reduced by using the supercapacitors. Hence the advantage of combining the energy battery with the supercapacitors are shown in the simulations.

Table 9: Advisor simulation results for the Wh/mi and the battery and capacitor losses and maximum currents

Energy storage	Driving cycle	miles	* Wh/mi	Battery losses kJ/mi	Capacitor Losses kJ/mi	Maximum battery current A	Maximum capacitor current A
Power battery 110 kg alone							
	FUDS	44.6	202	10		150	
	US06	32	272	25		380	
Energy battery 80 kg + Skeleton Tech SC 28kg							
	FUDS	44.6	192	5.5	6.6	80	150
	US06	32	244	16	12	90	320

***CHEV VOLT size PHEV**



Energy battery alone **Energy battery with 28kg caps**

Figure 4: Advisor simulation results with the energy battery alone and the energy battery with supercapacitors

6. Summary

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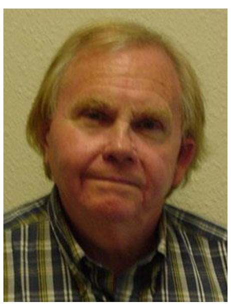

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