Performance, Charging, and Second-use Considerations for Lithium Batteries for Plug-in Electric Vehicles

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Abstract

This paper is concerned with batteries for use in plug-in electric vehicles. These vehicles use batteries that store a significant amount (kWh) of energy and thus will offer the possibilities for second-use in utility related applications such as residential and commercial backup systems and solar and wind generation systems. Cell test data are presented for the performance of lithium-ion batteries of several chemistries suitable for use in plug-in vehicles. The energy density of cells using NiCo (nickelate) in the positive electrode have the highest energy density being in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive have energy density between 80-110 Wh/kg and those using lithium titanate oxide in the negative electrode can have energy density between 60-70 Wh/kg. Tests were performed for charging rates between 1C and 6C. The test results indicate that both iron phosphate and titanate oxide battery chemistries can be fast charged. However, the fast charge capability of the titanate oxide chemistry is superior to that of the iron phosphate chemistry both with respect to temperature rise during charging and the Ah capacity retention for charging up to the maximum voltage without taper.

There are a number of possible second-use applications. Some of these applications are closely linked to utility operations and others are connected to commercial and residential end-users. Since the energy storage and power requirements for the end-user applications are comparable to those of the original vehicle applications and would require only minor reconfiguring of the packs, these applications are well suited for second-use. The applications closely related to utility operations do not seem well suited for second-use. Those applications require MW power and MWh of energy storage which are orders of magnitude larger than that of the vehicle applications. The primary barrier to implementation of the second-use is demonstrating the economic viability of the reuse of the batteries in terms of the cost of the batteries to the second owners and a guarantee that the used batteries would have satisfactory calendar and cycle life.

Introduction

This paper is concerned with batteries for use in plug-in electric vehicles. By plug-in vehicles is meant hybrid-electric vehicles and battery-powered electric vehicles that depend on charging from the grid to obtain all/or a significant fraction of the energy they use for propulsion. These vehicles use batteries that store a significant amount (kWh) of energy and thus will offer the possibilities for second use in utility related applications such as residential and commercial backup systems and solar and wind generation systems.

The batteries used in the plug-in vehicles are likely to be one of the lithium-ion chemistries. Results from testing a number of lithium-ion batteries in the Hybrid Vehicle Propulsion System Lab at the University of California-Davis will be discussed in terms of their performance (energy density and power density). In addition, fast charging characteristics of the different lithium battery chemistries are presented and how those differences could relate to the manner in which the batteries would be charged by consumers in the field.

A final topic considered in the paper is the potential second use of the plug-in vehicle batteries in utility related applications. A review will be given of what factors should be considered in assessing the likelihood that the vehicle batteries will find a market after their performance has degraded such that they are no longer suitable for use in the plug-in electric vehicles. These batteries will retain a large fraction (at least 75%) of their initial energy storage capacity, but likely a smaller fraction of their initial power capability. The factors to be considered include extended calendar life and cycle life and how to relate these characteristics to the condition of the batteries when removed from the plug-in vehicles.

Plug-in vehicle/battery design considerations

Battery sizing and selection

The selection of the battery for plug-in vehicles is a complicated process and depends on many factors. In simplest terms, the battery must meet the energy storage (kWh) and peak power (kW) requirements of the vehicle and fit into the space available. In addition, the battery must satisfy cycle life requirements both for deep discharge in the charge depleting mode and shallow cycling in the charge sustaining mode of operation. Further the battery unit must be designed to meet thermal management, cell-to-cell monitoring, and safety requirements. The final considerations are concerned with the initial and life cycle costs of the battery. The battery size and cost will vary markedly depending on the all-electric range of the vehicle.

It is convenient to start the discussion of the batteries for plug-in electric vehicles with consideration of battery-powered vehicles which depend completely on battery stored electricity for propulsion. The batteries in those vehicles are sized by the energy storage requirement and not the power required by the electric motor. The characteristics of battery-powered vehicles of various types are given in Table 1. For a range of 100 miles, the batteries in those vehicles store 20-40 kWh and are relatively heavy weighing 170-320 kg. The pulsed power density required of the batteries is 400-500 W/kg, which is modest for the lithium-ion batteries.

Table 1: Characteristics of battery-powered electric vehicles (EV) of various types

Vehicle type	Vehicle test weight kg	Battery Wgt. kg (1)	Battery kWh stored (2)	Electric motor kW (3)	Required Battery pulse power W/kg (4)	Wh/mi from battery (5)	0-60 mph Sec
Cars							
Compact	**1373**	**168**	**20.2**	**65**	**387**	**202**	**11.3**
Mid-size	**1695**	**208**	**24.9**	**102**	**490**	**249**	**8.9**
Full	**1949**	**238**	**28.5**	**122**	**513**	**285**	**8.6**
SUV							
Small	**2103**	**266**	**31.9**	**128**	**481**	**319**	**9.6**
Mid-size	**2243**	**278**	**33.3**	**143**	**514**	**333**	**9.3**
Full	**2701**	**317**	**38.0**	**160**	**501**	**380**	**9.6**

(1) Lithium-ion battery with an energy density of 120 Wh/kg
(2) All vehicles have a range of 100 miles
(3) Peak motor power
(4) Peak pulsed power required from the battery at 90% efficiency
(5) Average energy consumption on the FUDS and FHWAY drive cycles

In the case of plug-in hybrid vehicles, there is much design flexibility in selecting the battery size and the electric motor and engine powers, because the all-electric range is a design variable and the power demand of the vehicle can be met by a combination (blending) of motor and engine output even when the battery is being depleted. Typical design combinations for all-electric ranges between 10-40 miles are shown in Table 2 for a mid-size passenger car. The increased weight and decreasing power density

Table 2: Battery sizing and power density for plug-in hybrid vehicles for various all-electric range and electric motor power (mid-size passenger car)

Range miles	Electric motor kW	Engine power kW	Battery kWh *needed	Battery kWh** stored	Battery kg***	Battery kW/kg
10	50	100	2.52	3.6	30	1.66
15	55	100	3.78	5.4	45	1.22
20	60	75	5.04	7.2	60	1.0
30	75	60	7.56	10.8	90	.83
40	100	50	10.1	14.4	120	.83

* Vehicle energy useage from the battery: 250 Wh/mi
** Useable state-of-charge for batteries: 70%, weights shown are for cells only
*** battery energy density 120Wh/kg

requirement of the battery with increasing all-electric (battery depletion) range of the vehicle is typical of plug-in hybrid designs. The battery in a plug-in hybrid vehicle with a short all-electric range (<20 miles) will experience a deep discharge cycle almost every day and hence must be designed for more deep discharge cycles than the battery in a vehicle with a long all-electric range. It is clear from Table 2 that the requirements for batteries used in vehicles with short all-electric range are more demanding than those in other hybrid vehicles. This will result in those batteries being more expensive on a $/kWh basis than batteries in vehicles with long all-electric range and less likelihood that those batteries will be suitable for second-use recycling.

