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Abstract

This paper focuses on ultracapactors (electrochemical capacitors) as energy storage in vehicle applications and thus evaluates the present state-of-the-art of ultracapacitor technologies and their suitability for use in electric and hybrid drivelines of various types of vehicles. A key consideration in determining the applicability of ultracapacitors for a particular vehicle application is the proper assessment of the energy storage and power requirements. For hybrid-electric vehicles, the key issues are the useable energy requirement and the maximum pulse power at high efficiency. For a Prius size vehicle, if the useable energy storage is about 125 Wh and needed efficiency is 90-95%, analysis shown in this paper indicate that vehicles can be designed using carbon ultracapacitors (both carbon/carbon and hybrid carbon) that yield high fuel economy improvements for all driving cycles and the cost of the ultracapacitors can be competitive with lithium-ion batteries for high volume production and carbon prices of less than $20/kg. The use of carbon/carbon devices in micro-hybrids is particularly attractive for a control strategy (sawtooth) that permits engine operation near its maximum efficiency using only a 6 kW electric motor. Vehicle projects in transit buses and passenger cars have shown that ultracapacitors have functioned as expected and significant fuel economy improvements have been achieved that are higher than would have been possible using batteries because of the higher round-trip efficiencies of the ultracapacitors. Ultracapacitors have particular advantages for use in fuel cell powered vehicles in which it is likely they can be used without interface electronics.

Development of hybrid carbon devices is continuing showing energy densities of 12 Wh/kg and a high efficiency power density of about 1000 W/kg. Vehicle simulations using those devices have shown that increased power capability in such devices is needed before full advantage can be taken of their increased energy density compared to carbon/carbon devices in some vehicle applications. Energy storage system considerations indicate that combinations of ultracapacitors and advanced batteries (Wh/kg>200) are likely to prove advantageous in the future as such batteries are developed. This is likely to be the case in plug-in hybrids with high power electric motors for which it may be difficult to limit the size and weight of the energy storage unit even using advanced batteries.

Keywords: ultracapacitor, hybrid vehicles, fuel economy, energy density

1. Introduction

It is well recognized that the future development and successful marketing of hybrid and electric vehicles of various types are highly dependent on the performance and cost of the energy storage technologies available. There seems to be high confidence that the performance and cost of the other mechanical and electrical components in electric and hybrid drivelines are suitable for vehicle applications, but there remains considerable uncertainty regarding the energy storage technologies. Whether a particular energy storage technology is suitable for use in a particular type of vehicle depends both on its characteristics and the requirements for energy storage in the vehicle design. This paper is concerned with both the requirements for energy storage in various types of electric and hybrid vehicles and the characteristics of the energy storage devices being developed. This paper focuses on ultracapactors (electrochemical capacitors) as energy storage in vehicle applications and thus evaluates the present state-of-the-art of ultracapacitor technologies and its suitability for use in electric and hybrid drivelines of various types of vehicles. Comparisons are made of vehicle fuel economy performance using ultracapacitors and advanced batteries (primarily lithium) and applications identified in which ultracapacitors could be used in place of or with batteries to further reduce the energy use (fuel and/or electricity) of the vehicles. Cost considerations are included in the comparisons of the various ultracapacitor and battery energy storage systems.

2. Vehicle energy storage considerations

From a vehicle performance point-of-view, energy storage requirements are defined in terms of the peak power (kW) and energy storage capacity (Wh or kWh). The vehicle designer is also interested in the weight and volume of the energy storage unit which follows once the energy and power densities of the technologies are known. It is important to recognize that the energy capacity and the peak power refer to the useable energy capacity and the useable peak power from the energy storage unit for the particular application of interest. By “useable’ is meant the “quantity” that can be utilized from the storage unit consistent with other system constraints such as the effect of round-trip efficiency on peak power, depth of discharge on energy capacity and cycle life, and maximum charge voltage on energy capacity, cycle life and safety. These further considerations in most cases result in storage unit performance that is significantly less than one would infer from the name-plate ratings given by the manufacturer of the batteries or ultracapacitors.

A second difficulty in quantifying the peak power and energy requirements for hybrid-electric vehicles is that the useable power and energy requirements can be highly dependent on the control strategy linking operation of the engine and electric drive system. In the case of a charge sustaining hybrid, the useable energy required can vary from 100-300Wh depending on how often and at what power level the engine is used to recharge the energy storage unit [1-3]. In the case of the plug-in hybrids, the peak power requirement depends on the blending strategy of the electric motor and engine when the vehicle is operating in the “all-electric” or charge depleting mode [4,5]. If ultracapacitors and batteries are used together in either plug-in hybrid or electric vehicles, the strategy utilized for the load sharing between the two energy storage units has a large effect on the power requirements for each of them.

3. Ultracapacitor systems

3.1. Device characterization

An ultracapacitor unit in a vehicle consists of many cells in series and possibly also in parallel much as is the case for batteries. In most cases, a number of cells are combined into modules for convenience of assembling the ultracapacitor pack for the vehicle. Nevertheless, the cell characteristics are the key factors in determining the ultracapacitor unit performance. For ultracapacitors, the primary performance characteristics are

Table 1 Summary of the performance characteristics of ultracapacitor devices

Device	V rated	C (F)	R (mOhm)	RC (sec)	Wh/kg (1)	W/kg (95%) (2)	W/kg Match. Imped.	Wgt. (kg)	Vol. lit.
Maxwell*	2.7	2885	.375	1.08	4.2	994	8836	.55	.414
Maxwell	2.7	605	.90	.55	2.35	1139	9597	.20	.211
ApowerCap**	2.7	55	4	.22	5.5	5695	50625	.009	---
Apowercap**	2.7	450	1.4	.58	5.89	2574	24595	.057	.045
Ness	2.7	1800	.55	1.00	3.6	975	8674	.38	.277
Ness	2.7	3640	.30	1.10	4.2	928	8010	.65	.514
Ness (cyl.)	2.7	3160	.4	1.26	4.4	982	8728	.522	.38
Asahi Glass (propylene carbonate)	2.7	1375	2.5	3.4	4.9	390	3471	.210 (estimated)	.151
Panasonic (propylene carbonate)	2.5	1200	1.0	1.2	2.3	514	4596	.34	.245
EPCOS	2.7	3400	.45	1.5	4.3	760	6750	.60	.48
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
Power Sys. (activated carbon, propylene carbonate) **	2.7	1350	1.5	2.0	4.9	650	5785	.21	.151
Power Sys. (graphitic carbon, propylene carbonate) **	3.3 3.3	1800 1500	3.0 1.7	5.4 2.5	8.0 6.0	486 776	4320 6903	.21 .23	.15 .15
Fuji Heavy Industry-hybrid (AC/graphitic Carbon) **	3.8	1800	1.5	2.6	9.2	1025	10375	.232	.143
JSR Micro (AC/graphitic carbon)**	3.8	1000 2000	4 1.9	4 3.8	11.2 12.1	900 1038	7987 9223	.113 .206	.073 .132

(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

* Except where noted, all the devices use acetonitrile as the electrolyte

** all device except those with ** are packaged in metal containers, these devices are in laminated pouches

Table 2 Test data for the 3000F Maxwell device

Constant current discharge data 2.7V - 0

Current A	Time sec	Capacitance F	Resistance mOhm
50	153.4	2869	Not calculate
100	76.7	2883	Not calculate
200	38	2900	.375
300	25	2885	.333
400	18.4	2886	.40

Constant power discharges data 2.7 – 1.35V

Power W	W/kg *	Time sec	Wh	Wh/kg
63	115	135.3	2.349	4.27
102	186	82.7	2.332	4.24
201	365	40.8	.2.278	4.14
301	547	26.5	2.216	4.03
400	727	19.4	2.156	3.92
500	909	15.1	2.097	3.81

* weight of device - .55 kg

capacitance C (Farad) and resistance R (Ohm). To a reasonable approximation, the usable energy stored in the ultracapacitor cell is given by

$$E\ (\mathrm{Wh}) = \tfrac{1}{2}\, C\, V_r^{\,2}\, (3/4)/3600$$

where V_r is the rated voltage of the cell

The above equation assumes that the cell is discharged between its rated voltage V_r and ½ V_r. The rated voltage is the maximum voltage at which the cell should be used and in practice is usually somewhat less than the rated voltage at which the cell is tested to determine its rated energy density (Wh/kg). Derating the cell voltage is done to maximize the cycle life of the ultracapacitor unit in the vehicle. The useable pulse power capability [6] of the cell is given by

$$P_{max}\ (\mathrm{W}) = 9/16\ (1\text{-EFF})\ V_r^{\,2}/R$$

where EFF is the electrical efficiency of the pulse.

$$\mathrm{EFF} = V_{pulse}/3/4\ V_r$$

Often the power capability of a cell is calculated from the relationship $V_r^{\,2} / 4R$, which corresponds to an efficiency of 50%. This is not a useable efficiency for electric and hybrid vehicle applications. More practical efficiencies are 75-80% for electric (battery powered) and 90-95% for hybrid vehicle operation. In either case, the key cell performance characteristic for determining its maximum pulse power is its resistance R. The maximum usable constant power for the cell can be determined from its Ragone curve (Wh/kg vs.W/kg). Test data for typical ultracapacitor cells indicate that the energy density for a constant power discharge to $1/2V_r$ at a power density equal to that for a 95% efficient pulse results in a 10% decrease in energy density from the specified energy density of the cell (W/kg =200-300). Hence the useable pulse power capability of a cell is significantly higher than its constant power capability.

