Performances of batteries technologies in vehicle applications

Daniel Chatroux

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Abstract

The main four batteries technologies for electric vehicles are lead acid, NiCd, NimH and Lithium-ion batteries. Mainly, these technologies are compared with the supplier specifications. In our laboratory, monitoring of electric vehicle indicates significant differences between the supplier specifications and real use performances, because of the specification conditions. The goal of this study is to focus on the main relevant parameters to select battery technologies for electric vehicle applications and to give some figures on the technologies.

1. Batteries for vehicles applications

1.1. CEA and LITEN presentation

CEA (Commissariat à l'Energie Atomique et aux Energies Alternatives) is an energy research center in France dedicated to research and development in nuclear applications and in renewable energy development. At CEA Grenoble center, two main research fields at LITEN institute are fuel cells and lithium batteries (from component to system).

For lithium-ion batteries, the whole chain is involved: materials for Lithium ion accumulators, accumulator conception, production, battery packs design, battery management systems, electric vehicle integration and monitoring of vehicles.

In different projects, we replace existing Lead acid, NiCd or NimH battery packs by Lithium ion batteries. We observe a big difference between the stored energy according to the supplier specifications for different battery technologies and the ranges of the vehicles.

Another result is the difference between laboratory test results and number of cycles on vehicles in real operating conditions. This point impacts directly on kilometer costs.

This presentation focuses on some CEA results to give a first level of overview on this subject.

1.2. Differences between supplier specifications and effective vehicle ranges

The first case of great difference measured between supplier specification and vehicle range was presented at PCIM in 2009 [1] for NiCd technology. The monitoring of a small electric car with NiCd battery indicates that the stored energy in the batteries in real use is 8.7 kWh instead of 12 kWh as specified. This small car is an AX from Citroën. The same result has been published by the Idaho National Laboratory [2] for the monitoring of a Kangoo from Renault using the same NiCd technology.

For the AX battery pack, the gravimetric energy decreases from 46 Wh/kg (12 kWh specified for 250 kg) to 33 Wh/kg, (8.7 kWh in real use for 250 kg).

The difference between the real performance and the specification is the test conditions. This NiCd technology is tested for a three hours discharge. In real use, with a speed average of 90 km/h the battery is discharged in three quarters of hour. With this NiCd technology, the range is only 60-70 km. Because of the too fast discharge for this NiCd battery, a part of the energy is dissipated in the too high internal resistance and a part of the battery capacitance is not used in discharge because of diffusion phenomena. After the end of discharge and some times of storage, a part of this capacitance is available and it is possible to restart the vehicle for some additional kilometers.

Lead acid battery is well used for small electric vehicles. This technology has a low initial investment cost and seems to be an interesting challenge to provide a competitive kilometric cost. For three years, the laboratory has monitored Lead acid electric vehicles. In parallel we modify the vehicles to implant a lithium-ion one.

For a small two wheel vehicle (Trotty from Jean Claude Andruet) for the same level of energy, the range is presented in Figure 1 between the initial Lead Acid battery and our standard Lithium Iron phosphate (LiFePO4) module.

