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Review of the Present and Future Applications of Supercapacitors in Electric and Hybrid Vehicles

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Abstract

This report is concerned with supercapacitors (electrochemical capacitors) and their applications in electric drive vehicles in place of or in combination with batteries. The electric drive vehicles considered are hybrid vehicles (HEVs and PHEVs) and fuel cell vehicles. The first sections of this report deal with supercapacitor concepts and performance, including a description of the construction of devices and materials used in them and recent test data for commercial and prototype devices. The data for the new carbon/carbon device from Skeleton Technologies showed an energy density of 9 Wh/kg and 95% efficient power capability of 1730 W/kg. Both of these characteristics are significantly better than those of commercially available devices. Test data are shown for a hybrid supercapacitor from Yunasko that has an energy density greater than 30 Wh/kg and a 95% efficient power capability of 3120 W/kg. This device has the best performance of any supercapacitor device tested at UC Davis to date.

Various vehicle applications of supercapacitors have been reviewed in detail. Simulation results are presented for light duty vehicles and transit buses using supercapacitors in place of lithium batteries in hybrid vehicles and in combination with advanced batteries in plug-in electric vehicles. It was found in all cases that the vehicles using the supercapacitors had the same as or better performance than those using batteries and in general were more efficient. The cost of supercapacitors compared to lithium batteries was discussed briefly. It was shown that when one recognizes that the energy stored in the capacitors is less than 1/10 that in the batteries for hybrid applications, the price of supercapacitors needs to decrease to about .5- 1 cent Farad for capacitors to be cost competitive with high power batteries at $500-700/kWh. In addition, there is a good possibility that the life of the capacitors would be equal to that of the hybrid vehicles.

I. Introduction

This report is concerned with supercapacitors (electrochemical capacitors) and their applications in electric drive vehicles in place of or in combination with batteries. The electric drive vehicles considered are hybrid vehicles (HEVs and PHEVs) and fuel cell vehicles. Special attention is given to sizing the supercapacitor unit to minimize volume and cost and the control strategies that take advantage of the high efficiency and charge acceptance of supercapacitors compared to batteries. Present vehicle applications of supercapacitors include their use in braking systems and stop-go hybrids and future applications in charge sustaining and plug-in hybrids and battery powered electric vehicles using advanced batteries having high energy density (>300 Wh/kg).

The most common electrical energy storage device used in vehicles is the battery. Batteries have been the technology of choice for most applications, because they can store large amounts of energy in a relatively small volume and weight and provide suitable levels of power for many applications. Shelf and cycle life have been a problem/ concern with most types of batteries, but people have learned to tolerate this shortcoming due to the lack of an alternative. In recent times, the power requirements in a number of applications have increased markedly and have exceeded the capability of batteries of standard design. This has led to the design of special high power, pulse batteries often with the sacrifice of energy density and cycle life. Supercapacitors have been developed as an alternative to pulse batteries. To be an attractive alternative, capacitors must have much higher power and much longer shelf and cycle life than batteries. By "much" is meant about one order of magnitude higher.

Supercapacitors have much lower energy density than lithium batteries. Their lower energy density and higher cost ($/kWh) are often given by auto driveline designers as the reason why they have not used supercapacitors. However, as discussed in this report, the energy storage (kWh) requirement using supercapacitors is much smaller than using batteries in high power applications due to the much lower power capability (kW/kg) of the batteries. This can have a large effect on the effective energy density of the energy storage unit.

The first sections of this report deal with supercapacitor concepts and performance, including a description of the construction of devices and materials used in them and recent test data for commercial and proto-type devices. The next sections are concerned with present and future applications, how supercapacitors units are sized in particular applications, and simulations of vehicles using supercapacitors in their drivelines for energy storage. The final section deals with the cost of supercapacitors and comparisons of their cost with that of lithium batteries.

II. Supercapacitor Concepts

A supercapacitor, often referred to as an electrochemical capacitor, is an electrical energy storage device [1] that is constructed much like a battery (see Figure 1) in that it has two electrodes immersed in an electrolyte with a separator between the electrodes. The electrodes are fabricated from a high surface area, porous material having pore diameters in the nanometer (nm) range. The surface area of the electrode materials used in an electrochemical capacitor is much greater than that used in battery electrodes being 500-2000 m^2/gm. Charge is stored in the micropores at or near the interface between the solid electrode material and the electrolyte. The energy stored in the capacitor is given by $\frac{1}{2} CV^2$, where C is its capacitance (Farads) and V is the voltage between the terminals. The maximum or rated voltage of the capacitor is dependent on the electrolyte used in the device. The charge Q (coulombs) stored in the capacitor is given by CV. The charge and energy stored in the supercapacitor are calculated using the same expressions as for a simple dielectric capacitor. However, calculation of the capacitance of the electrochemical capacitor is much more difficult as it depends on complex phenomena occurring in the micropores of the electrodes.

The mechanisms for energy storage in electrochemical capacitors are double-layer and psuedo-capacitance processes. The physics and chemistry of these processes as they apply to electrochemical capacitors are explained in great detail in [2, 3].

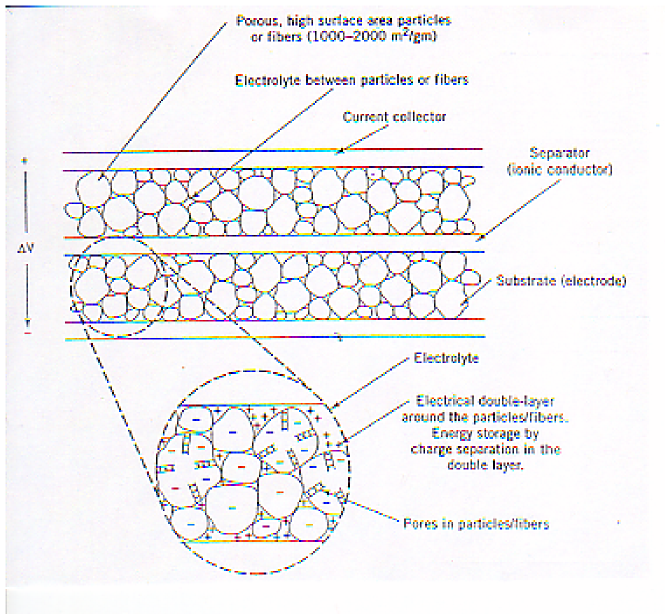

Figure 1 Schematic of an electrochemical capacitor

Energy is stored in the double-layer capacitor as charge separation in the double-layer formed at the interface between the solid electrode material and the liquid electrolyte in the micropores of the electrodes (see Figure 1). The ions displaced in forming the double-layer in the pores are transferred between the electrodes by diffusion through the electrolyte.