Ultracapacitor cells from various manufacturers world-wide have been tested at UC Davis [7-9]. The test results are summarized in Table 1 and test data for a particular cell, the Maxwell 3000F device, are given in Table 2. The performance of this cell is typical of commercially available carbon/carbon cells with a useable energy density of 4.2 Wh/kg and a pulse power of 994 W/kg for 95% efficiency. As discussed in a later section of the paper, higher energy density and higher power carbon/carbon cells are being developed, but they are not yet fully commercialized.

3.2. System sizing considerations

The weight and volume (kg and L) of an ultracapacitor pack can be estimated with good confidence if the characteristics of the cells to be used in the pack are known from previous testing. First it is necessary to calculate the kg and L of the cells. This can be done using the simple relationship

$$W_{cell}\,(kg) = (Wh)_{stored} / (Wh/kg)_{cell}$$

$$V_{cell}(L) = (Wh)_{stored} / (Wh/L)_{cell}$$

The packaged weight and volume of the cells are then calculated based on assumed values for the packing factors (pfw for weight and pfv for volume) for the modules.

$$W_{modules} = W_{cell}\,(kg)/pfw$$

$$V_{modules} = V_{cell} / pfv$$

Reasonable values for the packing factors [x] are pfw= .7 and pfv= .6.

The peak pulse power at any efficiency EFF can be calculated from the cell weight.

$$P_{EFF}\,(W) = W_{cell}\ \{9/16\ (1\text{-}EFF)\ V_r^2/R\}/\ w_{cell}$$

where w_{cell} is the weight of an individual cell (kg).

The number N_{cell} of cells in the unit is determined by dividing the system voltage V_{system} by the useable rated voltage V_{ru} of the cells. $N_{cell} = V_{system} / V_{ru}$ rounded off to the nearest integer. As noted previously, it is common practice to set V_{ru} slightly less than the rated voltage V_r of the cell in order to maximize the cycle life of the unit. Derating the cell voltage increases the number of cells by the ratio V_r/V_{ru} and decreases the useable energy density and power density by the ratio $(V_r/V_{ru})^2$. For example, for $V_r = 2.7$, $V_{ru} = 2.5$, the cell count would be increased by 8% and the energy and power densities decreased by 17%.

4. Vehicle application requirements

The energy storage requirements vary a great deal depending on the type and size of the vehicle being designed and the characteristics of the electric powertrain to be used. Energy storage requirements for various vehicle designs and operating strategies are shown in Table 3 for a mid-size passenger car. Requirements are given for electric vehicles and both charge sustaining and plug-in hybrids. These requirements can be utilized to size the energy storage unit in the vehicles when the characteristics of the energy storage cells are known. In some of the vehicle designs considered in Table 3, ultracapacitors are used to provide the peak power rather than batteries. The objective of

Table 3 Energy storage unit requirements for various types of electric drive mid- size passenger cars

Type of electric driveline	System voltage V	Useable energy storage	Maximum pulse power at 90-95% efficiency kW	Cycle life (number of cycles)	Useable depth-of-discharge
Electric	300-400	15-30 kWh	70-150	2000-3000	deep 70-80%
Plug-in hybrid	300-400	6-12 kWh battery 100-150 Wh ultracapacitors	50-70	2500-3500	deep 60-80%
Charge sustaining hybrid	150-200	100-150 Wh ultracapacitors	25-35	300K-500K	Shallow 5-10%
Micro-hybrid	45	30-50 Wh ultracapacitors	5-10	300K-500K	Shallow 5-10%

this paper is the evaluation of ultracapacitor technology (present and future) to assess whether these vehicle applications of ultracapacitors appear to be feasible and attractive.

For ultracapacitors, the key issue is the minimum energy (Wh) required to operate the vehicle in real world driving because the energy density characteristics of ultracapacitors are such that the power and cycle life requirements will be met in most cases if the unit is large enough to met the energy storage requirement.

5. Ultracapacitor technologies

There are a number of approaches being pursued to develop high energy density, high power capacitors suitable for use in vehicle applications. These approaches are identified in Table 4 along with the basic chemistry/physics [10,11] of the energy storage mechanisms, the materials used in the active electrodes, cell characteristics, and their potential performance (energy density, power density, etc.). Each of the capacitor types is described briefly in the following sections.

Table 4 Technology approaches for the development of high energy density electrochemical capacitors

Technology type	Electrode materials	Energy storage mechanisms	Cell voltages	Energy density Wh/kg	Power density kW/kg
Electric double-layer	Activated carbon	Charge separation	2.5-3	5-7	1-3
Advanced carbon	Graphite carbon	Charge transfer or intercalation	3-3.5	8-12	1-2
Advanced carbon	Nanotube forest	Charge separation	2.5-3	not known	not known
Pseudo-capacitive	Metal oxides	Redox charge transfer	2-3.5	10-15	1-2
hybrid	Carbon/metal oxide	Double-layer/ charge transfer	2-3.3	10-15	1-2
Hybrid	Carbon/lead oxide	Double-layer/faradaic	1.5-2.2	10-12	1-2

5.1 Double-layer capacitors (carbon/carbon)

Most of the electrochemical capacitors currently on the market are termed electric double-layer capacitors (EDLC). Energy storage in double-layer capacitors results from charge separation in microscopically thin layers formed between a solid, conducting surface and a liquid electrolyte containing ions. The dominant electrode material is microporous, activated carbon [12,13]. The double-layer is formed in the micropores of the high surface area carbon material. Either an aqueous or organic electrolyte can be used. Photographs of several commercially available devices are shown in Figures 1-3.

Figure 1 Maxwell 3000F and 650F capacitors

Figure 2 The NessCap 3000F capacitor

Figure 3 The Batscap 2700F capacitor

The performance of an electrochemical capacitor is simply related to the characteristics of the electrode material and the electrolyte used in the device. The relationship for the energy density (Wh/kg) can be expressed as

$$\mathrm{Wh/kg} = 1/8\ (\mathrm{F/g}) \times V_0^2\ /3.6 \qquad (1)$$

where F/g is the specific capacitance of the electrode material and V_0 is the cell voltage which depends primarily on the electrolyte used in the device. The weight of the materials in the cell other than carbon are neglected in Eq.(1). As shown in Table 1, the energy density of presently available carbon/carbon devices using an organic electrolyte is 4-5 Wh/kg. The carbons in these devices have a specific capacitance of about 100 F/gm [12]. Large improvements in the energy density of the carbon/carbon devices depends on developing carbons with higher specific capacitances of 150-200 F/gm and electrolytes that can tolerate higher voltages of 3-3.5V. These material improvements would result in cell energy densities of greater than 10 Wh/kg.

The power characteristics of a cell are proportional to V_0^2 /R where R is the DC resistance of the device. Estimation of the resistance of a cell, including the contribution of ion diffusion in the micropores and the effects of current transients in the electrodes, is not simple as shown in [14,15]. However, a first approximation for the resistance can be written as

$$R = 2/3\ t \times r_{\mathrm{electrol.}}\ /A_x\ + r_{\mathrm{contact}}/A_x \qquad (2)$$

where t is the electrode thickness, r_{electrol}' is the resistivity (Ohm-cm) of the electrolyte, r_{contact}' is the contact resistivity (Ohm-cm^2) of the carbon coating on the metal current collector and A_x is the geometric area of the electrode.