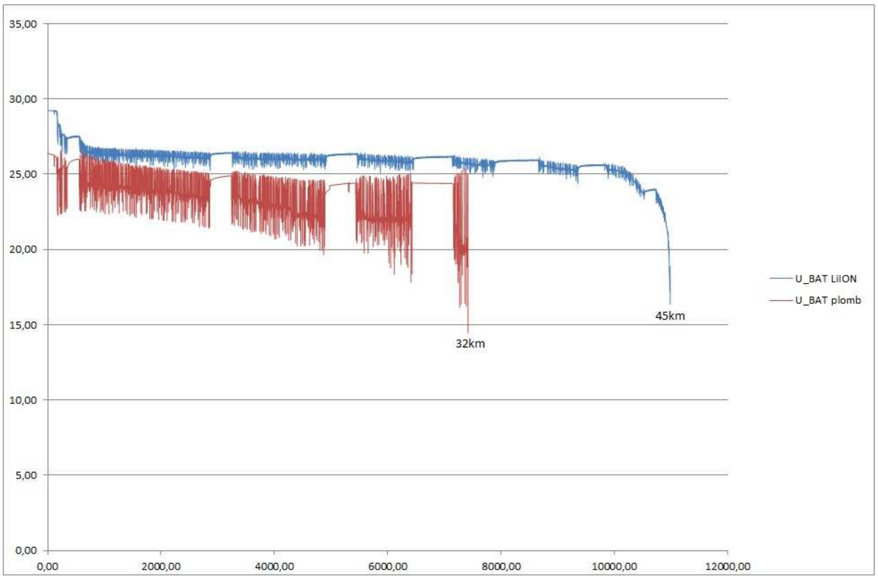

Figure 1: Voltages of Lead acid and LiFePO4 Lithium ion batteries for the same discharge profile, X-axis time in second, Y-axis voltage in Volts

With the same speed profile, the lead acid battery of 1.2 kWh provides a 32 km range and the 980 Wh LiFePO4 one provides a 45 km range. The LiFePO4 module has a lower internal resistance. The voltage drop is much lower than Lead acid one.

As for NiCd batteries, a part of the capacitance of the lead acid battery is not used for fast discharges.

1.3. Synopsis of accumulator supplier specifications for different technologies

The document [3] indicates the level of performance of different technologies of electrochemical accumulators.

	Lead acid	NiCd	NimH	ZEBRA	LiFePO4 Iron phosphate Li-ion	Li ion (1)	Li Polymer
Gravimetric energy (Wh/kg)	30-50	45-80	60-110	120	120-140	150-190	150-190
Energy density (Wh/l)	75-120	80-150	220-330	180	190-220	220-330	220-330
Power density (2) (W/kg)	up to 700		up to 900	200	up to 800 (3)	up to 1500	up to 250
Number of cycles	400-600(1) 1200(2)	2000	1500	800	>2000	500-1000	200-300
Self discharge per month	5%	20%	30% (4)	12 % per day (5)	5% (6)	10%	10%
Nominal voltage	2V	1,2V	1,2V	2,6 V	3,2V	3,6V	3,7V
Temperature range	-20°C +60°C	-40°C +60°C	-20°C +60°C	-40°C +50°C	0°C +45°C (charge) -20°C +60°C (discharge)	-20°C +60°C (7)	0°C +60°C
Advantages	Cost	Reliability, low temperature	Good energy density (Wh/l)	Good energy density (Wh/l), number of cycles	Good energy density (Wh/l), safetyy, cost, number of cycles	Excellent energy and power	Thin batteries are possible
Disadvantages	Poor energy instantaneous death	Low energy, toxicity	Raw material cost (8), temperature behavior	Power limitation, energy losses	Low temperature charge (7)	Security for big accumulator cost (7)	Low temperature performance cost (7)
Cost estimation (9) (€/kWh)	200 to 250 (a) 200 (b)	600	1500 to 2000	800 to 900	1000 to 1800	2000	1500 to 2000

(a) sealed (b) tubular

In this table, there are a lot of information.

The table can be completed with new results or precisions:

- (1) Li ion has several main families with different behaviors,
- (2) For all accumulators, there are energy versions optimized for energy but with lower power, and power versions with lower energy density,
- (3) the A123Systems company designed LiFePO4 for electric tools at 2 600 W/kg (for 10 s discharge) and VL10VFe of Saft - Jonhson Control have 5 kW/kg continuous discharge,
- (4) For high quality NimH, the initial self-discharge is high (30% for example) but decrease a lot in a second phase. In a Vectrix scooter, we measure than a NimH battery from GP is only half discharge after more than one year of storage,
- (5) ZEBRA is a high temperature accumulator with high temperature conditioning. Resistors are used to maintain the temperature in storage. Per year, the electricity to warm the accumulators in storage increases significantly the electricity cost,
- (6) For A123Systems in format 26650, the accumulators have low discharge after more than two years of storage,
- (7) As for LiFePO4, most Lithium ion technologies are adapted for discharge at negative temperatures, **but for charge the minimum temperature is around 0°C**. It's necessary to know the problem and to ask the question to the supplier on this point. In

real use, it's possible to charge at negative temperatures but with lower current. The low temperature charge has a great impact on the number of cycles. Specific tests on this point are necessary in practical,

- (8) Lanthanum, a rare earth, is used in the Hydrid,
- (9) Since 2005, the costs have decreased.