For an ideal double-layer capacitor, the charge is transferred into the double-layer and there are no Faradaic reactions between the solid material, ions, and the electrolyte. In that case, the capacitance (dQ/dV) is a constant and weakly dependent on voltage. For devices that ultilize pseudo-capacitance, most of the charge is transferred at the surface or in the bulk near the surface of the solid electrode material. Hence in this case, the interaction between the solid material and the ions/electrolyte involves Faradaic reactions which in most instances can be described as charge transfer reactions. The charge transferred in these reactions is voltage dependent resulting in the pseudo-capacitance ($C = dQ/dV$) being voltage dependent. Three types of electrochemical processes have been utilized in the development of supercapacitors using pseudo-capacitance. These are (1) surface adsorption of ions from the electrolyte, (2) redox reactions involving ions from the electrolyte [2, 3], and (3) the doping and undoping of an active conducting polymer material in the electrode [4].

Supercapacitors can be fabricated with one electrode being of a double-layer (carbon) material and the other electrode being of a battery-like material (see Figure 2). Such devices are often referred to as *hybrid capacitors* [5]. Most of the hybrid capacitors developed to date have used metal oxides (for example, lead or nickel oxide) as the battery-like material in the positive electrode. The energy density of these devices can be significantly higher than for double-layer capacitors. Hybrid capacitors can also be assembled using two non-similar mixed metal oxides or doped conducting polymer materials [4].

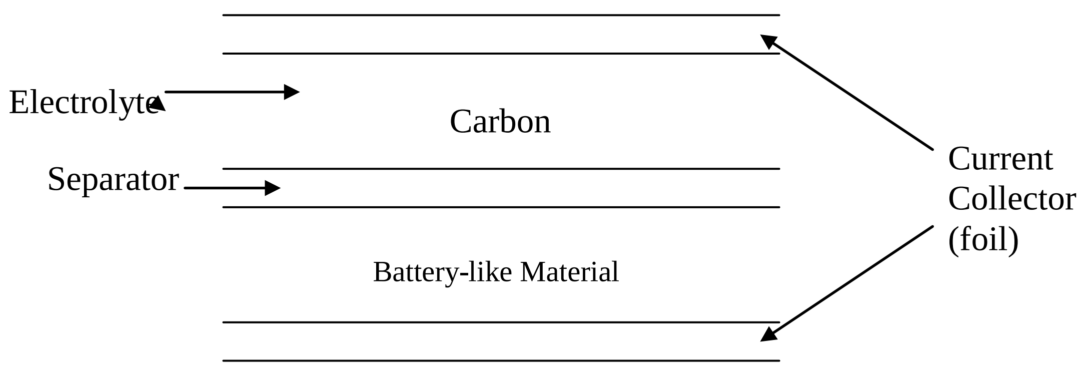

Figure 2 Schematic of a hybrid electrochemical capacitor

III. Test Results for Advanced Supercapacitors

A number of new supercapacitor devices have been tested in the laboratory at the University of California-Davis (6, 7). These devices include carbon/carbon devices from Estonia (Skeleton Technologies) and Ukraine (Yunasko) and hybrid devices from Ukraine (Yunasko) and Japan (JSR Micro). As indicated in Tables 1, the carbon/carbon device from Skeleton Technology (Figure 3) has high power capability with no sacrifice in energy density. In fact, the Skeleton Technology device has the highest energy density (9 Wh/kg) of any carbon/carbon device tested at UC Davis. This is due to improved carbon (higher specific capacitance) and an increase in the rated voltage from 2.7V to 3.4V resulting from the use of an improved organic electrolyte.

The JSR Microdevices (Figure 4) utilize a graphitic carbon in the negative and an activated carbon in the positive. Such devices are often referred to as lithium capacitors (LiC). Lithium ions are intercalated into the negative and stored in the double-layer at the positive electrode. The voltage of the LiC varies between 3.8V and 2.2V. The characteristics of the JSR Micro devices (1100F and 2300F) are given in Tables 2 and 3. When packaged in a laminated pouch, the energy densities of the devices are about 10 Wh/kg and 19 Wh/L. When packaged in rigid, plastic case as shown in Figure 1 for the 2300F device, the energy densities are 7.5 Wh/kg and 13 Wh/L. The laminated pouch power densities are 2400 Wh/kg and 4500 W/L for 95% efficient pulses. Both values are high values, especially for hybrid ultracapacitors.

The Yunasko 5000F hybrid device (Figure 3) utilizes carbon and a metal oxide in both electrodes. Different metal oxides are used in the two electrodes and the percentages of the metal oxides are relatively small. Test results for the device are given in Table 3. The voltage range of the device is 2.7 - 1.35V. The energy density is 30 Wh/kg for constant power discharges up to 4 kW/kg. The device has a low resistance and consequently a high power capability of 3.1 kW/kg, 6.1 kW/L for 95% efficient pulses.

Figure 3: Photograph of the 3200F Skeleton Technologies device

Table 1: Test data for the Skeleton Technologies 3200F device

Device characteristics:
Packaged weight 400 gm
Packaged volume 284cm3

Constant current discharge data

Current A	Time sec	Capacitance F	Resistance mOhm Steady-state R	RC sec
50	107.7	3205		
100	52.7	3175		
200	25.5	3178	.475	1.51
300	16.5	3173	.467	1.48
350	14	3202	.485	1.55
400	12	3168	.468	1.48

Discharge 3.4V to 1.7V
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
106	265	123.1	3.62	9.05	12.8
201	503	64.9	3.62	9.05	12.8
301	753	42.4	3.55	8.88	12.5
400	1000	31.1	3.46	8.65	12.2
500	1250	24.3	3.38	8.45	11.9
600	1500	19.8	3.3	8.25	11.6

Pulse power at 95% efficiency
$P = 9/16\ (1\text{- eff})\ V_R^2/R_{ss}$, $(W/kg)_{95\%} = 1730$, $(W/L)_{95\%} = 2436$
Matched impedance power
$P = V_R^2 / 4\ R_{ss}$, (W/kg) = 15,400

Figure 4: Photographs of the JSR Micro 1100F and 2300F devices

Table 2: Characteristics of the JSR Micro 1100F ultracap 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

Figure 5: Photograph of the 5000F Yunasko Hybrid ultracapacitor 5000F device

Table 3: Characteristics of the Yunasko hybrid supercapacitor

Constant current

	2.7-2.0V				2.7-1.35		
Current A	Time sec	Ah	Resistance short time mOhm		Time sec	Ah	Capacit. F
50	83.7	1.16			88.9	1.25	3556
100	36.1	1.0	1.53		44.9	1.25	3870
150	25.1	1.05	1.59		29.5	1.23	4060
200	7.1	.39			21.1	1.17	3801
250	4.1	.28			15.2	1.06	4130