The key factor in achieving high power capability is reducing the cell resistance. As shown in Table 1, most of the presently available carbon/carbon cells have relatively low resistance with power capability of about 1000 W/kg for 95% efficient pulses. A few of the cells have a power capability in excess of 2500 W/kg. It can be expected that even higher power density capability will be possible with the higher specific capacitance carbons as that will permit the use of thinner carbon coatings in the electrodes.

5.2. Pseudo-capacitors

In an electric double-layer capacitor (EDLC), the active ions in the electrolyte are not transferred onto or into the solid electrode surface. If the ions in the double-layer are transferred to the surface and combine with atoms on the surface, the mechanism is termed “pseudo-capacitance” [14, Chapters 10-11]. Redox reactions are good examples of this process and metal oxides are good candidates for use in the electrodes of pseudo-capacitive devices. Eqns (1,2) can be used to estimate the characteristics of these devices, but the specific capacitance of the electrode materials used are significantly higher than the microporous carbons. Research [11] is being done on devices using pseudo-capacitance, but such devices are not presently commercially available. No proto-types have yet been tested that exhibited both energy density >10 Wh/kg and power density >2000 W/kg, 95% efficiency. Achieving high cycle life (>200,000 cycles) utilizing pseudo-capacitance is also a concern.

5.3. Hybrid (asymmetric) capacitors

This category of electrochemical capacitors refers to devices in which one of the electrodes is microporous carbon and the other electrode utilizes either a pseudo-capacitance material or a Faradaic material like that used in a battery. These devices are often referred to as asymmetric capacitors. The charge/discharge characteristics of the hybrid capacitors have features of a double-layer capacitor (a linear voltage vs. time for a constant current charge/discharge) and that of a battery (voltage limits fixed by the potential of the battery-like electrode). As indicated in Table 1, the energy density of the hybrid capacitors utilizing intercalation carbon (graphite) in one of the electrodes is significantly higher than that of the carbon/carbon double-layer capacitors. However, even though the power density of those devices is relatively high (about 1000 W/kg, 95%), the power capability has not increased proportional to the increase in energy density.

6. Energy storage cost considerations

Reducing the present high cost/price of EDLCs is a key issue in achieving high market penetration in the future especially of mid-size and large devices. There are many applications for which EDLCs are presently precluded or even seriously considered because they remain too expensive even though their selling price has decreased significantly in recent years. The cost of manufacture of any product is closely tied to volume with the cost decreasing rapidly with increased volume up to relatively high production rates. Potential sales of EDLCs are in the many millions of units per year so automated production facilities are necessary to reduce the unit costs to levels at which the large markets can develop. Semi-automated production facilities presently exist at a number of companies for EDLCs of all sizes. In fact, production capabilities exceed sales volumes for most devices and that is the reason the price of devices has decreased markedly in recent years. It is common to speak of the price of devices in terms of cents per Farad (cents/F) or $/Wh stored. It is easier to interpret the price information on the cents/F basis as it does not concern the cell voltage or what fraction of energy stored can be used in a particular application. For example, for a 10F device, if the price is quoted as 10 cent per Farad, the device cost would be $1. Similarly, a 2500F device would cost $25 at 1 cent/F.

The cost to manufacture an EDLC (carbon/carbon) device depends on the material and production costs. At the present time, material costs are high. The cost of carbon suitable for use in EDLCs can be as high as $100/kg with the average price being in the

Table 5 Material costs for a 2.7V, 3500F capacitor *

carbon			Electrolyte ACN		Device	unit	costs		
F/gm	gmC/dev.	$/kg	$/L	$/kg salt	Total mat. $	$/kg	$/Wh	$/kW	Ct./F
75	187	50	10	125	17.0	29	6.4	29	.48
120	117	100	10	125	15.5	26	6	26	.44
75	187	5	2	50	3.6	6.0	1.3	6	.10
120	117	10	2	50	2.5	4.2	.93	4.2	.070

*4.5 Wh/kg, 1000 W/kg-95% eff.

\$30-\$50/kg range. The cost of the electrolyte solvent is also high in the range of \$ 5-10 per liter for both propylene carbonate and acetonitrile. The ionic salts that dissociate in the solvent into the positive and negative ions that move into and out of the double-layer in the microporous carbon to store the energy are also expensive being \$50-\$100/kg. Since the analysis of EDLCs is straightforward, material costs can be calculated [16,17] with good accuracy. The result of a typical costing exercise is shown in Table 5. Note the strong dependency of the cents/F and \$/Wh unit costs for the device on the unit material costs. Presently the price of EDLCs is high because both the material and manufacturing costs are high. With more automated production and reduced material costs, it is anticipated that the price of ECCs in high volume can be in the range of 1-2 cents/F for small devices and .25-.5 cents/F for large devices like those needed for vehicle applications.

EDLCs can not compete with batteries in terms of \$/Wh, but they can compete in terms of \$/kW and \$/unit to satisfy a particular vehicle applications. 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 EDLC is determined by the minimum energy storage requirement. The power and cycle life requirements are usually easily satisfied. Hence the EDLC 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 EDLC unit is 125 Wh and that in the battery unit is 1500 Wh, the unit costs of the capacitors and battery are related by

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

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

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

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

and in Table 6 for a range of battery costs.

Table 6 Relationships between capacitor and battery costs

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 6 indicate that for the charge sustaining hybrid application, EDLC 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 cost of the EDLCs are about one-fourth those of the batteries.

7. Comparisons of ultracapacitors and batteries

As discussed in [18,19], cells and modules of several lithium-ion battery chemistries have been tested in the laboratory at UC Davis. The performance characteristics of the lithium-ion batteries are summarized in Table 7. Also shown in the table are the characteristics of other batteries for comparison. The energy and power densities of the various batteries vary over a wide range and indicate clearly the trade-offs between energy and power capabilities in various battery designs. The consequences of these trade-offs for meeting energy storage requirements will be discussed in the next section where combinations of batteries and ultracapacitors are considered. The power to energy ratio (P/E) of the batteries is also given in Table 7. The power and energy characteristics of batteries and ultracapacitors are compared in Table 8. The P/E ratio for the capacitors

Table 7 Performance characteristics of various batteries

Battery	Ah/ wgt.kg	R mOhm	Wh/kg	W/kg 90%	W/kg 80%	P/E 90%	P/E 80%
Chemistry							
Iron phosphate							
EIG	15/.424	2.5	115	897	1585	7.8	13.8
A123	2.1/.07	12	88	1132	2000	12.9	22.8
K2	2.5/.082	17	86	682	1205	7.9	14.0
Lithium titanate							
Altairnano	12/.34	2.2	70	693	1225	9.9	17.5
Altairnano	3.8/.26	1.1	35	2260	4020	64.5	115
EIG	11/.44	1.9	43	620	1100	14.4	23.8
Li(NiCo)O_2							
EIG	18/.45	3.0	140	913	1613	6.5	11.6
GAIA	42/1.53	.48	94	1677	2965	17.8	31.5
Quallion	1.7/.047	70	170	374	661	2.2	3.9
Quallion	1.3/.043	59	144	486	860	3.4	6.0
NiMt hydride							
Panasonic. HEV	6.5/1.04	11.4	46	393	695	8.5	15.1
EV	65/		68	87	154	1.3	2.3
Lead-acid							
Panasonic HEV	25/		26	146	258	5.6	9.9
EV	60/		34	89	157	2.6	4.6
Zn-Air							
Revolt Technology			450	200		.5-1.0	1-2

$P_{max} = \text{Eff.}\ (1-\text{Eff.})\ (V_{oc})^2/R$

P/E = (W/kg) / Wh/kg

Table 8 Comparisons of the energy and power characteristics of ultracapacitors and batteries

Device technology	Nominal cell voltage	Wh/kg	W/kg 90%	P/E 90%	P/E 80%
Carbon/carbon supercapacitors	2.7	5	2500- 5000	500-1000	1000-2000
Hybrid carbon supercapacitors	3.8	12	1635	140	280
Lithium-ion batteries					
Iron phosphate	3.25	90-115	700-1200	8-13	14-23
Lithium titanate	2.4	35-70	700-2260	10-65	18-115
$NiCoMnO_2$	3.7	95	1700	19	34
	3.7	140	500	3.5	6.2
	3.7	170	400	2.4	4.3
Ni Mt hydride HEV	1.2	46	400	8.6	15
Lead-acid HEV	2.0	26	150	5.6	10
Zn-air	1.3	450	200-400	.5-1.0	.9-1.8

is at least a factor of ten higher than that of batteries with the factor increasing in general as the energy density of the batteries increases.