2. Results on electric vehicles

2.1. Performances of packs on electric vehicles

In AX vehicle, for the initial NiCd battery pack, there are twenty battery modules 6V 100Ah in series. The gravimetric energy for module, based on supplier specification, is 54 Wh/kg. Each module weights 13.2 kg. So the energy per module should be 712 Wh. For the twenty modules, the energy should be 14 kWh at the beginning of the life to be at the level of 12 kWh at the end of the life (vehicle supplier specification). For main accumulators, the end of life is achieved for a loss of 20% of the initial capacity.

Because of additional mass the weight of the whole pack is 290 kg,. According to the vehicle supplier specifications (12 kWh), the gravimetric energy for the pack should be defined at the end of the life. The gravimetric energy based on real energy supplied in electric car running at 90 km/h is 30 Wh/kg.

Accumulator	Energy kWh	Weight	Gravimetric energy
6V 100Ah beginning of life	710 Wh	13,2 kg	**54 Wh/kg (specified)**
20 accumulators beginning of life	14.2 kWh	264 kg	54 Wh/kg
20 accumulators end of life	12 kWh	264 kg	45 Wh/kg
Pack beginning of life	14.2 kWh	290 kg	49 Wh/kg
Pack end of life	12 kWh	290 kg	41 Wh/kg
Pack measured	8.7 kWh	290 kg	**30 Wh/kg (real use)**

The supplier specification for gravimetric energy (54 Wh/kg) is in the range of the literature value (45-80 Wh/kg). The battery pack in real use provides only 30Wh/kg for only 10% additional mass between accumulators and pack.

For the Vectrix, an electric scooter with NimH battery manufactured by Gold Peak (GP) the gravimetric energy for accumulator based on supplier specifications is 47 Wh/kg [5]. This value is low compared to literature values (60 - 110 Wh/kg). This accumulator is designed for power to provide the accelerations to the scooter, that is why this value is low for NimH technology. Because of this choice, in real use, the energy supplied by the battery pack is in the same order of magnitude 40 Wh/kg.

Figure 2 describes the gravimetric energy for three battery packs, one with Lithium ion with iron phosphate ($LiFePO_4$) with an energy optimization design (red curve), one with $LiFePO_4$ with power optimization (brown), and two for lead acid (yellow and black).

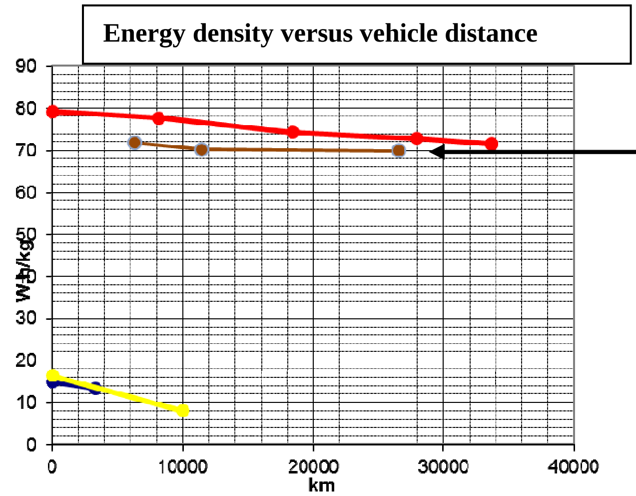

Figure 2: Gravimetric energy (Wh/kg) for energy LiFePO4, power LiFePO4 and Lead-acid batteries

For Lead-acid battery, Trotty is an example of two or three hours discharge (long discharge). For a car, the discharge time is around one hour only. The delivered energy decreases. The gravimetric energy may be less than 20 Wh/kg.