Constant power

		2.7-2.0V				2.7-1.35		
Power W	W/kg	Time sec	Wh	Wh/kg		Time sec	Wh	Wh/kg
55	743	164	2.5	33.8		172	2.63	35.5
155	2094	58.1	2.5	33.8		62.8	2.7	36.5
252	3405	23.8	1.66	22.4		35.4	2.42	32.7
303	4095	16.6	1.4	18.9		28.3	2.38	32.2
350	4730	11.9	1.16	15.7		22.4	2.18	29.5
400	5405	8.3	.92	12.4		17.3	1.92	25.9
500	6756	4.3	.60	8.1		10.8	1.5	20.3

Weight 74 g, volume 38 cm3 pouch packaged
Pulse efficiency 95%

$P= .95x.05\ V^2/R = .95x.05x\ (2.7)^2/.0015 = 231$

$(W/kg)_{95\%} = 3120$, $(W/L)_{95\%} = 6078$

A summary of the characteristics of the various supercapacitors tested at UC Davis are given in Table 4. Except for the devices from Skeleton Technologies and Yunasko, all the devices listed in the table are commercially available. Most of the commercial carbon/carbon devices have an energy density of 4-5 Wh/kg and a power capability of 1000 W/kg for 95% efficient pulses. The high power capability of the hybrid devices indicates that their increased energy density can be fully exploited in applications such as hybrid vehicles in which the device would be sized by the energy storage requirement.

Table 4: Summary of supercapacitor device characteristics

Device	V rate	C (F)	R (mOhm) (3)	RC sec	Wh/kg (1)	W/kg (95%) (2)	W/kg Match. Imped.	Wgt. (kg)	Vol. lit.
Maxwell	2.7	2885	.375	1.1	4.2	994	8836	.55	.414
Maxwell	2.7	605	.90	.55	2.35	1139	9597	.20	.211
Vinatech	2.7	336	3.5	1.2	4.5	1085	9656	.054	.057
Vinatech	3.0	342	6.6	2.25	5.6	710	6321	.054	.057
Ioxus	2.7	3000	.45	1.4	4.0	828	7364	.55	.49
Ioxus	2.7	2000	.54	1.1	4.0	923	8210	.37	.346
Skeleton Technol.	3.4	3200	.47	1.5	9.0	1730	15400	.40	.284
Skeleton Technol.	3.4	850	.8	.68	6.9	2796	24879	.145	.097
Yunasko*	2.7	510	.9	.46	5.0	2919	25962	.078	.055
Yunasko*	2.75	480	.25	.12	4.45	10241	91115	.060	.044
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	5200	1.5	7.8	30	3395	30200	.068	.038
Ness	2.7	1800	.55	1.0	3.6	975	8674	.38	.277
Ness	2.7	3640	.30	1.1	4.2	928	8010	.65	.514
Ness (cyl.)	2.7	3160	.4	1.3	4.4	982	8728	.522	.379
LS Cable	2.8	3200	.25	.80	3.7	1400	12400	.63	.47
BatScap	2.7	2680	.20	.54	4.2	2050	18225	.50	.572
JSR Micro (graphitic carbon/ AC) *	3.8	1100 2300 (plast. case)	1.15 .77	1.21 1.6	10 7.6	2450 1366	21880 12200	..144 .387	.077 .214

(1) Energy density at 400 W/kg constant power, Vrated - 1/2 Vrated

(2) Power based on P=9/16*(1-EF)*V2/R, EF=efficiency of discharge

(3) Steady-state resistance including pore resistance

* All devices except those with * are packaged in metal/plastic containers: those with * are laminated pouched packaged

IV. Simulation Results for Selected Applications

Vehicle applications of supercapacitors (electrochemical capacitors) have been discussed in the literature for many years beginning in the late 1980s [8]. These applications have been quite slow in materializing. However, at the present time there are a few of applications that have been commercialized. These include hybrid-electric transit buses in the United States and China [9, 10], electric braking systems in passenger cars [11], and recently in stop-go hybrid vehicles [12, 13]. This latter application is the first one that is potentially a mass market application in the world-wide auto industry. There are several potential future applications that are discussed later in this report which could be large scale opportunities for supercapacitors. These future applications include plug-in hybrids, battery electric vehicles using advanced, high energy density batteries, and hybridized fuel cell vehicles. All these applications will be considered in the next section in which simulations of vehicles utilizing supercapacitors in their electrified drivelines are discussed.

In this section, simulation results are presented for a number of electric and hybrid vehicles that utilize electric motors in their driveline. All of these applications have the need for electric energy storage on board the vehicle which can be recharged from an engine driven generator and/or regenerative braking and/or from the grid/wall-plug. In all cases, the energy storage unit could be either a battery or supercapacitor. In this section, the use of supercapacitors will be considered and in the next section comparisons will be made with systems using lithium batteries. The supercapacitors will be sized to meet the energy storage requirement (Wh or kWh) of the applications taking into account the capability of supercapacitors to use a large fraction of the energy stored with long cycle life (> 500,000 for most supercapacitor technologies). In addition, the supercapacitors can provide high power for both charge and discharge over their complete range of SOC (at least down to 75% depth of discharge on an energy basis). Batteries, on the other hand, can provide their maximum power only in short pulses (5-10 seconds) and only over a limited range of state-of-charge. In order to attain cycle life comparable to supercapacitors, the usable change in the SOC of the battery is usually less than 10%. Further to achieve power capability (W/L) even close to some commercial supercapacitors, but not the highest power proto-type supercapacitors, the energy density of the battery will have to be compromised. Hence comparing supercapacitors and batteries for a particular application is not a simple matter.

The various potential applications are considered separately in the following sections. All the simulations have been run using the **Advisor** vehicle simulation program modified with special routines at UC Davis [14-18].

Stop-Go Hybrids

In this application, the engine is turned off and on when the vehicle stops and the accessory loads are met from the electric energy storage. The energy storage is recharged from regenerative braking and from an engine powered alternator or generator. In more advanced systems, the motor/generator can assist the engine during vehicle accelerations in addition to starting the engine at each stop. The electric motor/generator is small being less than 5 kW. In this application, the supercapacator can be used in combination with a lead-acid battery. The main use of the battery is to provide accessory loads when the time period of the stop is longer than can be sustained with the supercapacitor unit (ex. >60sec). This time can be extended by using larger supercapacitor units. This application was studied in [19-21]. These studies indicated that a supercapacitor unit storing 10-25 Wh would be sufficient for the stop-go application without motor assist during accelerations and up to about 50 Wh with motor assist capability. There seems little doubt that the cycle life of the supercapacitors can be that of the vehicle; however, the cycle life of the lead acid battery is still uncertain and is strongly dependent on its design/type, electrolyte, and separator [22, 23].