8. Combinations of ultracapacitors and batteries

It has been recognized for many years that combining ultracapacitors and batteries would significantly reduce the stress on the batteries in vehicle applications in which the batteries are subject to high current pulses in both charge and discharge. It is further recognized that to gain maximum advantage from this arrangement would require the use of interface electronics to control the currents from the battery. There has been some laboratory testing of this arrangement [20,21], but little work directly with vehicles. In general, experience to date has been that if batteries were available that could meet both the energy and power requirements of the vehicle design, the designers chose to use batteries alone even though they realized batteries plus ultracapacitors would have some advantages. In other words, designers will not select a battery/capacitor combination unless there are clear, large advantages to do so. As discussed in the following paragraphs, this may be the case when one considers the use of advanced batteries (Wh/kg >200) in PHEVs and EVs.

In PHEVs and EVs, it is desirable for the battery to be sized by the energy needed to sustain a specified all-electric range. In that case, the weight and volume of the battery pack would follow directly from its energy density (Wh/kg, Wh/l). This means that battery technologies with high energy density will be strongly favored. However, the batteries must also be able to meet the power requirements of the large electric motors used in the PHEVs and EVs. Unfortunately battery designed to attain maximum energy density in most cases require a sacrifice in power capability as shown in Table 7. As a consequence, for some vehicle designs the battery will be sized by the power requirement and not the energy requirement resulting in a larger and more expensive battery than would be the case if the battery had a higher power density. Design options using batteries of various energy densities are shown in Table 9 for a PHEV with all-electric ranges of 10-40 miles. The effect of electric motor size (50, 70 kW) on the required power densities are also shown in Table 9. Note that for the shorter all-electric ranges and a battery energy density of 200 Wh/kg, the power densities required exceed by a considerable margin those of the batteries shown in Table 7. In those cases, it makes sense to consider combining batteries with ultracapacitors. This design option is shown in Table 10. Note that the combination of the 200 Wh/kg battery and the carbon/carbon ultracapacitors results in the lowest weight energy storage unit for all the PHEV ranges even for a 50 kW electric motor. It can be expected that the weight advantage of the combination will be even larger for batteries with an energy density greater than 200 Wh/kg. These results indicate that combining batteries and ultracapacitors will become increasingly advantageous as designers consider using the more advanced batteries with higher energy density.

Table 9 Battery sizing and power density for various ranges and motor power

Battery			200 Wh/kg			100 Wh/kg			70Wh/kg		
Range miles	kWh *needed	kWh** stored	** kg	50 kW kW/kg	70kW kW/kg	kg	50kW kW/kg	70kW kW/kg	kg	50kW kW/kg	70kW kW/kg
10	2.52	3.6	18	2.78	3.89	36	1.39	1.94	51	.98	1.37
15	3.78	5.4	27	1.85	2.59	54	.92	1.30	77	.65	.91
20	5.04	7.2	36	1.39	1.94	72	.69	.97	103	.49	.68
30	7.56	10.8	54	.93	1.30	108	.46	.65	154	.32	.46
40	10.1	14.4	72	.69	.97	144	.35	.49	206	.24	.34

* Vehicle energy useage from the battery: 250 Wh/mi

** useable state-of-charge for batteries- 70%; weights shown are for cells only

Table 10 Storage unit weights using a combination of batteries and ultracapacitors for various all-electric ranges and 70kW power

Wh/kg	5	200		100		70	
Range miles	Ultracap kg *	Battery Kg**	Combin-ation kg	Battery kg	Combin-ation kg	Battery kg	Combin-ation kg
10	20	18	38	36	56	51	71
15	20	27	47	54	74	77	97
20	20	36	56	72	92	103	123
30	20	54	74	108	128	154	174
40	20	72	92	144	164	206	226

* The carbon/carbon ultracapacitor unit stores 100 Wh useable energy

** Weights shown are for cells only; packaging into modules not included

9. Computer simulations of hybrid and electric vehicles

Simulation of the operation of hybrid vehicles equipped with various alternative powertrains and energy storage technologies (nickel metal hydride and lithium-ion batteries and ultracapacitors) can be performed using the UCDavis version of **Advisor.** The following alternative hybrid powertrain arrangements have been modeled:

a. Single-shift, parallel (Honda)
b. Single-planetary, dual-mode (Toyota/Prius)
c. Multiple-planetary, dual-mode (GM)

d. Multiple-shaft, dual-clutch transmission (VW and Borg-Warner)
e. Series – range extended EV (GM Volt)

Table 11 Ultracapacitor units for hybrid vehicle applications

Vehicle design	ultracap energy stored Wh	ultracap peak power kW	system voltage V	No. of cells	Capac-itance F	Max. power 90% eff. kW	Weight (kg) / volume (L)	
							cells	unit*
Micro-hybrid	30	6	48					
Carbon/carbon				18	2550	>10	6 / 4.6	9/ 9.2
Hybrid carbon				14	2000	5.7	2.8/ 1.8	4.3/ 3.6
Charge sustaining hybrid	150	35	200					
Carbon/carbon				80	2865	>50	30/ 23	46/ 46
Hybrid carbon				65	2000	26	13/ 9	20/ 18
Plug-in Hybrid 12 kWh bat. **	200	45	300					
Carbon/carbon				120	2200	> 100	40/ 30	61/ 60
Hybrid carbon				84	2000	36	18/ 12	28/ 24

* Packaging factors: weight .65 volume .5
** Energy density of the battery in the Plug-in hybrid - 200 Wh/kg,
Vehicle electric use 156 Wh/km

The results of the simulations for selected cases are discussed in this paper, but more complete results are given in [22-24]. This paper will focus on the use of ultracapacitors for energy storage and will be concerned primarily with the fuel economy gains that can be achieved utilizing a sawtooth control strategy that optimizes the efficiency of the engine. Most of the simulations are performed using the single-shaft, parallel arrangement because that arrangement is closest to the standard driveline and leads to satisfactory vehicle operation even when the ultracapacitor energy storage is depleted.

The sawtooth strategy has essentially two modes – charge depleting (operation in the electric mode with the engine off) and recharging (engine on at relatively high power to recharge the ultracapacitor or battery). In the charge depleting mode, system efficiency is maximized by relying on the electric drive, which is inherently efficient; in the recharge mode, the engine runs in the most efficient region (torque and speed) of the engine map. In this mode, the engine both recharges the ultracapacitors and provides power to drive the vehicle. The ultracapacitors are also recharged during regenerative braking. With these two modes, the engine can be run at its most efficient states while keeping the energy storage within a given SOC range. The electric drivelines and ultracapacitor units utilized in the simulations for various designs are shown in Table 11. Ultracapacitor units were envisioned using both the carbon/carbon and hybrid carbon technologies.

Simulations of mid-size passenger cars using the ultracapacitors in micro-hybrid, charge sustaining, and plug-in hybrid powertrain designs were performed using the **Advisor** vehicle simulation program. All the powertrains were in the same vehicle having the following characteristics: test weight 1660 kg, $C_d = .3$, $A_F = 2.25\ m^2$, RRCF =.009. The engine map used in the simulations was for a Ford Focus 2L, 4-cylinder engine. The rated engine power was 120 kW for the conventional ICE vehicle and the micro-hybrid and 110 kW for the charge sustaining and plug-in hybrids. All the hybrids use the single-

Table 12 Summary of the vehicle fuel economy simulation results using ultracapacitors for various driving cycles L/100 km/ mpg