The loss of performance between accumulator gravimetric energy and battery pack due to additional mass, electronic, and safety devices. The loss of gravimetric energy is around 20% because the integration of Lithium ion accumulators requires more connections, mechanicals parts and electronic than Lead acid, NiCd or NimH batteries.

Another point is the ageing of the battery packs.

The worst case is for lead acid in a small car, the distance is only 10 000 km for the pack deterioration (Fig.2). This point has very important impact on kilometer cost. Lead acid seems to be a cost effective solution for electric vehicles but this technology is not adapted for the discharge in the range of one hour. The first impact is the gravimetric energy divided by two. The second impact measured is low number of cycles. With this technology, the initial cost is low but the kilometric cost may be high due to poor reliability. Lead acid batteries are more adapted for discharge in some hours, for vehicles with very low speed.

Energy LiFePO4 accumulators provide more energy at room temperature, but this energy decreases at low temperature [4] and the ageing is faster. This technology is adapted only for long range vehicles and temperature conditioning is necessary.

Power LiFePO4 accumulators provide good performances with the possibility of fast charge and without temperature conditioning. We measure a difference between winter and summer around 10%.

2.2. Some new results of a small electric car with iron phosphate battery technology

Now with our small car equipped with power LiFePO4 battery (brown curve), two runs of 10000 km have been performed within a month. Each day the car runs 500 to 600 km with six runs with five fast charge and one slow night charge. The charge duration is limited by the maximum current of the existing charging station to 45 minutes.

The first run of more than 10 000 km in one month was from 15th of July to 15th of August. In 10 000 km, less than 1% of capacitance decrease has been measured. The second run from the 1st of October to the 31st of October confirms the first result in distance and capacity losses.

In these tests, the capacity loss is only 1.7 % for 30 000 km with high temperature due to summer temperature and fast charge temperature rise. With standard linear decrease hypothesis, the battery could provide energy for 300 000 km in the same intensive utilization.

3. Conclusion

In our monitoring activity we measure great differences between batteries supplier's specifications and real pack measurement in vehicles applications.

In vehicle application the discharge rate of the battery pack, may be higher than supplier specification. A part of the energy is dissipated in series resistances. A part of the capacitance is not used.

	Lead acid	**NiCd**	**NimH**	**ZEBRA**	**LiFePO4** Iron phosphate Li-ion	**Li ion (1)**	**Li Polymer**
Specified gravimetric energy (Wh/kg	30-50	45-80	60-110	120	120-140	150-190	150-190
Measured pack gravimetric energy (Wh/kg)	20	30	40	?	70-80	100 ?	?

According to supplier specifications, lead acid seems to be a low cost solution for small electric vehicles. In a car, because of the fast discharge (around one hour) the real gravimetric energy is very low, with a great impact on vehicle mass. This solution provides poor vehicle performances. The initial cost seems promising but the fast ageing has a very important impact on kilometric cost.

Power LiFePO4 is a good candidate for electric vehicle because of the safety of the chemistry, the low cost of the material, and the great number of cycles in real applications. The gravimetric energy of the accumulators specified by the suppliers is lower than other Lithium-ion chemistry but we see that the good criteria is the real measurement and the comparison of the gravimetric energy of the global pack

The replacement of lead acid or NiCd or NimH provides lower mass, extended range from 50 to 100% and the promises of competitive kilometric costs in some years.

4. Literature

[1] Bruno Béranger, Daniel Chatroux, Eric Fernandez, Sébastien Fiette CEA-LITEN Experience feedback on electric vehicles of the French car fleet – battery impact PCIM 2009

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[3] Virginie Schwarz, Bernard Gindroz ADEME „Le stockage électrochimique“ Mines Energies Dossier stockage de l'Energie Janvier-Février 2005

[4] Julien Dauchy CEA-LITEN France Comparison between energy and power one for electrical vehicle applications PCIM 20010

[5] Daniel Chatroux, Marion Perrin, Power electronic and battery analysis of Vectrix Scooter, PCIM 2011, Nüremberg.