Battery/grid considerations

The batteries in plug-in hybrid vehicles are intended to be recharged off the grid either at the home of the vehicle owner or at a public charging station. For vehicles with short all-electric range (< 20 miles), the charging can be done off a standard 120V plug in 3-4 hours or less. For vehicle storing more than 10 kWh, a higher voltage charger (208V) will be needed unless the charging is done overnight. If the battery has fast charging capability (charging in 10 minutes or less), a high voltage, high power charger will be needed. This would in most cases be a public charging station built for the convenience of plug-in hybrid vehicle owners. For example, to charge the battery in the vehicle with a 30 mile range in 10 minutes requires a charger power of at least 50 kW.

The time of day for charging batteries in plug-in vehicles is somewhat uncertain. It seems likely that most of the charging of batteries in EVs will occur at night because the capacity of the batteries is relatively large and the owners expect that most charging will take place at home using a high voltage charger. For plug-in hybrids, the time of charging is more uncertain as significant charging can be done with 120V chargers and the owners are likely to take advantage of limited time recharging as a means of attaining higher effective fuel economy with their hybrid vehicles. In addition, there is the possibility that some owners of vehicles with a longer all-electric range will utilize fast charging stations as a means of extending all-electric operation of their vehicle. In either case, the result could be that the plug-in vehicles will be charged occasionally when the utilities power demand is high during mid-day and the afternoon. This could be the case even if the electrical rates were high during those periods.

Batteries for plug-in vehicles

It is well recognized that the key issue in the marketing of plug-in vehicles is the availability of batteries with sufficient performance (energy and power) and low enough initial cost and long enough cycle/calendar life to permit the design of vehicles attractive to prospective vehicle buyers. The consensus view is the battery will be of the lithium-ion type, but which of the lithium-ion chemistries to use is still a major question. The selection will depend on a number of factors: useable energy density, useable power density, cycle and calendar life, safety (thermal stability), and cost. The most developed of the lithium-ion chemistries is that used in consumer electronics – that is carbon/graphite in the negative electrode and nickel cobalt and other metal oxides in the positive electrode. That chemistry yields the best performance (energy density and power density), but also has the greatest uncertainty concerning safety. The other chemistries (iron phosphate in the positive and lithium titanate in the negative) being developed are known to have less favorable performance, but less concern regarding safety and longer cycle life. These latter chemistries have been evaluated in detail in the present study.

The lithium-ion battery technology used for consumer electronics applications is reasonably mature and in 2008 over one billion, small (18650) cells were manufactured and sold. These cells utilized graphite/carbon in the negative and nickelate (LiNiCoAlO) in the positive. The graphite/nickelate chemistry yields cells with the highest energy density and power capability of the chemistries being developed for vehicle applications primarily because the cell voltage and the specific charge (mAh/gm) of the positive electrode material are higher than for the other chemistries. The material and cell characteristics of the various chemistries are shown in Table 3. If performance of the cell was the only consideration, there would be little interest in developing cells/batteries with the other chemistries. However, cycle life and safety (thermal stability) as well as cost are important considerations in selecting batteries for vehicle applications. Unfortunately the graphite/nickelate chemistry has shown in the consumer electronics applications to have safety and cycle life limitations, which can become even more serious for the large cells/batteries needed for vehicle applications. Hence development is underway using lithium manganese spinel and iron phosphate for the positive electrodes and lithium titanate oxide for the negative electrode. As indicated in Table 3, these chemistries have significantly lower performance than the graphite/nickelate chemistry, but longer cycle life and higher thermal stability. It is more difficult to compare the power capability of the different chemistries, because there is the inherent trade-off between energy density and power capability via the design of the electrodes and choice of material properties (primarily particle size and surface area). Nevertheless, the cells with the higher cell voltage tend to have higher power capability. The goal of the developments of the other chemistries is to minimize the penalty in performance without significant sacrifice of the inherent advantages of the respective emerging chemistries. A number of companies world-wide are presently developing lithium-ion batteries utilizing the various electrode chemistries. Most of these companies are relatively small and are not well known in the battery business, but nevertheless their technologies are representative of the possibilities for the development of the emerging battery technologies.

A number of cells/chemistries were tested in the lab at UC Davis to assess their use in plug-in vehicles. Most of the cells for the consumer electronics applications are spiral wound packaged in a rigid container. Some cells are prismatic (thin, flat) in shape, but they are also packaged in a rigid container. All these cells (Figure 1) are small (1-3 Ah) and can be used in vehicle applications only if larger cells/modules are assembled by placing many of the small cells in parallel. This can be done, but it requires special attention to safety issues. For vehicle applications, larger cells (up to 100 Ah) are being developed so it is not necessary to assemble parallel strings of the cells in the modules. In all cases, the modules consist of a number of cells in series to attain a reasonably high module voltage. In some cases, the larger cells (Ah > 10 Ah) are packaged in a soft laminated pouch (see Figure 2), which are then placed in a rigid container to form a high voltage module. Some of the larger cells are spiral wound (see Figure 3), but the trend in cell development seems to be toward soft packaging. Whether this proves to be a wise trend remains to be seen as there are strong, well founded concerns about the robustness and reliability of the soft packaging for vehicle applications. The large format cells/modules are clearly of prime interest for consideration for second use applications.