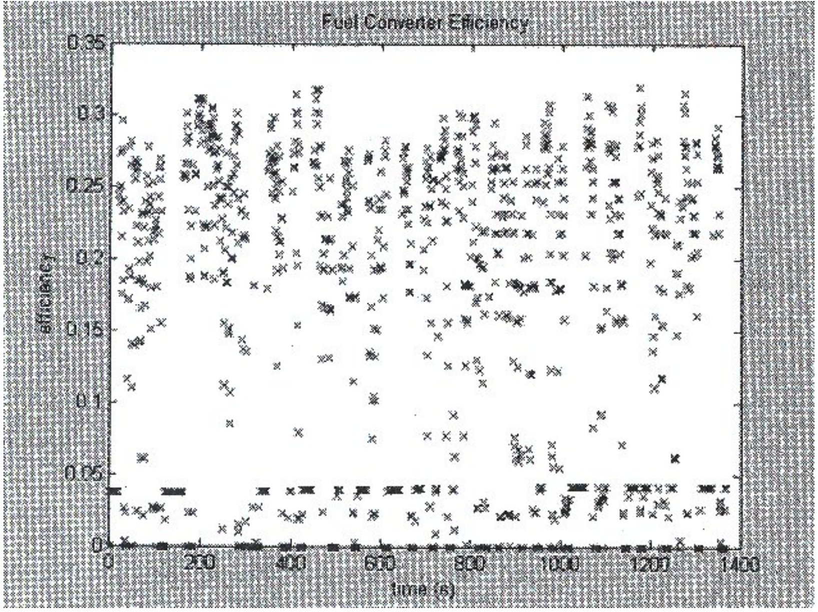
Driveline type	Energy storage type	Voltage and weight cells (kg)	EM Peak kW	FUDS	HWFET	US06	ECE-EUDC
ICE baseline				10/ 23.8	6.9/ 34.4	9.6 24.7	9.7/ 24.6
Micro-HEV	Lead-acid/ ultracaps	48					
	Carbon/carbon	6 kg	6	5.7/ 41.7	5.3/ 44.7	7.8/ 30.6	5.9/ 40.2
	Hybrid carbon	3 kg	6	7.3/ 32.8	6.3/ 38.0	8.9/ 26.7	7.1 33.4
Charge sustaining hybrid	Ultracaps	200					
	Carbon/carbon	30 kg	35	5.4/ 43.8	5.0/ 47.9	7.1/ 33.6	5.5/ 43.2
	Hybrid carbon	13 kg	35	5.8/ 40.9	5.2/ 45.8	8.0/ 29.9	5.8/ 41.3
Plug-in hybrid .	12 kWh Li battery (200 Wh/kg) and ultracaps	300	70 kW with 45 kW from caps				
	Carbon/carbon	40 kg	45	5.5/ 43.2	5.0/ 47.7	7.0/ 33.9	5.5/ 42.9
	Hybrid carbon	18 kg	45	5.8 41.2	5.2/ 46.2	7.9/ 30.2	5.8/ 41.2

shaft approach similar to the Honda Civic hybrid. The same induction electric motor map was used for all the vehicle designs.

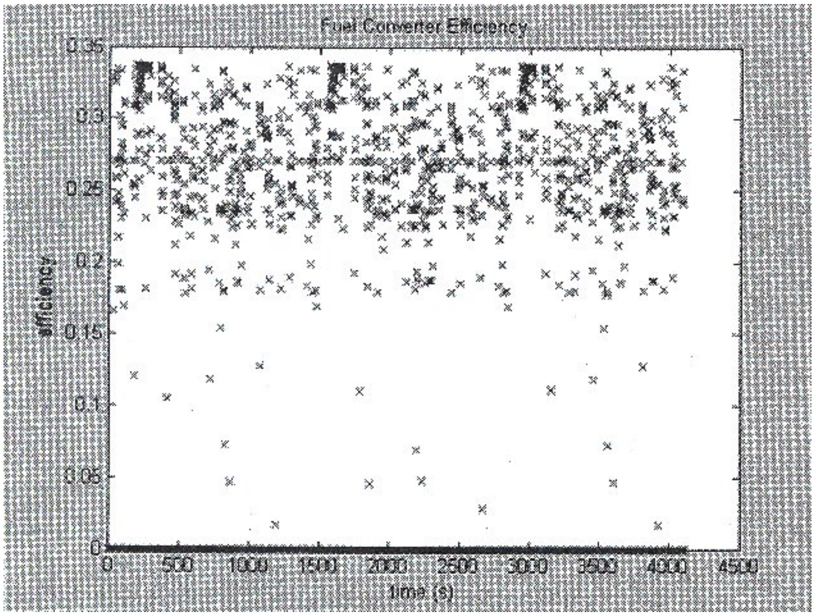
The simulation results are summarized in Table 12 for a conventional ICE vehicle and each of the hybrid designs. Results are given for fuel usage in terms of both L/100 km and mpg for various driving cycles. It is clear from Table 12 that large improvements in fuel usage are predicted for all the hybrid powertrains using ultracapacitors for energy storage. The simulation results will be discussed separately for each hybrid design.

9.1. Micro-hybrids

The results for the micro-hybrids are particularly interesting and surprising, because of the large fuel economy improvements predicted. These improvements were about 40% on the FUDS and ECE-EUD cycles and 20% on the Federal Highway and US06 cycles using the carbon/carbon ultracapacitor units. The improvements were significantly less using the hybrid carbon units because of their lower round-trip efficiencies. In the micro-hybrid designs, the rated engine power used was the same as that in the conventional ICE vehicle in order that the performance of the hybrid vehicle when the energy storage in the ultracapacitors is depleted would be the same as the conventional vehicle. The ultracapacitors were used to improve fuel economy with only a minimal change in vehicle acceleration performance. The control strategy used was to operate on the electric drive when possible and to recharge the ultracapacitors when the engine was operating. As shown in Figure 4, this resulted in a large improvement in average engine efficiency from 19% in the ICE vehicle to 30% in the micro-hybrid even though the electric motor had a peak power of only 6 kW.



Engine operating efficiency for the ICE vehicle-
average engine efficiency .19



Engine operating efficiency for the micro-hybrid -
average engine efficiency .30

Figure 4 A comparison of engine efficiencies for a conventional ICE vehicle and a micro-hybrid on the FUDS cycle using carbon/carbon ultracapacitor

Additional computer simulations were made for higher motor power (up to 12 kW) and larger ultracapacitor energy storage (up to 50 Wh). It was found that the improvements in fuel economy were only marginally greater. Using a motor power of 3 kW reduced the fuel economy improvement on the FUDS by more than 50%. Note from Table 12 that the fuel economy improvements using the carbon/carbon ultracapacitors were for all the cycles greater than those using the hybrid carbon devices. This was the case because the round-trip efficiencies for the carbon/carbon units were 95-98% and those of the hybrid carbon units were 75-90% for the various driving cycles. As noted previously, the hybrid carbon devices had higher energy density, but even though their power density for 95% efficiency was relatively high (1050 W/kg), it was not proportionally higher – that is twice as high- as the carbon/carbon devices with lower energy density. These results show clearly that it is essentially to develop high energy density ultracapacitors with proportionally higher power density; otherwise their use in vehicle applications will be compromised.

9.2. Charge sustaining hybrids

The fuel economy simulation results for charge sustaining hybrids are also shown in Table 12 for a mid-size passenger car using both carbon/carbon and hybrid carbon ultracapacitors. Using the carbon/carbon ultracapacitor unit, the fuel savings are about 45% for the FUDS and ECE-EUD cycles and about 27% for the Federal Highway and US06 cycles. These improvement values are higher than for the micro-hybrid, but not by as large a factor as might be expected. The prime advantage of the high power electric driveline in the charge sustaining hybrid is that it yields large fuel economy improvements even for high power requirement driving cycles like the US06. The fuel economy improvements using the hybrid carbon ultracapacitor unit are not much less (5-10%) than those with the carbon/carbon unit even though the round-trip efficiency of the hybrid carbon unit is only 85-90% compared to 98% for the carbon/carbon unit. Since the weight/volume of the hybrid carbon unit is relatively small - 43% of that of the carbon/carbon unit, it appears that the charge sustaining hybrid application is a better one for the hybrid carbon technology than the micro-hybrid application.

9.3. Plug-in hybrids

The plug-in hybrid vehicle studied is one that utilizes a high energy density battery (200 Wh/kg) and ultracapacitors that would provide two-thirds of the power to a 70kW electric motor. The electric energy use of the vehicles in the charge depleting mode (engine off) is assumed to be 156 Wh/km resulting in a charge depleting range of 60 km (38 mi.) for 80% DOD of the battery. The fuel economy results shown in Table 12 are for vehicle operation in the charge sustaining mode after the energy battery (12 kWh) has been depleted. As expected in this mode, the operation of the plug-in hybrid vehicle is essentially the same as previously discussed for the charge sustaining hybrid. Hence the hybrid carbon ultracapacitor unit would also be suitable for the plug-in hybrid. The combined weight of the cells in the battery and hybrid carbon ultracapacitors would be 78 kg for a plug-in hybrid with an all-electric range of about 40 miles. The combined weight using the carbon/carbon ultracapacitors would be 100 kg. Using a high power lithium-ion battery with an energy density of 100 Wh/kg without ultracapacitors, the weight of the battery cells alone would be 120 kg. Hence for plug-in hybrids combining a battery with ultracapacitors is an attractive design option.