Table 5: Summary of Advisor results for the 2001 Honda Insight

Vehicle configuration *	mpg FUDS cycle	mpg Highway cycle
Conventional ICE	42.7	56
Insight		
NREL default	55	75.2
Micro-HEV**		
Caps-LA bat, 4 kw EM	59.7	75.9
Caps-LA bat, 1 kw EM	53.8	73
Mild-HEV		
NMH bat, 10 kW EM	77	83.6
Ultracaps, 10 kW EM	77.7	83.9

*Insight C_D =.25, A_F=1.9m^2 , W=1036 kg, CVT, 50 kW 3 cyl. Engine

** Carbon/carbon supercapacitors, 20 Wh, 5 kg (cells)

Table 6: Mild-HEV and Micro-HEV Advisor simulation results using carbon/carbon and hybrid supercapacitors

Mid-size passenger car: weight 1660 kg, C_d .3, A_f 2.2 m2, fr .009

Energy storage system	Weight of the ultracaps (kg)*	Energy stored	mpg FUDS	mpg FEDHW	mpg US06
Mild HEV 20 kW motor					
Yunasko hybrid	12 6	300 Wh 150 Wh	47.4 45.3	46.5 46.0	32.2 31.6
JM Energy hybrid	11	100 Wh	47.8	47.2	31.9
Yunasko C/C	22	100 Wh	46.0	46.4	31.6
Maxwell C/C	28	100Wh	47.2	47.5	32.2
Skeleton 2014 C/C 3200F	13	115	47.8	47.0	31.9
High power LiTiO battery	14	1120	40.6	40.3	30.5
ICE Ford Focus engine 120 kW			25.5	36.8	26.8
Fuel economy improvement			80%	27%	19%
Micro start stop HEV	Supercap. with a lead- acid battery, 4 kW electric motor				
Yunasko hybrid	5 kg 3 kg	150 Wh 75 Wh	32.4 32.1	41.4 41.2	28.9 28.5
Yunasko C/C	11 kg	50Wh	32.2	41.2	28.6
Maxwell C/C	12 kg	50 Wh	32.3	41.3	28.3
Skeleton C/C 3200F	5	50Wh	33.1	40.2	28.0
Fuel economy improvement			26%	12%	7%

*weight of cells only without packaging in a pack

Simulations have been run for both subcompact and mid-size passenger cars [24, 25]. The results are shown in Tables 5 and 6. The results of the simulations for the subcompact micro-hybrid with power assist shown in Table 5 indicate that fuel economy improvements of up to 35% can be attained for urban driving using small supercapacitor units with electric motors of less than 5kW. The improvements are smaller, but still significant for highway driving. Results for a mid-size car are given in Table 6. The fuel economy improvements using a 4 kW electric motor are smaller than for the sub-compact, but still 26% for city driving and 12% on the highway. The supercapacitor unit using commercially available Maxwell capacitors weighed about 12 kg and stored 50Wh of energy. The simulation results for both the subcompact and mid-size cars indicate the supercapacitors should work well in micro-hybrids and that even with power assist the capacitor unit and electric motor can be of small size. The round-trip efficiency of the capacitor units are greater than 95% for all the cases.

Charge Sustaining Mild Hybrids

Supercapacitors can be used alone in place of batteries in mild charge sustaining hybrid vehicles. As shown in [26, 27], this can be done by operating the hybrid vehicle on the electric drive only when the power demand is less than the power capability of the electric motor; when the vehicle power demand exceeds that of the electric motor, the engine is operated to meet the vehicle power demand plus to provide the power to recharge the supercapacitor unit. In this mode, the electric machine is used as a generator and the engine operating point is near its maximum efficiency line (torque vs. RPM). The recharging power is limited by the power of the electric machine because most superacapacitors have a pulse power efficiency greater than 95% for W/kg values of 1-2.5 kW/kg (see Table 4). This control strategy is intended to keep the engine from operating in the low efficiency part of the Torque, RPM map. As indicated in Figure 6, the size (kW) of the electric motor can be relatively small even for large passenger cars using V-8 engines.

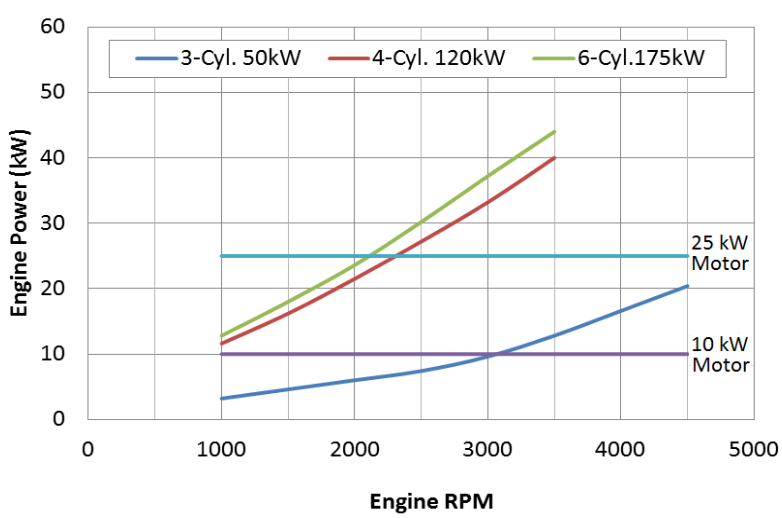

Figure 6: Minimum engine power for efficiency operation for various size engines

Simulations of mid-size passenger cars using supercapacitors in mild charge sustaining hybrid powertrains are given in Table 6 (top part). The simulations were performed using the **Advisor** vehicle simulation program modified with special routines at UC Davis [14-16]. The engine map used in the simulations was for a Ford Focus 2L, 4-cylinder engine. The engine rated power was 125 kW for both the conventional ICE vehicle and the hybrids. Special attention in the simulations was on the use of the advanced ultracapacitors whose characteristics were given in Tables 1-3. All the hybrids use the single-shaft arrangement similar to the Honda Civic hybrid. The same permanent-magnetic AC electric motor map (Honda Civic) was used in all the hybrid vehicle designs. The energy storage capacity of the supercapacitor unit was varied between 100-300Wh depending on the energy density of the cells.

The fuel economy simulation results are given for hybrids using carbon/carbon and advanced ultracapacitors. The influence of the supercap technology and the size (Wh) of the energy storage unit on the fuel economy improvement was of particular interest. The fuel economy improvements range from over 70% on the FUDS to about 20% on the US06 driving cycle, but the effect of supercapacitor size and technology on the improvement was small. The prime advantage of the larger energy storage (Wh) feasible with the higher energy density supercapacitors is that the larger fuel economy improvements can be sustained over a wide range of driving conditions. All the advanced supercapacitors have high power capability and thus can be used with the high power electric motor used in charge sustaining hybrid drivelines. Thus the advanced supercapacitor technologies give the vehicle designer more latitude in powertrain design and in the selection of the control strategies for on/off operation of the engine. Also shown in Table 6 are simulation results for a mild hybrid using a high power lithium titanate oxide (LTO) battery. The fuel economies for the vehicle using the battery are all lower than those using the supercapacitors primarily because the round-trip efficiency with the capacitors was higher than with the batteries. For example, for the FUDS cycle the efficiency was 98% with the capacitors and 91% with the lithium battery.