Table 3: Characteristics of lithium-ion batteries using various chemistries

Chemistry Anode/cathode	Cell voltage Max/nom.	Ah/gm Anode/cathode	Energy density Wh/kg	Cycle life (deep)	Thermal stability
Graphite/ $NiCoMnO_2$	4.2/3.6	.36/.18	100-170	2000-3000	fairly stable
Graphite/ Mn spinel	4.0/3.6	.36/.11	100-120	1000	fairly stable
Graphite/ $NiCoAlO_2$	4.2/3.6	.36/.18	100-150	2000-3000	least stable
Graphite/ iron phosphate	3.65/ 3.25	.36/.16	90-115	>3000	Stable
Lithium titanate/ Mn spinel	2.8/2.4	.18/.11	60-75	>5000	most stable

Figure 1: Small, spiral wound cells

Figure 2: Pouch packaged cells

44 Ah cell **7.5 Ah**

Figure 3: Spiral wound large cells

In order to determine the performance of the cells/modules, the following tests were performed:

1) **Constant current tests** starting at C/1 and up to currents at which the Ah capacity of the cell begins to show a significant decrease with rate.
2) **Constant power tests** starting at about 100 W/kg and up to powers (W/kg) at which the energy density (Wh/kg) begins to show a significant decrease with rate.
3) **5 sec pulse tests** at high currents (5-10C) at states of charge between 90% -10% to determine the open-circuit voltage and resistance from which the power capability of the cells can be calculated.

The power capability of the cells/modules was determined in the present study by determining the open-circuit voltage and resistance as a function of state-of-charge and calculating the pulse power using the following equation:

$$P = Eff\,(1\text{-}Eff)\,V_{oc}^{\,2}/R$$

where Eff is the pulse efficiency, $Eff = V_{pulse}/V_{oc}$

The power density is simply calculated as P/battery weight or volume. This method is not too different from that given in the USABC test manual for PHEV batteries and can be applied for cells/modules independent of the vehicle in which they would be used.

Test data for the 15Ah EIG iron phosphate cell and the Altairnano 11Ah titanate oxide cell are given in Tables 4 and 5. Detailed test data for other cells and modules are given in [1, 2].

Table 4: Test data for the 15 Ah EIG iron phosphate cell

Iron Phosphate				
FO 15A	**Weight .424kg**	**3.65-2.0V**		
Power (W)	**W/kg**	**Time (sec)**	**Wh**	**Wh/kg**
62	142	2854	49.5	117
102	240	1694	48.0	113
202	476	803	45.1	106
302	712	519	43.5	103
401	945	374	41.7	98
Current (A)	**Time (sec)**	**Ah**	**Crate**	**Resistance mOhm**
15	3776	15.7	.95	
30	1847	15.4	1.95	2.5
100	548	15.2	6.6	
200	272	15.1	13.2	
300	177	14.8	20.3	

Table 5: Test data for the Altairnano 11Ah lithium titanate oxide cell

Constant current test data (2.8-1.5V)

I(A)	nC	Time (sec)	Ah	Resistance mOhm
10	.8	4244	11.8	--
20	1.7	2133	11.9	--
50	4.5	806	11.2	2.2
100	9.2	393	10.9	2.1
150	15.3	235	9.8	--
200	---	116	6.4	--

Resistance based on 5 sec pulse tests

Constant power test data (2.8-1.5V)

Power W	W/kg	Time sec	nC	Wh	Wh/kg
30	88	2904	1.2	24.2	71.2
50	147	1730	2.1	24.0	70.7
70	206	1243	2.9	24.2	71.0
100	294	853	4.2	23.7	69.7
150	441	521	6.9	21.7	63.8
170	500	457	7.9	21.6	63.5
260	764	255	14	18.4	54.2
340	1000	103	35.0	9.7	28.6

Mass: .34 kg

The iron phosphate cell could be used in a plug-in hybrid with an all-electric range of 20-40 miles and the titanate oxide cell would be better suited for vehicles with a short all-electric range of 10-15 miles.

Comparisons of the performance of lithium-ion cells of the different chemistries from various battery developers

A summary of the data for the different chemistries is shown in Table 6. It is clear from the table that both the energy density and power capability of the cells vary over a wide range and that there are significant trade-offs between energy and power with all the chemistries. Energy density and power capability are discussed separately.

Energy density

It is clear from Table 6 that the energy density of cells using NiCo (nickelate) in the positive electrode have the highest energy density being in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive have energy density between 80-110 Wh/kg and those using lithium titanate oxide in the negative electrode can have energy density between 60-70 Wh/kg. Hence in terms of energy density, the rankings of the different chemistries are clear and the differences are significant: 1. NiCo, 2. iron phosphate, 3. lithium titanate oxide. The question of what fraction of the energy density is useable in a specific vehicle application could decrease the relative advantage of the different chemistries.

Table 6: Summary of the performance characteristics of lithium-ion cells of different chemistries from various battery developers

Manufacturer	Technology type	Ah	Voltage range	Wh/kg at 300 W/kg	$(W/kg)_{90\%eff.}$ 50% SOC
K2	Iron phosphate	2.4	3.65-2.0	86	667
EIG	Iron phosphate	10.5 15.7	3.65-2.0	83 113	708 919
A123	Iron phosphate	2.1	3.6-2.5	88	1146
Lishen	Iron Phosphate	10.2	3.65-2.0	82	161
EIG	Graphite/ Ni CoMnO2	18	4.2-3.0	140	895
GAIA	Graphite/ LiNiCoO2	42	4.1-3.0	94	1742 at 70%SOC
Quallion	Graphite/ Mn spinel	1.8	4.2-3.0	144	491 at 60%SOC
		2.3	4.2-3.0	170	379 at 60%SOC
Altairnano	Lithium Titanate	11 52	2.8-1.5	70 57	684 340
EIG	Lithium Titanate	12.0	2.7-1.5	43	584

Power capability

The situation regarding the power capability (W/kg) of the different chemistries is not as clear as was the case for energy density because of the energy density/power capability trade-offs inherent in battery design. Further the question of the maximum useable power density is also application specific. In order to have a well-defined basis for comparing the different chemistries and cells, the power density (W/kg) for a 90% efficient pulse at 50% SOC is shown in Table 6. The power densities can vary over a wide range even for a given chemistry. This is particularly true for the graphite/NiCoMn chemistry. In general, it seems possible to design high power batteries (500-1000 W/kg at 90% efficiency) for all the chemistries if one is willing to sacrifice energy density and likely also cycle life. The data in Table 6 indicate that high power iron phosphate cells can be designed without a significant sacrifice in energy density. When power densities greater than 2000 W/kg for lithium-ion batteries are claimed, it is for low efficiency pulses. For example, for an efficiency of 65%, the 15Ah EIG iron phosphate battery has a pulse power of 2330 W/kg rather than the 919 value for a 90% efficient pulse.