9.4. Series – range extended EV

This hybrid vehicle is essentially an electric vehicle with on-board electricity generation via an engine-powered generator or a fuel cell for range extension. In the case of the GM Volt, it is intended to be utilized as a plug-in hybrid with much of the electricity used provided by a relatively large battery. It could, however, be used as a charge sustaining hybrid using a smaller battery. Battery-powered and series hybrid vehicles are modeled/simulated at UC Davis using SIMPLEV, which is a vehicle simulation program developed at the Idaho National Engineering Laboratory [25]. Component efficiency maps are available in SIMPLEV for a wide variety of engines, electric, and lithium-ion batteries. The available control strategies permit the simulation of series hybrids as plug-in and charge sustaining hybrids. Simulations were performed using the SIMPLEV program for series hybrid vehicles for comparison with battery-powered (BEV) and parallel hybrid vehicle results [26]. The electric drivelines of the series hybrid vehicles would be the same as that of the battery-powered vehicles except that the batteries stored only 40% of the energy in the BEVs. The engine/generator power was selected such that the vehicles had acceptable steady gradeability on generator electricity alone. Ultracapacitors could be used in the plug-in, series hybrids if the batteries were unable to provide the peak power to the electric motor. As discussed previously, this would become most likely if the plug-in range was relatively short and/or high energy density batteries of modest power density were being used in the vehicle. In those cases, the ultracapacitors would greatly reduce the power demands on the battery and lead to less stress on the battery and longer cycle life.

Simulation results for series hybrids are summarized in Table 13 for a mid-size passenger car and SUV.

Table 13 Summary of the vehicle characteristics and simulation results

Vehicle	Test weight kg	Engine/ generator kW	Battery kWh	FUDS mpg	Highway Mpg
Mid-size car					
Series HEV (1)	1830	40 (2)	10	40	47
CS HEV	1640			36	44
Conventional ICE	1640			20	32
Mid-size SUV					
Series HEV (1)	2150	55 (3)	13.3	29	31
CS HEV	1910			28	32

Conventional ICE (4)	1910			16	25

(1) All-electric range of 30 miles, lithium-ion batteries – 120 Wh/kg
(2) Electric motor power 105 kW
(3) Electric motor power 145 kW
(4) All the vehicles have the same acceleration performance (0-60 mph in 9 sec)

As plug-in hybrids, the series hybrids have an all-electric range of about 30 miles if the batteries are discharged to 80% of their rated capacity. The simulation results indicate that the fuel economy of the series hybrid is slightly higher than that of the parallel charge sustaining hybrid when both are operated in the charge sustaining mode. The engine/generator was sized such that the series hybrids were full-function vehicles. Thus all the hybrid vehicles including the series hybrids in the all-electric mode have performance equivalent to the conventional ICE vehicle.

9.5. Fuel cell vehicles

Ultracapacitors can be used to meet the peak power transients in vehicles powered by a fuel cell. This was initially done by Honda in their “FCV” fuel cell vehicle [27]. The capacitors were used to load level the fuel cell during accelerations and to recovery energy during regenerative braking. In the Honda system, the capacitors were used without interface electronics. Connecting the fuel cell and capacitors in parallel without electronics functions better than is the case with batteries because the V vs. I curve of the fuel cell is inherently more sloped than that of a battery. Hence as the ultracapacitor is discharged and its voltage decreases, the fuel cell will provide higher power which either drives the vehicle or recharges the capacitors. Hence the system is inherently self controlling to a large extent.

A fuel cell connected in parallel with ultracapacitors in a mid-size SUV (test weight 1960 kg) has been simulated using a special version of the SIMPLEV program available at UC Davis. In the simulation, the fuel cell is modeled as a battery whose V, I curve is independent of SOC. The rest voltage and resistance are based on the V, I curves of state-of-the art fuel cells (Ballard or UTC) [28]. The resistance of the equivalent battery is specified to yield a fuel cell with the desired rated power at a selected cell voltage. In this analysis, the cell voltage for rated power was taken to be .65V/cell. The fuel cell power used was 50 kW for the vehicle with capacitors and 100 kW for the vehicle without capacitors. The energy stored in the capacitors was 300 Wh and the system voltage was 300V. The electric motor had a power of 100 kW for both vehicles.

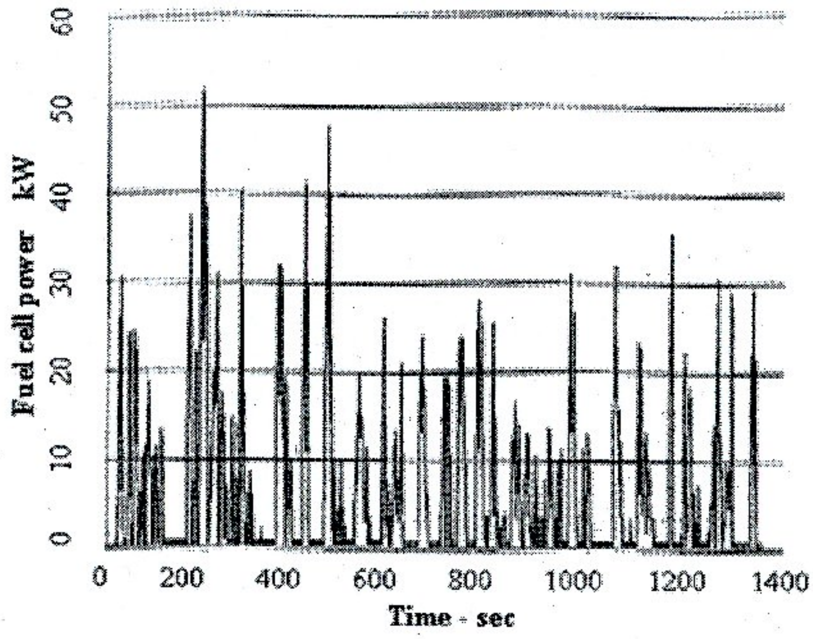
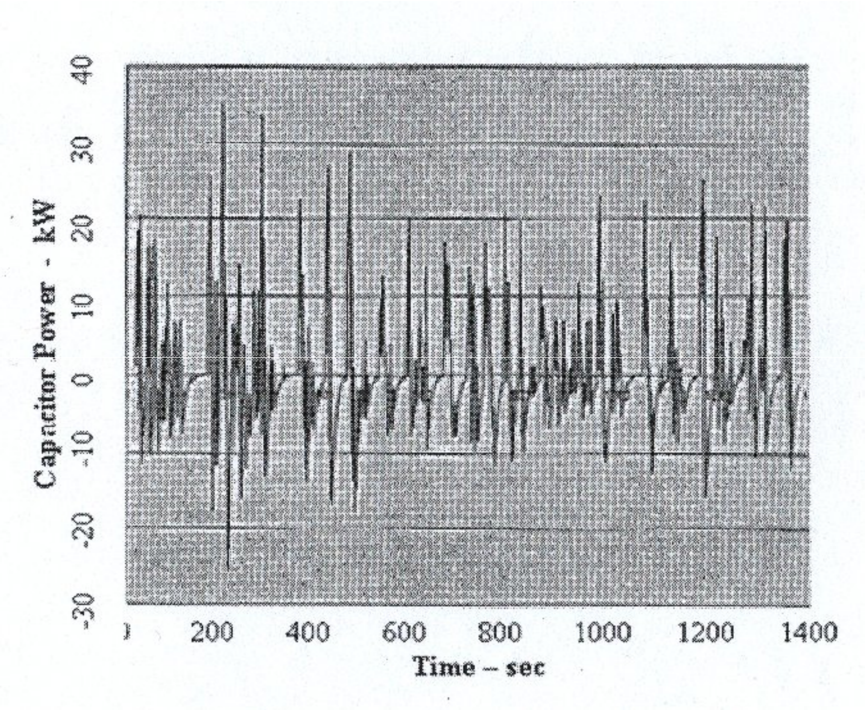