Hybrid Transit Buses

Table 7: Inputs for the China hybrid transit bus simulations

Vehicle parameter	
Test weight (kg)	16000
Drag coefficient C_D	.65
Frontal area (m^2)	8.0
Rolling resistance (kg/kg)	.008
Wheel radius (m)	.495
Overall gear ratio	16
Electric motor (kW)	150
Generator (kW)	125
Supercapacitors	400-800 Wh useable
Engine power (kW) Natural gas	135

Simulations were also run for hybrid transit buses operating in China [10] using supercapacitors. The packs in the buses use 3000 F carbon/carbon cells from Maxwell Technologies. The inputs for the simulations are shown in Table 7 and the results are given in Table 8. Note that the hybrid buses used a series arrangement which is common for transit buses.

The simulation results indicate the hybrid transit buses should function well using commercial supercapacitors and show fuel economy improvements of 30-50% on most city driving cycles using natural gas engines. The fuel economy improvement is much higher (200-300 %) for very low speed driving cycles with frequent stops. The energy consumption of the hybrid buses is much higher with air conditioning in operation and the fuel economy improvement is significantly decreased.

Table 8: Fuel economy of hybrid transit buses using supercapacitors for energy storage

Vehicle configuration (1)	Driving cycle	Natural gas engine hybrid	Fuel economy improvement factor (4)
Series hybrid/ carbon/carbon capacitors *		Wo/W AC (2), (3)	Wo/W AC (2), (3)
	NY CC	4.0/2.6	1.54/1.24
	NY GTC	4.6/1.5	3.07/1.36
	NY Manhattan	4.2	1.56
	WV city	5.4/3.4	1.46/1.17
	CBD	5.3	1.33
	EPA-transient	6.0/4.5	1.25/1.15
	WVsub	5.7	1.14
Natural gas engine/ transmission		mpg Gasoline equiv. w/o AC (2)	mpg Gasoline equiv. with AC (3)
	NY CC	2.6	2.1
	NY GTC	1.5	1.1
	NY Manhattan	2.7	
	WV city	3.7	2.9
	CBD	4.0	
	EPA-transient	4.8	3.9
	WVsub	5.0	

(1) 400-800 Wh useable energy in the carbon/carbon supercapacitors, 125 kW generator, 150 kW electric motor, 135 kW engine
(2) Accessory load 1.1 kW without air-conditioning (w/o AC)
(3) Accessory load 12 kW with air-conditioning (with AC)
(4) Gasoline equivalent fuel economy mpg

Fuel Cell Vehicles

Simulations were performed for fuel cell vehicles using supercapacitors. The special simulation program that was developed at UC Davis is described in detail in [17, 18]. The application of the program to assess fuel cell operation with battery and supercapacitor energy storage can be found in [28]. A particular question that will be discussed in this report is how supercapacitors can be best utilized in fuel cell vehicles. The simplest approach is to connect the supercapacitor unit directly to the fuel cell without electronics. A second approach is to place electronics between the supercapacitors and the fuel cell to match the voltage of the supercapacitors and the fuel cell as the power from the fuel cell is controlled according to a prescribed control strategy. Two strategies were employed – (1) the fuel cell was load leveled with the supercaps providing the peak power demand, (2) the fuel cell provided all the power up to a set level and the supercaps assisted when the power demand was higher than the set maximum level. Commercially available carbon/carbon supercapacitors were used in the simulations along with high efficiency DC/DC electronics. The vehicle inputs for the simulations are given in Table 9.

Table 9: Vehicle simulation parameters

Vehicle and System Parameters	
Drag Coefficient	0.3
Frontal Area (m2)	2.2
Rolling Resistance	0.01
Vehicle Hotel Load (kW)	0.3
Vehicle Mass without energy storage (kg) *	1500
Electric Motor (kW)	75
Fuel Cell Stack and Auxiliaries	
Max. Net Power (kW)	87.6
Gross Power (kW)	106
Number of Cells	440
Cell Area (cm2)	510
Compressor (kW)	17.2
Energy Storage units	
Supercapacitor capacity (Wh)	100
Supercapacitor pack voltage	432
LiTiO battery Capacity (kWh)	1.5
LiTiO battery voltage	405

The results of the simulations are shown in Table 10 for the FUDS and USO6 driving cycles. Results are shown for supercapacitors and for a LiTiO power battery. In all cases, the use of energy storage improves the gasoline equivalent fuel economy. The various cases are compared in terms of a fuel economy improvement factor using the fuel cell vehicle without energy storage as the baseline. Fuel economy improvements up to 25% were attained with the most efficient arrangement being the supercapacitor unit connected directly to the fuel cell without electronics. This arrangement yielded an improvement of 25% on the FUDS cycle and 18% on the US06 cycle. Most of this improvement in fuel economy is due to energy recovery from regenerative braking which becomes possible with any of the energy storage units. The most efficient of the fuel cell power control approaches was the power assist strategy with the supercapacitors, but using the power assist strategy and electronics, the fuel economies with the supercapacitors were only about 1% better than with the batteries; however, the direct connection case of the supercapacitors was 5-8% better than the battery case with electronics. The comparisons between using supercapacitors or batteries with fuel cells are dependent on the characteristics of the batteries and supercapacitors available and the efficiency of the DC/DC electronics. Hence it is reasonable to conclude that either supercapacitors or high power batteries can be used with fuel cells and the effect on fuel economy would be not significantly different.

Table 10: Comparisons of the fuel economies of fuel cell vehicles using supercapacitors and batteries with and without electronics

Vehicle Topology	Drive Cycle	Fuel Economy / Improvement Factor	
		Power Assist	Load Leveling
FC-Battery Hybrid with 1500 Wh Battery and Power Electronics	FUDS	78.6 / 1.16	72.8 / 1.07
	US06	56.6 / 1.12	51.9 / 1.02
FC-UC Hybrid with 100 Wh UC and Power Electronics	FUDS	79.2 / 1.16	78.8 / 1.16
	US06	57.3 / 1.13	55.0 / 1.08
FC-UC Hybrid with 100 Wh UC and without Power Electronics	FUDS	85.0 / 1.25	
	US06	59.6 / 1.18	
FCV without Energy Storage	FUDS	68.0 / ----	
	US06	50.7 / ----	

Plug-in Electric Vehicles (PEVs) Using Advanced High Energy Density Batteries

It seems likely that high power energy storage will be needed to supplement the capabilities of advanced high energy densities batteries, such as metal air and lithium sulfur, being developed [29, 30]. These batteries can have very high energy density (> 500 Wh/kg), but will likely have only modest power density especially for regenerative braking. The problem likely will be the cathode of those batteries – particularly the air cathode.