Fast charging characteristics of lithium-ion batteries

There is presently considerable interest in fast charging of batteries in both battery-powered and plug-in hybrid vehicles. It is claimed that both the lithium titanate oxide and iron phosphate chemistries can be fast charged in about ten minutes. A series of tests have been performed using the 11Ah titanate oxide cell and the 15Ah iron phosphate cell whose characteristics were discussed previously. Tests were performed for charging rates between 1C and 6C. The cells were charged to a maximum (clamp) voltage and then the current was tapered to 1/10 the initial charge current. For all the tests, the cells were discharged at the 1C rate (1hr.) to determine the effect of charging rate on cell Ah capacity. The test results, which are summarized in Table 7, indicate that both battery chemistries can be fast charged. However, the fast charge capability of the titanate oxide chemistry is superior to that of the iron phosphate chemistry both with respect to temperature rise during charging and the Ah capacity retention for charging up to the maximum voltage without taper. For example, in the case of the lithium titanate oxide cell charged at 66A in 620 sec, the 1C capacity was 11.2 Ah compared to 12.0 Ah for a 1C (1 hr) charge.

Both cells were also fast charged for five repeated cycles to investigate the effect on the temperature rise and Ah capacity. In these tests, the cells were not actively cooled. The results for the lithium titanate oxide cell are shown in Table 8 and in Figure 4 . The charge time to the maximum voltage (cut-off of charge) was 614 sec with a temperature rise during charging of 4.5 deg C. However, the temperature decreased back to ambient during the discharge so that the temperature remained stable during the five cycles. The capacity of the cell was 11.2Ah for each cycle.

These tests indicate that fast charging of the lithium batteries should be possible without great difficulty if high power charging stations are available. Recent life cycle data (see Figure 5) taken by Altairnano indicate that the 11 Ah cells have long cycle life under fast charge (x C) conditions so the effect of fast charging on cycle life should not be a concern for the lithium titanate oxide batteries.

Table 7: Fast charge test data for lithium-ion chemistries

EIG iron phosphate 15 Ah cell

Charge Current (Amps)	Time to Cutoff (secs)	Taper Time (secs)	Charge to Cutoff (Amp-hrs)	Total Charge (Amp-hrs)	Discharge (Amp-hrs)	Temp Rise During Cha Initial Temp (C)	Temp Change (C)
15	3630	210	15.2	15.4	15.50	22.5	0
30	1770	210	14.7	15.4	15.45	22.5	1.5
45	1140	199	14.2	15.4	15.38	22.5	3
60	840	172	13.9	15.3	15.30	23.5	4.5
75	630	184	13.1	15.3	15.29	25.5	5.5
90	480	219	11.9	15.2	15.17	23	7
120	240	316	7.9	15.2	15.16	25	9
No Taper							
60	780.4		12.9		12.99		
90	464.8		11.6		11.60		

Altairnano titanate oxide 11 Ah cell

Charge Current (Amps)	Time to Cutoff (secs)	Taper Time (secs)		Charge (Amp-hrs)	Discharge (Amp-hrs)	Temp Rise During Cha Initial Temp (C)	Temp Change (C)
11	3920	81	11.9	12.0	12.00	22.5	0
22	1950	68.5	11.9	12.0	12.00	22	0.5
33	1300	57.7	11.9	12.0	12.00	22.5	1.5
44	970	59.2	11.8	12.0	12.01	23	2.5
55	760	74.8	11.6	12.0	11.97	21.5	4
66	620	83	11.3	12.0	11.97	22.5	4.5
88	440	103.1	10.7	12.0	11.97	24	6.5

Table 8: Repeated fast charging cycles for the 11Ah lithium Titanate oxide cell

66 Amps charge to 2.8V 12A discharge to 1.5V no active cooling

Cycle	Charge or Discharge	Time to Cutoff (secs)	charge Amp-hrs	Discharge Amp-hrs	Initial Temp (C)	Highest Temp (C)
1	Chg	614.4	11.26		21.5	26
2	Dischg			11.19	24	22
2	Chg	614.7	11.27		21.5	26.5
3	Dischg			11.18	24	22
3	Chg	614.5	11.27		21.5	26
4	Dishcg			11.18	24	22
4	Chg	614.1	11.26		21.5	26
5	Dischg			11.17	23.5	22
5	Chg	614.1	11.26		21.5	26