Figure 5 Fuel cell alone on the FUDS cycle



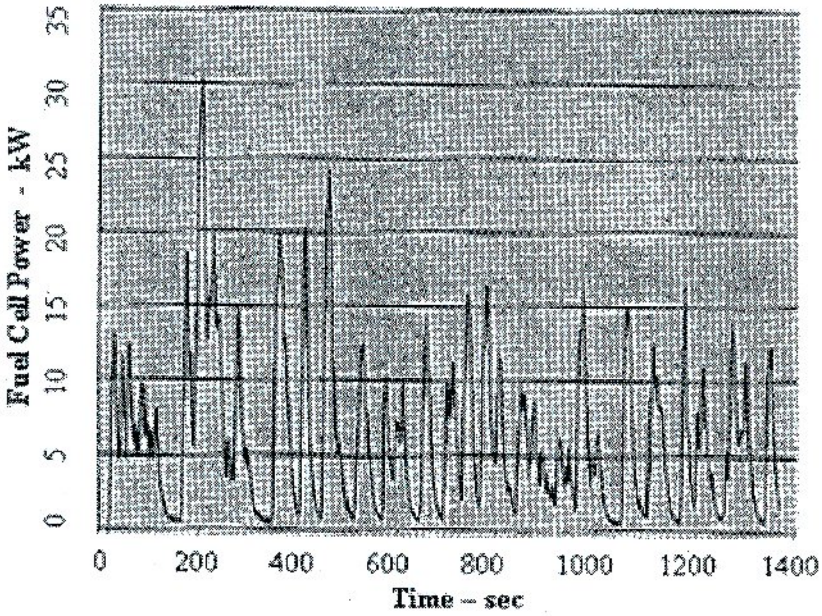


Figure 6 Fuel cell and ultracapacitor in parallel without interface electronics on the FUDS cycle

The simulation results for the power profiles of the fuel cell and fuel cell/capacitor-powered vehicles are given in Figures 5 and 6. The presence of the capacitors significantly reduces the power demand on the fuel cell even with the capacitors connected in parallel. The maximum fuel cell power on the FUDS was 30.2 kW with the capacitors and 51.9 kW in the case of the fuel cell alone. The average fuel cell power was the same for both cases. As expected, the capacitors provide most of the power when their voltage is relatively high and the fuel cell provides high power when the capacitors become significantly discharged. The fuel cell rapidly recharges the capacitors when the power demand is reduced. If interface electronics are used to control the current from the fuel cell, it is possible to maintain the fuel cell operation at a near constant power [29]. This is probably the preferred arrangement of fuel cell and ultracapacitors, but it is more expensive. In their present fuel cell vehicle, the Clarity, Honda utilizes a lithium-ion battery and interface electronics to load level the fuel cell [30].

10. Vehicle projects using ultracapacitors

There have been a number of demonstration projects of hybrid-electric vehicles using EDLCs [31-38]. Most of these projects have involved transit buses and trucks, but a few have involved passenger cars. In some instances, the capacitors have been used in conjunction with batteries – lead-acid or nickel cadmium. In all cases, the ultracapacitors used were of the carbon/carbon type.

10.1. Transit buses

In the United States, the company must active in utilizing EDLCs in hybrid-electric powertrains for buses and large trucks has been the ISE Corporation in San Diego, California [31,32]. ISE has developed a 360V capacitor unit consisting of 144 2600F Maxwell cells connected in series (see Figure 7). The weight and volume are 114 kg and 189L, respectively. The unit stores .325 kWh of energy (.245 kWh useable). In a transit bus, two of the units are used in series resulting in a voltage of 720V and energy storage of 0.650 kWh. The peak power capability of the combined unit is over 300 kW. ISE utilizes this EDLC unit with a 225 kW electric motor in series hybrids using gasoline and diesel engines and hydrogen fuel cells. Since the capacitor unit stores only about .5 kWh, it can provide power only during vehicle acceleration and recover energy during braking and the engine or fuel cell must provide all the power during cruise and high climbing. ISE has built over 100 buses using the EDLC energy storage units for transit companies in Southern California. The buses are in daily revenue service. Fuel economy records indicate that the hybrid buses using ultracapacitors achieve 25-30 % better fuel economy than the diesel powered buses and consistently better fuel economy than hybrid buses using batteries [31]. The measured round-trip efficiency of the ultracapacitor unit was 94%.

Nominal Voltage	360V*
Peak Voltage	403V**
Rated Current	400A
Capacitance	18.05F
Total Energy Stored nominal / max.	0.325kWh / 0.407kWh
Leakage Current	5mA nominal
Operating Temperature	-35 to 65 °C
Weight	240lbs
Dimensions wxlxh	24"x40"x12"
Standard Pack	144 Capacitors
Fire Suppression System	Heat Activated Halotron System

Figure 7 The ISE ECC unit (360V, .325 kWh)

10.2. Passenger car

A recent passenger car project involving ECCs in a hybrid-electric driveline is discussed in [33, 34]. The project was termed "SUPERCAR" and was funded by the European Community (EC). It was a joint project between EPCOS, the EDLC developer, and Siemens VDO, the vehicle integrator. The parallel hybrid passenger car (VW Golf) combined an EDLC module and lead-acid battery into a 42V, 10 kW (peak) electric driveline with a 66 kW engine. The vehicle was tested on both the chassis dynamometer and the road. The tests showed a 16-18% improvement in fuel economy compared to the standard ICE car.

The capacitor unit consisted of 24 3600F cells connected in series (see Table 1 for the cell characteristics). The rated voltage of the unit is 60V and its capacitance and resistance are 150F and 8 mOhms, respectively. The unit is shown in Figure 8.
Additional passenger car projects are discussed in [38, 39, 40].

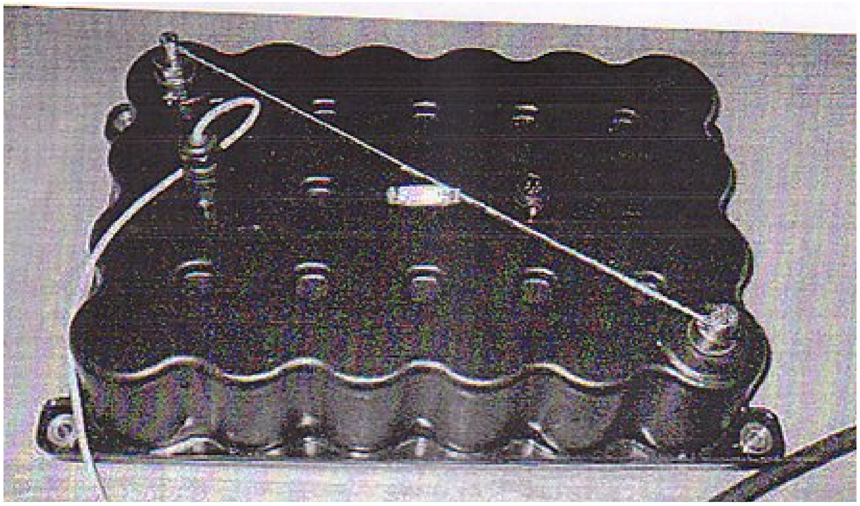


Figure 8 The EPCOS 60V ECC module (150F, 56 Wh)

11. Summary and conclusions

This paper is concerned with both the requirements for energy storage in various types of electric and hybrid vehicles and the characteristics of the energy storage devices being developed. The paper focuses on ultracapactors (electrochemical capacitors) as energy storage in vehicle applications and thus evaluates the present state-of-the-art of ultracapacitor technologies and their suitability for use in electric and hybrid drivelines of various types of vehicles.

A key consideration in determining the applicability of ultracapacitors for a particular vehicle application is the proper assessment of the energy storage and power requirements. For hybrid-electric vehicles, the key issues are the useable energy requirement and the maximum pulse power at high efficiency. For a Prius size vehicle, if the useable energy storage is about 125 Wh and needed efficiency is 90-95%, the test data and analysis shown in this paper indicate that vehicles can be designed using carbon ultracapacitors (both carbon/carbon and hybrid carbon) that yield high fuel economy improvements for all driving cycles and the cost of the ultracapacitors can be competitive with lithium-ion batteries for high volume production and carbon prices of less than \$20/kg. The use of carbon/carbon devices in micro-hybrids is particularly attractive for a control strategy (sawtooth) that permits engine operation near its maximum efficiency using only a 6 kW electric motor. Vehicle projects in transit buses and passenger cars using ultracapacitors have shown that the ultracapacitors have functioned as expected in the vehicles and significant fuel economy improvements have been achieved that are higher than would have been possible using batteries because of the higher round-trip efficiencies of the ultracapacitors (lower losses in charging and discharging the energy storage unit). Ultracapacitors have particular advantages for use in fuel cell powered vehicles in which it is likely they can be used without interface electronics.