For plug-in hybrid vehicles (PHEV), supercapacitors can be used in combination with batteries if the power capability of the batteries is insufficient to meet the power requirement of the vehicle. The control strategy in the charge depleting mode is to limit the power from the battery to the average power needed by the vehicle with the supercapacitor providing the additional power during vehicle accelerations. The supercapacitors also accept all the energy recovered during regenerative braking. If engine operation is needed, the strategy is to recharge the supercapacitors using engine power. In the charge sustaining mode of operation of the PHEV, the electric drive is operated using only the supercapacitors as previously described for the HEVs.

A detailed study of plug-in hybrids using advanced batteries is presented in [31, 32]. The characteristics of the advanced batteries used in the simulations are given in Table 11. The simulation results are summarized in Tables 12 and 13 showing results for the charge depleting and charge sustaining modes of the PHEV.

Table 11: Characteristics of present and future battery cell technologies for EVs and PHEVs

Chemistry Anode/cathode	Cell voltage Max/nom.	Ah	Wgt. kg	R mOhm	EV Wh/kg	HEV W/kg 95%	EV W/kg 75%	Cycle life (deep)	Thermal stability
Present technology batteries									
Graphite/ $NiCoMnO_2$	4.2/3.6	30	.787	1.5	140	521	2060	2000-3000	fairly stable
Graphite/ Mn spinel	4.0/3.6	15	.424	2.7	127	540	2120	1500	fairly stable
Future technology batteries									
Graphite/ composite MnO_2	4/3.6	5	.09	20	200	250	1350	----	fairly stable
Silicon carbon composites/ composite MnO_2	4/3.6	20	.24	4.5	295	621	2250	---	fairly stable
Rechargeable Zinc-Air	1.3/1.15	20	60	6.6	385	156	616	----	very stable
Present Technology Power devices									
supercapacitor Activated carbon/activated carbon	2.7/1.35	500F	.068	1.3	5.5	2320	11600	500K	Very stable
Power battery Lithium titanate oxide	2.8/2.5	4	.23	1.15	40	1310	5170	20-50 K	Very stable

Table 12: Simulation results for the advanced batteries with supercapacitors

Battery Type (1)	cycle	Range mi.	kW max. control	kW max bat.	Eff. Bat.	kW max. Cap.	Eff. Cap.	Wh/mi Bat.	Operat. mode	mpg 20mi	mpg 40mi	Chg. Sust. HEV mpg
Compos. MnO2	FUD	22	40	18	.94	40	.97	215	AE	none	97	52.8
32kgbat	HW	20	45	18	.91	45	.96	227	AE	none	109	56.3
20kgcap	US06	30	68	21	.91	68	.94	180	blended	71.9	56	38.3
Si Carb/ Compos. MnO2	FUD	20	40	18	.94	40	.97	220	AE	none	99	52.8
22kgbat	HW	20	45	19	.91	45	.97	225	AE	none	110	56.8
20kgcap	US06	30	68	21	.91	68	.94	190	blended	71.1	52	38.4
Rech. Zn-air	FUD	40	45	19	.87	45	.97	228	AE	none	none	54.5
32kgbat	HW	38	45	19	.81	45	.97	242	AE	none	none	57.7
20kgcap	US06	66	68	21	.82	68	94	149	blended	62.4	60	38.8

(1) weight of cells only

Table 13: Simulation results for the batteries alone

Battery Type (1)	cycle	Range mi.	kW max. control.	kW max. bat.	Eff. Bat.	Wh/mi Bat.	Operat. mode	mpg 20mi.	mpg 40mi	mpg Chg. sust. HEV
NiCoMn	FUD	27	30	30	.94	125	blended	134	85	47
30 kg	HW	24	20	20	.93	137	blended	110	87	47
	US06	57	58	58	.88		blended	48	45	37
Compos. MnO2	FUD	36	30	30	.92	135	blended	134	104	46.9
32kgbat	HW	31	20	20	.91	147	blended	167	113	46.6
	US06	64	58	58	.87	92	blended	48	48	34.1
Si Carb/ Compos. MnO2	FUD	35	30	30	.93	138	blended	138	106	46.9
22kgbat	HW	32	20	20	.92	148	blended	169	114	46.9
	US06	64	58	58	.88	87	blended	48	48	35.7
Rech. Zn-air	FUD	66	30	30	.84	139	blended	139	137	39.4
32kgbat	HW	63	20	20	.83	156	blended	169	169	41.1
	US06	93	36	36	.72	101	blended	48.5	48.5	30.1

(1) weight of cells only

With the batteries in combination with the supercapacitors, the PHEVs were able to operate in the all-electric mode until the battery SOC=30% on the FUDS and HW highway driving cycles. In all cases for the US06 driving cycle, the vehicle had blended operation (engine and electric drive both needed) in the charge depleting mode. The use of the supercapacitors with the batteries permits all-electric operation of the vehicle over a wide range of driving conditions with higher Wh/mi for all the driving cycles. Hence in the charge depleting mode, the fuel economy (mpg) is higher by 50-100% using the supercapacitors for all the batteries. The fuel economy in the charge sustaining mode is also higher for all the driving cycles using the supercapacitors, but only by 15-40% in most cases. The acceleration times of the vehicle were lower using the supercapacitors than for the batteries alone. With the supercapacitors, the acceleration times were 2.7 sec for 0-30 mph and 6.9 sec for 0-60 mph. For the batteries alone, the acceleration times varied somewhat with the battery used ranging from 2.9-3.2 sec for 0-30 mph and 8.6-9.8 sec for 0-60 mph. Hence in all respects, vehicle performance was improved using the supercapacitors for all the batteries studied.

The effects of the load leveling of the power demand from the batteries using the ultracapacitors are that both the average currents and the peak currents from the batteries are lower by a factor of 2-3. The minimum voltages of the batteries are significantly higher using the capacitors and the voltage dynamics (fluctuations) are dramatically reduced. Hence the stress on the battery and resultant heating are much reduced. The simulation results also show that the supercapacitors are utilized over a wide voltage range indicating that a large fraction of their usable energy storage (100 Wh) is being used to load level the batteries. This is only possible using a DC/DC converter between the battery and the DC- bus.