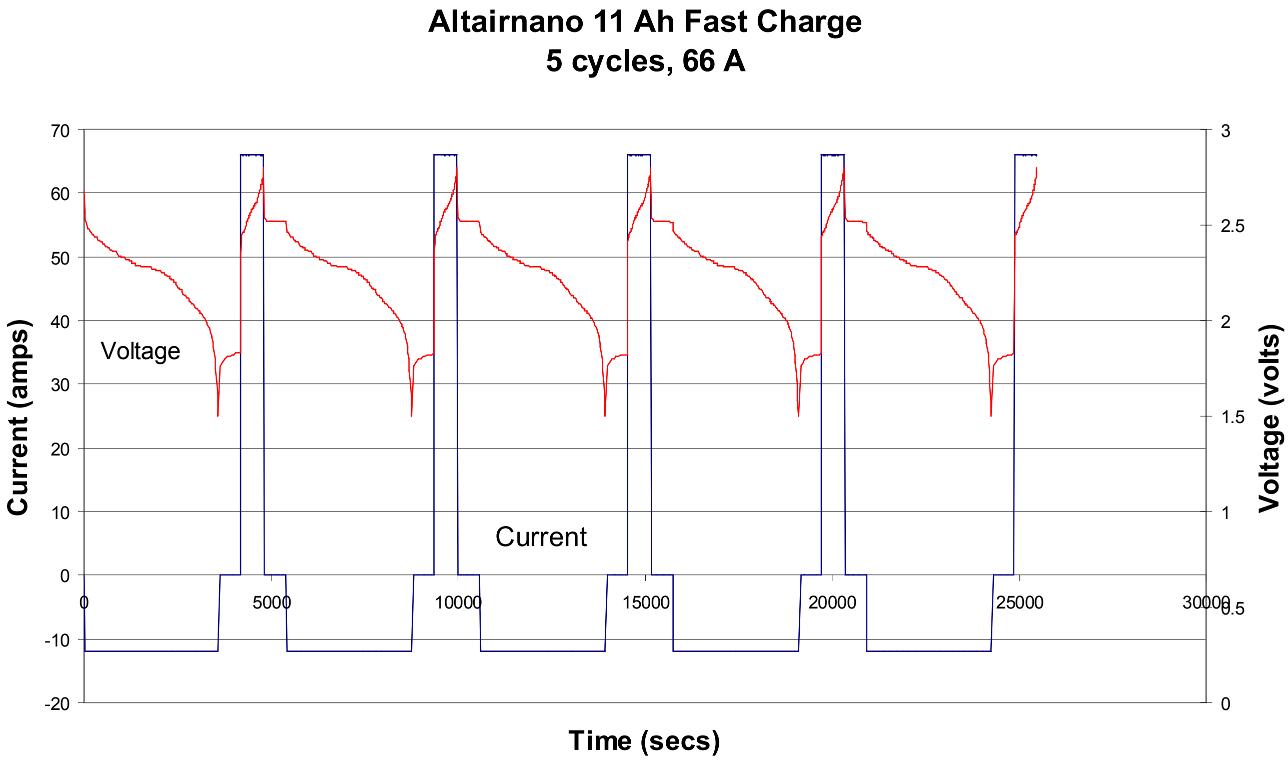

Figure 4: Five fast charge cycles for the Altairnano 11Ah lithium titanate cell

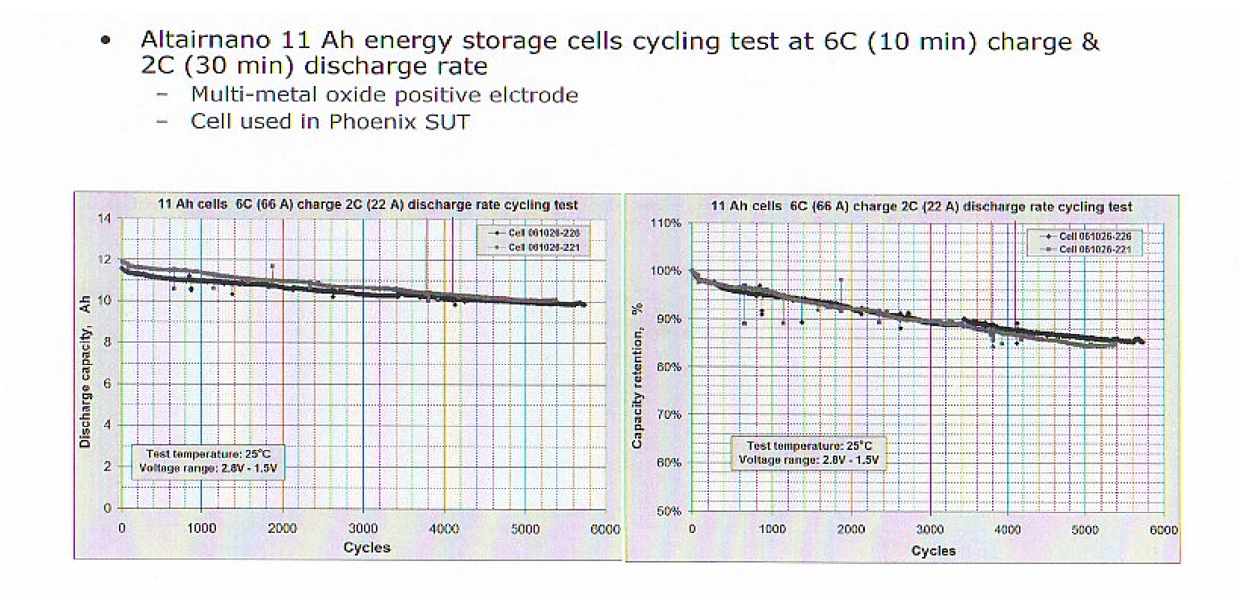

Figure 5: Life cycle data from Altairnano for the 11 Ah cell under fast charging (6C) conditions

Plug-in hybrid vehicle simulations using various battery chemistries

Simulations of Prius plug-in hybrids have been performed with **Advisor** utilizing lithium-ion batteries of the different chemistries [3, 4]. The UC Davis test data were used to prepare the battery input files needed in **Advisor**. Simulations were made for battery packs weighing 60 kg and 120 kg. The results of the simulations are given in Table 9a,b. Note from Table 9 that plug-in hybrids can be designed using the various lithium-ion batteries as well as a nickel metal hydride battery. However, the charge depleted (CD) electric ranges of the various designs and their fuel economy in the CD mode are much different and the differences are highly dependent on the driving cycle. The CD ranges are larger for the batteries with the higher energy densities and the fuel economies in the CD mode are highest for the batteries that are capable of high peak power. High battery power capability permits the vehicle to operate in the all-electric mode (engine off) until the energy in the battery is depleted. The fuel economy in the charge sustaining (CS) mode is dependent on the driving cycle, but not significantly on the battery energy density and weight of the battery pack. The weight of the battery and its energy density have a large effect on CD operation as would be expected. The simulation results show that the selection of the battery chemistry for plug-in hybrids is closely linked to the details of the vehicle design and performance specifications and expected driving cycle. Economic factors such as cycle life and battery cost and battery management and safety issues must also be considered in selecting the most appropriate battery chemistry of plug-in hybrids.