Carbon/carbon ultracapacitors are presently available from a number of companies. The useable energy density of these devices is about 4.5 Wh/kg and the power density of a 95% efficient pulse is about 1000 W/kg. A limited number of carbon/carbon devices with a high efficiency power density of greater than 2000 W/kg have been tested. Development of hybrid carbon devices is continuing showing energy densities of 12 Wh/kg and a high efficiency power density of about 1000 W/kg. Vehicle simulations using those devices have shown that increased power capability in such devices is needed before full advantage can be taken of their increased energy density compared to carbon/carbon devices in some vehicle applications. Energy storage system considerations indicate that combinations of ultracapacitors and advanced batteries (Wh/kg>200) are likely to prove advantageous in the future as such batteries are developed. This is likely to be the case in plug-in hybrids with high power electric motors for which it may be difficult to limit the size and weight of the energy storage unit even using advanced batteries.

References

1. Burke AF. Comparisons of Lithium-ion Batteries and Ultracapacitors in Hybrid-electric Vehicle Applications. EET-2007 European Ele-Drive Conference, Brussels, Belgium, June 1, 2007.
2. Burke AF, Miller M, McCaffrey Z. The World-wide Status and Application of Ultracapacitors in Vehicles: Cell and Module Performance and Cost and System Considerations. EVS-22, Yokohama, Japan, October 2006.
3. Peasaran A. Factors and Conditions for Widespread Use of Ultracapacitors in Automotive Applications. Proceedings of the Advanced Capacitor World Summit 2007. San Diego, California, July 2007.
4. Burke AF, Van Gelder E. Plug-in Hybrid-Electric Vehicle Powertrain Design and Control Strategy Options and Simulation Results with Lithium-ion Batteries. EET-2008 European Ele-Drive Conference, Geneva, Switzerland, March 12, 2008.
5. Markel T, Brooker A, Gonder J, O'Keefe M, Simpson A, Thornton M. Plug-in Hybrid Vehicle Analysis. NREL/MP-540-40609, November 2006.

6. Burke AF, Miller M, Van Gelder E. Ultracapacitors and Batteries for Hybrid Vehicle Applications, EVS-23. Long Beach, California, December 2007.
7. Burke AF, Miller M. Present and Projected Performance of Hybrid Electrochemical Capacitors. 4th International Symposium on Large Ultracapacitor Technology and Applications. Tampa, Florida, May 13-14, 2008.
8. Burke AF, Miller M. Tests of New Ultracapacitors and Comparisons with Lithium-ion Batteries for Hybrid vehicle Applications. Proceedings of the 16th International Seminar on Double-layer Capacitors and Hybrid Storage Devices. Deerfield Beach, Florida, December 2007.
9. Burke A, Miller M. Supercapacitors for Hybrid-electric Vehicles: Recent Test Data and Future Projections. Advanced Capacitor World Summit 2008. San Diego, California, July 14-16, 2008.
10. Burke AF. Materials Research for High Energy Density Electrochemical Capacitors. Material Research Society, Symposium Series JJ. November 2008.
11. ECS Interface, Special issue-Electrochemical Capacitors – Powering the 21st Century. 17(1), Spring 2008.
12. Simon P, Burke AF. Nanostructured carbons: double-layer capacitance and more. ECS Interface, Special issue-Electrochemical Capacitors – Powering the 21st Century, 17(1), pp. 38-41, Spring 2008.
13. Burke AF. R&D Considerations for the Performance and Application of Electrochemical Capacitors. Electrochimica Acta. 53(3). pp. 1083-1091, December 2007.
14. Conway BE. Electrochemical Capacitors- Scientific Fundamentals and Technological Applications. Kluwer Academic Publishers, 1999.
15. Levie RD. Advances in Electrochemistry and Electrochemical Engineering. Vol. 6, Electrochemical Responses of Porous and Rough Electrodes, pp. 329-397. P. Delahay, Editor, Interscience Publishers, 1967.
16. Anderman M. Comparison of the Value Proposition of an Ultracapacitor vs. a High Power Battery for Hybrid Vehicle Applications. Proceedings of the Advanced Capacitor World Summit 2004. Washington, D.C., July 2004.
17. Anderman M. Could Ultracapacitors Become the Preferred Energy Storage Device for Future Vehicles? Proceedings of the 5th International Advanced Automotive Battery Conference. Honolulu, Hawaii, June 15-17, 2005.
18. Burke AF, Miller M. Emerging Lithium-ion Battery Technologies for PHEVs: Test Data and Performance Comparisons. Pre-conference Battery Workshop, Plug-in 2008, San Jose, California, July 21, 2008.
19. Burke AF, Miller M. Performance Characteristics of Lithium-ion Batteries of Various Chemistries for Plug-in Hybrid Vehicles. EVS-24, Stavanger, Norway, May 2009.
20. Miller. ANL reports on bat and cap combinations.

21. Burke AF, Miller M. Electrochemical Capacitors as Energy Storage in Hybrid-Electric Vehicles: Present Status and Future Prospects. EVS-24, Stavanger, Norway, May 2009.
22. Burke AF, Zhao H, Van Gelder E. Simulated Performance of Alternative Hybrid-Electric Powertrains in Vehicles on Various Driving Cycles. EVS-24, Stavanger, Norway, May 2009.
23. Burke AF. Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles. IEEE Journal, special issue on Electric Powertrains, 95(4), April 2007.
24. Burke AF. Application of Ultracapacitors in Mild/Moderate Hybrid-electric Vehicles. ESScap06, Switzerland, November 2006.
25. Cole GH. SIMPLEV: A Simple Electric Vehicle Simulation Program-Version 2. EG&G Report No. DOE/ID-10293-2, April 1993 .
26. Burke AF. Electric and Hybrid Vehicle Design and Performance. Chapter 6, pp. 129-189, Environmentally Conscious Transportation, edited by M. Kutz, John Wiley & Sons , 2008.
27. Knight B. Information on the ultracapacitors used in the Honda Fuel Cell Vehicle. March 2003.
28. United Technologies paper on the characteristics of UTC fuel cell stacks, Proceedings of the Second International Advanced Battery Conference, Las Vegas, Nevada, February 4-7, 2002.
29. Zhao, H. and Burke, A.F, Optimum Performance of Direct hydrogen Hybrid Fuel Cell Vehicles, EVS-24, Stavanger, Norway, May 2009.
30. Honda news releases on the Clarity fuel cell vehicle, available on the internet, 2009.
31. Bartley T. Ultracapacitors – No Longer Just a Technology: Real, Safe, Efficient, Available. Proceedings of the Advanced Capacitor World Summit 2004. Washington, D.C., July 2004.
32. Bartley T. Ultracapacitor Energy Storage in Heavy-duty Hybrid Drive Update. Proceedings of the Advanced Capacitor World Summit 2005. San Diego, California, July 2005.
33. Schwake A. EC-funded Project “SUPERCAR”: Ultracapacitor Modules for Mild Hybrid Applications. Proceedings of the Second International Symposium on Large Ultracapacitor (EDLC) Technology and Application, Baltimore, Maryland, May 16-17, 2006.
34. Knorr R. SUPERCAR – Results of a European Mild Hybrid Project. Proceedings of the 6th International Advanced Automotive Battery and Ultracapacitor Conference. Baltimore, Maryland, May 17-19, 2006.
35. King RD. etc. Ultracapacitor Enhanced Zero Emissions Zinc Air Electric Transit Bus – Performance Test Results. 20th International Electric Vehicle Symposium, Long Beach, California, 2003.

36. King RD. etc. Performance and Emissions Test Results of a Low-floor, Low-emissions Transit Bus with a 225 kW Hybrid –Electric Propulsion System. EVS-21, Monaco, April 2005.
37. Armiroli P. etc. Valeo Stars+System, Ultracapacitors: the way for Regen for Micro-Mild Hybrids. Proceedings of the Fourth International Symposium on Large Ultracapacitor Technology and Application, Tampa, Florida, May 2008.
38. Wight G., etals. Integration and Testing of a DC/DC Controlled Suupercapacitor into an Electric Vehicle. Proceedings of EVS-18, Berlin, Germany, October 2001.
39. Okamura M, Hayashi K, Ohta H. Status Report on ECaSS and Nanogate-Capacitors. Proceedings of the 16th International Seminar on Double-Layer Capacitors & Hybrid Energy Storage Devices, Deerfield Beach, Florida, December 2006.
40. Gonder, J. Pesaran, A., Lustbader, J., and Tataria, H., Fuel Economy and Performance of Mild Hybrids with Ultracapacitors – Simulations and Vehicle Test Results, presented at the 5th International Symposium on Large EC Capacitor Technology and Applications, Long Beach, California, June 9-10, 2009

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