In summary, the simulation results indicate that using supercapacitors, batteries with a wide range of power characteristics can be used in PHEVs and also EVs without sacrificing vehicle performance and subjecting the batteries to high stress and resultant shorter cycle life. This could be especially important in the future as high energy density batteries such as Zinc-air and possibly lithium-air are developed. It is likely that those battery types will not have commensurate increases in useable power density and without supercapacitors, the battery unit in PHEVs and EVs would be sized by the maximum power requirement (kW) rather than the range (mi)/energy requirement (kWh). This would significantly increase weight, volume, and the cost of the battery unit. It is also unlikely that the air electrode will have charge acceptance capability and thus regenerative braking performance approaching that of supercapacitors or even lithium-ion batteries. This is another advantage of the use of supercapacitors with the air-electrode batteries.

V. Lithium Batteries vs. Supercapacitors as High Power Energy Storage

In most electrified vehicle applications, the powertrain designer has the choice between lithium batteries and supercapacitors for high power energy storage. At the present time (2014), the designers in most cases select lithium batteries because of their higher energy density and lower cost. As a result of this choice the designers have to over-size the battery to attain the required power and cycle life and also have to tolerate reduced efficiency of the vehicle compared to what it would have been using supercapacitors. In this section of the report, these design compromises will be considered in detail.

The examples selected for discussion are the group of light-duty vehicles shown in Table 14 powered by mild hybrid and fuel cell drivelines. The energy storage unit in each vehicle could be either a lithium battery or a carbon/carbon supercapacitor. Note in Table 14 that the energy stored in the supercapacitor is in most cases less than 10% of the energy stored in the battery. Nevertheless, both the battery and the supercapacitors must provide the power required by the electric motor. This is not a problem for the mild hybrid vehicles in which the electric motors are relatively low power, but it is not reasonable to expect the battery alone to meet the maximum power required by the large motors in the fuel cell vehicles. As noted in Table 14, it has been assumed that the fuel cell will provide half the electric power to the motors in those vehicles when maximum power is demanded. This approach seemed better than doubling the size (kWh) of the batteries to meet the maximum power requirement. Also shown in Table 14 is the power density and corresponding efficiency at peak power for the battery and supercapacitor. In all cases the efficiency of the supercapacitor is higher than that of the battery which will be reflected in the energy efficiency of the vehicle.

Simulations were performed for the vehicles listed in Table 14. The battery used in the simulations was scaled from the 4 Ah lithium titanate oxide (LTO) cell developed by Altairnano [33]. This cell, which was designed to have high power capability, has an energy density of 35 Wh/kg and 95% efficient power density of 1305 W/kg. This power capability is comparable to that of commercially available carbon/carbon supercapacitors. The supercapacitor used in the simulations was a prototype cell from Yunasko [34]. This cell had an energy density of 4.5 Wh/kg and a 95% efficient pulse power capability of about 8000 W/kg. As indicated in Table 15, the fuel economies calculated for the various vehicles with the supercapacitor energy storage were only 3-5% higher than with the high power LTO battery technology. The efficiency of both energy storage units was high (95-98%) for all the runs on the FUDS and HW cycles. The high efficiency on the driving cycles resulted because the occasional peak power on the cycles was only about one-half the peak power of the electric motors.

Table 14: Efficiencies of lithium batteries and carbon/carbon supercapacitors at peak power demand conditions

Mild hybrid vehicles

Vehicle type	Eng. Pow kW	Electric motor kW	Battery kWh	battery kW/kg (1)	Battery efficiency	Supercap Wh	Supercap kW/kg (2)	Super cap efficiency
Compact	97	15	1.0	1.4	94	75	.9	97.5
Mid-size	125	25	1.5	1.5	93.5	100	1.1	97
Full-size	160	50	2.0	2.3	90	100	2.3	96
Small SUV	140	25	1.5	1.5	93.5	100	1.1	97
Mid-size SUV	150	40	2.0	1.8	92	150	1.2	97
Delivery truck	200	50	3.0	1.5	93.5	200	1.1	97

Fuel cell vehicles

Vehicle type	Fuel cell kW	Electric motor kW	Battery kWh	Battery kW/kg (1), (3)	Battery efficiency (3)	Supercap Wh (4)	Supercap kW/kg (2)	Super cap efficiency
Compact	60	95	1.0	8.6	78.5	75	5.7	90
Mid-size	75	110	1.5	6.6	84	100	5.0	91.5
Full-size	100	140	2.5	5.0	89	100	6.3	88.5
Small SUV	85	120	1.5	7.2	82.5	100	5.4	91
Mid-size SUV	100	125	2.0	5.6	86	150	3.8	93.5
Delivery truck	125	200	4.0	4.5	90	200	4.5	92

(1) Energy density of the battery is 90 Wh/kg based on the weight of cells, $(W/kg)_{95\%}$ = 1200
(2) Energy density of supercap is 4.5 Wh/kg based on cell weight, $(W/kg)_{95\%}$ = 3000
(3) fuel cell provides 50% of peak power

Table 15: Comparisons of the fuel economy of mild hybrid and fuel cell vehicles using supercapacitors and high power lithium batteries Mild hybrid vehicles

Vehicle Type	Eng. Pow kW	Electric motor kW	Supercap. mpg (1)	Batteries mpg (2)
Compact	97	15	47.4/49.8	45/47.7
Mid-size	125	25	41.1/44.2	40.3/43.1
Full-size	160	50	38.1/43.5	38.5/42.0
Small SUV	140	25	39.1/43.0	37.8/42.1
Mid-size SUV	150	40	36.2/39.5	34.3/38.4
Delivery truck	200	50	12.2/10.7	11.8/10.7

Fuel cell vehicles

Vehicle type	Fuel cell kW	Electric motor kW	Battery kWh	Supercap. mpg gasol. Equiv (3)	Batteries mpg gasol. Equiv (3)
Compact	60	95	1.0	83.8/79	80.3/78.1
Mid-size	75	110	1.5	78.4/71.9	73.5/70.6
Full-size	100	140	2.5	67.4/64.2	64.5/63.5
Small SUV	85	120	1.5	72.7/70.4	70.9/71.4
Mid-size SUV	100	125	2.0	65/61.6	61.5/61.2
Delivery truck	125	200	4.0	19.6/15.7	18.8/16.1

(1) Carbon/carbon supercapacitor 1200 F from Yunasko
(2) LiTiO battery from Altairnano 3.8 Ah
(3) mpg FUDS cycle/ mpg Highway cycle

Mild hybrid vehicles

Vehicle type	Eng. Pow. kW	Electric motor kW	Supercap. mpg (1)	Batteries mpg (2)
Compact	97	15	47.4/49.8	45/47.7
Mid-size	125	25	41.1/44.2	40.3/43.1
Full-size	160	50	38.1/43.5	38.5/42.0
Small SUV	140	25	39.1/43.0	37.8/42.1
Mid-size SUV	150	40	36.2/39.5	34.3/38.4
Delivery truck	200	50	12.2/10.7	11.8/10.7