Table 9a: Simulation results for Prius PHEVs using various lithium-ion batteries

		60 kg Battery			
		Varta (Ovonic)	LFP (A123)	NCM (Gaia)	LTO (Altairnano)
		Ni-MH	Li-Ion	Li-Ion	Li-Ion
(1) Power					
(Cell power density)	W/kg	333	1100	1700	680
Pack Power Density[a]	W/kg	250	825	1275	510
Battery Peak Power	kW	15	50	77	31
Motor peak power[b]	kW	**13**	**42**	**65**	**26**
(2) Energy Capacity					
(Cell Energy density)	Wh/kg	71	90	96	70
Pack Total Energy Density[a]	Wh/kg	54	68	72	53
Total Energy	kWh	3.21	4.05	4.32	3.15
Available Energy[c]	kWh	**2.57**	**3.24**	**3.46**	**2.52**
Cell Voltage	V	**13.4**	**3.2**	**3.6**	**2.3**
Cell Capacity	Ah	**15**	**19**	**20**	**15**
# of Cells	#	**16**	**67**	**60**	**94**
(3) PHEV performance (US06)					
CD electricity use	Wh/mile	171	225	175	157
CD range	miles	15	14	20	16
CD gasoline use	mpg	98	3000	inf	425
CS gasoline use	mpg	44	44	43	43
(3) PHEV performance (UDDS)					
CD electricity use	Wh/mile	149	126	97	93
CD range	miles	17	26	36	27
CD gasoline use	mpg	800	inf	inf	inf
CS gasoline use	mpg	67	73	69	71
(3) PHEV performance (HWFET)					
CD electricity use	Wh/mile	178	155	120	114
CD range	miles	14	21	29	22
CD gasoline use	mpg	1500	inf	inf	inf
CS gasoline use	mpg	66	67	64	66

[a] Assuming packing factor = 0.75

[b] Assuming motor efficiency equals = 0.85

[c] Assuming DOD = 0.8

Table 9b: Simulation results for Prius PHEVs using various lithium-ion batteries

		120 kg Battery			
		Varta (Ovonic) Ni-MH	LFP (A123) Li-Ion	NCM (Gaia) Li-Ion	LTO (Altairnano) Li-Ion
(1) Power					
(Cell power density)	W/kg	333	1100	1700	680
Pack Power Density[a]	W/kg	250	825	1275	510
Battery Peak Power	kW	30	99	153	61
Motor peak power[b]	kW	**25**	**84**	**130**	**52**
(2) Energy Capacity					
(Cell Energy density)	Wh/kg	71	90	96	70
Pack Total Energy Density[a]	Wh/kg	54	68	72	53
Total Energy	kWh	6.43	8.10	8.64	6.30
Available Energy[c]	kWh	**5.14**	**6.48**	**6.91**	**5.04**
Cell Voltage	V	**13.4**	**3.2**	**3.6**	**2.3**
Cell Capacity	Ah	**30**	**37**	**40**	**29**
# of Cells	#	**16**	**68**	**60**	**94**
(3) PHEV performance (US06)					
CD electricity use	Wh/mile	246	182	169	187
CD range	miles	21	36	41	27
CD gasoline use	mpg	329	inf	inf	inf
CS gasoline use	mpg	43	44	45	42
(3) PHEV performance (UDDS)					
CD electricity use	Wh/mile	146	104	97	104
CD range	miles	35	62	71	48
CD gasoline use	mpg	inf	inf	inf	inf
CS gasoline use	mpg	69	71	71	72
(3) PHEV performance (HWFET)					
CD electricity use	Wh/mile	171	127	118	126
CD range	miles	30	51	59	40
CD gasoline use	mpg	inf	inf	inf	inf
CS gasoline use	mpg	66	66	66	66

[a] Assuming packing factor = 0.75
[b] Assuming motor efficiency equals = 0.85
[c] Assuming DOD = 0.8

Assuming packing factor = 0.75
Assuming motor efficiency equals = 0.85

Second-use of plug-in vehicle batteries

General considerations

The high cost of batteries continues to be one of the primary barriers to the commercialization of plug-in electric vehicles. In addition, vehicle applications are more demanding on batteries than most other applications in terms of performance and cycle life. Hence there is considerable interest in the possibility that vehicle batteries could be used in other applications after they are no longer suitable for use in vehicles. If this second use of vehicle batteries is feasible, it could defray part of the high initial cost of the batteries to the original vehicle owner. In this paper, batteries to be used in plug-in electric vehicles are of particular interest along with second applications of interest to electric utilities. A detailed study of this problem as it related to nickel metal hydride batteries is given in [5]. The present study is concerned with lithium-ion batteries, but the considerations are closely related to those discussed in the earlier study. There have been recent studies [6, 7] of electrical energy storage in utility applications which are pertinent to the present second use study. The results of those studies are also relevant to the present study.

As shown in Tables 1 and 2, the requirements for batteries to be used in vehicle applications vary markedly with the application in terms of energy stored, peak power, and size (kg). These differences are highlighted in Table 10 for plug-in hybrids and battery powered vehicles of various ranges. As a result of these differences, the cell size (Ah) and module/pack characteristics of batteries available to be recycled from plug-in electric vehicles will vary over a wide range.

Table 10: Battery and cell characteristics for plug-in electric vehicles

Electric range mi	System voltage	Weight of cells kg *	Energy stored kWh **	Ah/cell	Peak power kW	P/E ratio	Peak W/kg
10	150	30	3.6	24	50	13.9	1666
15	200	45	5.4	27	55	10.2	1222
20	250	60	7.2	29	60	8.3	1000
30	300	90	10.8	36	75	6.9	833
40	300	120	14.4	48	100	6.9	833
50	300	150	18	60	100	5.6	667
100	300	208	25	83	105	4.2	505

* energy density of the cells 120 Wh/kg

** useable fraction of stored energy 70%

The batteries in the hybrid vehicles presently being marketed in California are warranted for 10 years or 120,000 miles by the vehicle manufacturer. These warranties are set in regulations of the California Air Resources Board. It is expected that the same warranties would apply t o the batteries in the plug-in vehicles. For deep-discharge batteries, end-of-life is usually defined as when the battery capacity decreases by 20% from the rated value and/or the peak (pulse) power capability decreases by 25% from the initial value due to an increase in battery resistance. It is easier for the vehicle owner to discern a decrease in battery capacity (decrease in range) than a decrease in power capability. Hence it can be expected there would be some variability in the condition of the batteries when it is determined their performance is no longer satisfactory for the vehicle application. Clearly properly assessment of he condition of the batteries made available for reuse is essential and will require careful attention.

Since the energy and power requirements of the batteries in the second-use application would be expected to be significantly less demanding than in the vehicle application, it will be necessary to determine the calendar and cycle life of the partially expended batteries in the new application. This will require careful testing of the used vehicle batteries both to determine their condition and the life remaining, which is likely to vary for different second-use applications.

Potential second-use applications

As discussed in [5-8], there are a number of possible second-use applications. These include the following:

(a) Transmission quality
(b) Spinning reserve
(c) Regional regulation
(d) Load leveling base generation
(e) Load leveling renewable generation
(f) Peak reliability and peak shaving
(g) UPS systems
(h) Light commercial load leveling
(i) Telecommunications backup
(j) Residential load leveling

The energy storage system requirements for the various applications are summarized in Table 11.

Table 11: Energy storage system requirements for various applications

Application	Duration	Energy storage	Power
Transmission quality	10-100 sec pulses	<1 MWh	100 MW
Spinning reserve	15 minutes	7.5 MWh	20 MW
Regional regulation	Continuous cycling	2 MWh	10-20 MW
Load leveling base generation	>5 hrs	50 MWh	10 MW
Load level renewable generation	1-10 hrs	1-10 MWh	1-5 MW
Peak reliability Peak shaving	3-4 hrs.	3-4 MWh	1-2 MW pulses

UPS			
Light commercial load leveling	3 hrs.	75-100 kWh	200 kW pulses 25 kW average
Telecommunications backup	5-10 hrs.	25-50 kWh	5 kW
Residential load leveling	3 hrs.	3-4 kWh	10 kW peak 1 kW average

The system requirements in Table 11 seem to indicate that the second-use of batteries from plug-in vehicles are best suited for the last three applications. The energy storage and power requirements for those applications are comparable to those of the original application in vehicles and would require only minor reconfiguring of the packs. In addition, the cell size (Ah) of the plug-in vehicle batteries would be appropriate resulting in the need to series/parallel relatively few packs in these applications. It seems unlikely that the battery packs from Prius-type charge sustaining hybrids presently be sold in large numbers would be appropriate for second-use applications, because their cell size is so small (<5 Ah using lithium-ion cells) and the packs will store less than 1 kWh.

The applications closely related to utility operations require MW power and MWh of energy storage which are orders of magnitude larger than that of the vehicle applications. Configuring battery packs for the utility applications would require packs from hundreds of vehicles which would be expensive and difficult to maintain uniform quality of performance of the large packs.

Residential/commercial applications with PV

Batteries can be used in grid-connected residential and commercial PV systems either for load leveling the demand and/or storing energy for later use when electricity is higher price or because the installation is in a remote area, off-grid. The voltage of the DC side of the residential systems is in the range of 24-150V and that of large commercial systems in the range of 500-600V. The peak power of the residential systems is 3-5 kW and that of the commercial systems 100-200 kW. A schematic of these systems is shown in Figure 6. Battery charging is done using by a battery charge controller that usually chops the PV panel voltage down to that needed to charge the battery. Electrical energy to the DC/AC inverter can be provided by the PV panel or battery alone or the PV panel and battery in combination. For crystalline silicone cells, a standard 1.5 ft x 5 ft panel can provide 40V and 200W. These panels or sub-sizes of the panels would be arranged in series and parallel to get the voltage and current required by the system.

The energy stored in the batteries could be relatively small. For example in a residential system, the batteries could be 60Ah and the voltage 96V resulting in about 6 kWh of storage. For a commercial system, the corresponding values could be 300 Ah, 400V, and 120 kWh. These battery system requirements are certainly doable with batteries from plug-in vehicles especially those with a reasonably long electric range.

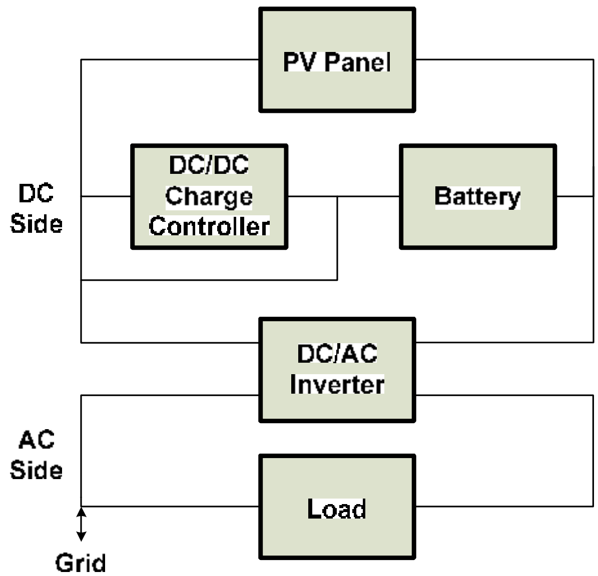

Figure 6: PV/battery system schematic

Prospects and barriers

In principle, it would seem that implementation of the second-use of plug-in electric vehicle batteries in the small scale applications that seem most appropriate should not be overly difficult. These applications could be essentially local to the vehicles from which the batteries are taken and require only relatively short transportation of the used batteries for processing and distribution to the new customers. The primary barrier to implementation would be demonstrating the economic viability of the reuse of the batteries in terms of the cost of the batteries to the second owners and a guarantee that the used batteries would have satisfactory calendar and cycle life. It would be necessary to convince potential customers of the recycled batteries that their use is more cost effective for them than purchasing new batteries, which could include low cost lead-acid batteries.