Fuel cell vehicles

Vehicle type	Fuel cell kW	Electric motor kW	Battery kWh	Supercap. mpg gasol. Equiv (3)	Batteries mpg gasol. Equiv (3)
Compact	60	95	1.0	83.8/79	80.3/78.1
Mid-size	75	110	1.5	78.4/71.9	73.5/70.6
Full-size	100	140	2.5	67.4/64.2	64.5/63.5
Small SUV	85	120	1.5	72.7/70.4	70.9/71.4
Mid-size SUV	100	125	2.0	65/61.6	61.5/61.2
Delivery truck	125	200	4.0	19.6/15.7	18.8/16.1

(1) Carbon/carbon supercapacitor 1200 F from Yunasko
(2) LiTiO battery from Altairnano 3.8 Ah
(3) mpg FUDS cycle/ mpg Highway cycle

Further mild hybrid simulations showed that using the commercially available Maxwell supercapacitors which have a 95%efficient power capability of 1000 W/kg reduced the FUDS fuel economy by only 5%, but utilizing high energy density lithium batteries with 95% efficient power capability of 600-700 W/kg reduced the fuel economy by 20-25%. The efficiency of those batteries on the FUDS cycle was only 76% rather than 96% for the LTO battery technology. Hence to compete with supercapacitors in hybrid vehicles, special high power lithium batteries are needed and those batteries will be more expensive than the high energy density lithium batteries and be larger because of their lower energy density.

VI. Cost Considerations

Supercapacitors can not compete with batteries in terms of $/Wh, but they can compete in terms of $/kW and $/unit to satisfy a particular vehicle application. Both energy storage technologies must provide the same power and cycle life and sufficient energy (Wh) for the application. The weight of the battery is usually set by the system power requirement and cycle life and not the minimum energy storage requirement. Satisfying only the minimum energy storage requirement would result in a much smaller, lighter battery than is needed to meet the other requirements. On the other hand, the weight of the supercapacitor is determined by the minimum energy storage requirement. The power and cycle life requirements are usually easily satisfied. Hence the unit can be a more optimum solution for many applications and its weight can be less than that of the battery even though its energy density is less than one-tenth that of the battery.

Consider the example of a charge sustaining hybrid like the Prius. If the energy stored in the capacitor unit is 125 Wh and that in the battery unit is 1500 Wh, the unit costs[1] of the capacitors and battery are related by

$$(\$/\text{Wh})_{cap} = .012\ (\$/\text{kWh})_{bat}$$

The corresponding capacitor costs in terms of cents/Farad and $/kWh are given by

$$(\text{cents/F})_{cap} = .125 * 10^{-3} * (\$/\text{kWh})_{bat} * V_{cap}^{\ 2}$$

$$(\$/\text{kWh})_{cap} = 9.6 * 10^{4}\ (\text{cents/F})_{cap} / V_r^2$$

The evaluation of the above equations for a range of battery costs is shown in Table 18.

Table 16: Relationships between supercapacitor and battery unit costs resulting in the same energy storage pack cost

Battery cost $/kWh	Battery cost* $/kW	Ultracap cost cents/F V_{cap} =2.6	Ultracap cost cents/F V_{cap} =3.0	Ultracap cost** $/kWh V_{cap} =3.0	Ultracap cost $/kW V_{cap} =3.0
300	30	.25	.34	3626	7.3
400	40	.34	.45	4800	9.6
500	50	.42	.56	5973	11.9
700	70	.59	.78	8320	16.6
900	90	.76	1.0	10667	21.3
1000	100	.84	1.12	11947	23.9

* battery 100 Wh/kg, 1000 W/kg; ** capacitor 5 Wh/kg, 2500 W/kg

The results shown in Table 18 indicate that for the charge sustaining hybrid application, supercapacitor costs of .5-1.0 cents/Farad are competitive with lithium battery costs in the range of $500-700/kWh. Note also that the $/kW costs of the capacitor unit are about one-fourth those of the batteries. The present price of supercapacitors is presently in the range of 1-2 cents/F, but with high volume productions and increases in energy density, the price of capacitors will continue to decrease. In addition, high power batteries, being more expensive than high energy density lithium batteries [35], are likely priced at $1000/kWh or higher. Hence in the near future, it is likely that supercapacitor energy storage units for hybrid vehicle applications can be cost competitive with lithium battery units.

VII. Summary and Conclusions

This report is concerned with supercapacitors (electrochemical capacitors) and their applications in electric drive vehicles in place of or in combination with batteries. The electric drive vehicles considered are hybrid vehicles (HEVs and PHEVs) and fuel cell vehicles. The first sections of this report deal with supercapacitor concepts and performance, including a description of the construction of devices and materials used in them and recent test data for commercial and proto-type devices. The data for the new carbon/carbon device from Skeleton Technologies showed an energy density of 9 Wh/kg and 95% efficient power capability of 1730 W/kg. Both of these characteristics are significantly better than those of commercially available devices. Test data are shown for a hybrid supercapacitor from Yunasko that has an energy density greater than 30 Wh/kg and a 95% efficient power capability of 3120 W/kg. This device has the best performance of any supercapacitor device tested at UC Davis to date.

Various vehicle applications of supercapacitors have been reviewed in detail. Simulation results are presented for light duty vehicles and transit buses using supercapacitors in place of lithium batteries in hybrid vehicles and in combination with advanced batteries in plug-in electric vehicles. It was found in all cases that the vehicles using the supercapacitors had the same as or better performance than those using batteries and in general were more efficient. Simulations were made using carbon/carbon and advanced hybrid supercapacitors. Sufficient energy could be stored in the carbon/carbon devices for all the vehicles to perform well with high efficiency on appropriate driving cycles indicating that for hybrid vehicles supercapacitors can be used in place of the lithium batteries currently being used. The higher energy density of the new hybrid devices permits more energy to be stored, but the effect of the larger energy storage on vehicle performance and efficiency is small. It is expected that the increased energy density will reduce the unit cost ($/Wh) of the devices and in addition, make vehicle designers more comfortable using supercapacitors than in the past. The simulation results for the fuel cell vehicles indicated that the use of supercapacitors would permit the use of energy storage units storing much less energy and having higher efficiency than using lithium batteries.

The cost of supercapacitors compared to lithium batteries was discussed briefly. It was shown that when one recognizes that the energy stored in the capacitors is less than 1/10 that in the batteries for hybrid applications, the price of supercapacitors needs to decrease to about .5- 1 cent/Farad for capacitors to be cost competitive with high power batteries at $500-700/kWh. In addition, there is a good possibility that the life of the capacitors would be equal to that of the hybrid vehicles.

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