There are several ways in which reuse of the batteries could be utilized to reduce the cost of plug-in vehicle batteries either initially or over time as the vehicle is used. In any case, the purchasers of plug-in vehicles would have to benefit from the value of the second-use of the batteries. This could be done by subtracting some fraction of the sale price of the reused batteries from the initial cost of the new plug-in vehicle batteries. This could be done most easily if the same company owned the batteries over their complete life, including second-use. Another approach is for the plug-in vehicle owner to lease the batteries or pay for the batteries as they used electricity stored in the batteries. In either case, the cost of the batteries would be paid over their life time significantly reducing the initial cost of the plug-in vehicle.

One of the barriers to implementing the second-use battery market is the difficulty in establishing a business case for second-use company. Over a period of time this will require information regarding the performance, cycle life, and price of new plug-in vehicle batteries and the likely condition of the batteries when they would be removed from the vehicle at end of life after at least 5-10 years of service. The second-use company would also need sufficient information regarding the condition of the batteries and the second-use application to be able to set a reliable warranty for the batteries. In addition, they would need a good indication of the size of the markets they would be involved with. The end result would have to be a price for the reused batteries that would foster both the markets for the plug-in vehicles and the second-use batteries. An analysis of these markets should be undertaken as soon as the needed input information becomes available.

Summary and conclusions

This paper is concerned with batteries for use in plug-in electric vehicles. These vehicles use batteries that store a significant amount (kWh) of energy and thus will offer the possibilities for second-use in utility related applications such as residential and commercial backup systems and solar and wind generation systems. Lithium-ion batteries for plug-in hybrid vehicles with all-electric ranges of 10-40 miles and battery-powered vehicles with a range of 100 miles are characterized in terms of cell size (Ah), energy storage (kWh), and power (kW) and are used for various discussions in this paper.

Cell test data are presented for the performance of lithium-ion batteries of several chemistries suitable for use in plug-in vehicles. The energy density of cells using NiCo (nickelate) in the positive electrode have the highest energy density being in the range of 100-170 Wh/kg. Cells using iron phosphate in the positive have energy density between 80-110 Wh/kg and those using lithium titanate oxide in the negative electrode can have energy density between 60-70 Wh/kg. The question of what fraction of the energy density is useable in a specific vehicle application can decrease the relative advantage of the different chemistries. The situation regarding the power capability (W/kg) of the different chemistries is not as clear as was the case for energy density because of the energy density/power capability trade-offs inherent in battery design. The power densities can vary over a wide range even for a given chemistry. This is particularly true for the graphite/NiCoMn chemistry. In general, it is possible to design high power batteries (500-1000 W/kg at 90% efficiency) for all the chemistries if one is willing to sacrifice energy density and likely also cycle life.

There is presently considerable interest in fast charging of batteries in both battery-powered and plug-in hybrid vehicles. A series of tests were been performed using the 11Ah titanate oxide cell and the 15Ah iron phosphate cell. Tests were performed for charging rates between 1C and 6C. The test results indicate that both battery chemistries can be fast charged. However, the fast charge capability of the titanate oxide chemistry is superior to that of the iron phosphate chemistry both with respect to temperature rise during charging and the Ah capacity retention for charging up to the maximum voltage without taper. Both cells were also fast charged for five repeated cycles to investigate the effect on the temperature rise and Ah capacity. In these tests, the cells were not actively cooled. These tests indicate that fast charging of the lithium batteries will be is possible without great difficulty if high power charging stations are available.

Simulations of Prius plug-in hybrids have been performed with **Advisor** utilizing lithium-ion batteries of the different chemistries. Simulations were made for battery packs weighing 60 kg and 120 kg. Plug-in hybrids can be designed using the various lithium-ion batteries as well as a nickel metal hydride battery. However, the charge depleted (CD) electric ranges of the various designs and their fuel economy in the CD mode are much different and the differences are highly dependent on the driving cycle. The CD ranges are larger for the batteries with the higher energy densities and the fuel economies in the CD mode are highest for the batteries that are capable of high peak power. High battery power capability permits the vehicle to operate in the all-electric mode (engine off) until the energy in the battery is depleted. The fuel economy in the charge sustaining (CS) mode is dependent on the driving cycle, but not significantly on the battery energy density and weight of the battery pack. The simulation results show that the selection of the battery chemistry for plug-in hybrids is closely linked to the details of the vehicle design and performance specifications and expected driving cycle. Economic factors such as cycle life and battery cost and battery management and safety issues must also be considered in selecting the most appropriate battery chemistry of plug-in hybrids.

The high cost of batteries continues to be one of the primary barriers to the commercialization of plug-in electric vehicles. If the second-use of vehicle batteries is feasible, it could defray part of the high initial cost of the batteries to the original vehicle owner. There are a number of possible second-use applications. Some of these applications are closely linked to utility operations and others are connected to commercial and residential end-users. Since the energy storage and power requirements for the end-user applications are comparable to those of the original vehicle applications and would require only minor reconfiguring of the packs, these applications are well suited for second-use. The applications closely related to utility operations do not seem well suited for second-use. Those applications require MW power and MWh of energy storage which are orders of magnitude larger than that of the vehicle applications. Configuring battery packs for a utility application would require packs from hundreds of vehicles which would be expensive and be difficult to maintain uniform quality of performance of the large packs.

. The primary barrier to implementation of the second-use would be demonstrating the economic viability of the reuse of the batteries in terms of the cost of the batteries to the second owners and a guarantee that the used batteries would have satisfactory calendar and cycle life. It would be necessary to convince potential customers of the recycled batteries that their use is more cost effective for them than purchasing new batteries, which could include low cost lead-acid batteries. Establishing a business case for second-use company will require information regarding the performance, cycle life, and price of new plug-in vehicle batteries and the likely condition of the batteries when they are removed from the vehicle at end of life after at least 5-10 years of service. The second-use company will need sufficient information to be able to set a reliable warranty for the batteries. In addition, they would need a good indication of the size of the markets they would be involved with. The end result would have to be a price for the reused batteries that would foster both the markets for the plug-in vehicles and the second-use batteries.

An analysis of these markets should be undertaken as soon as the needed input information becomes available.

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