Evaluation of performance characteristics of various lithium-ion batteries for use in BEV application

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***Abstract*- The purpose of this paper is to assess the capabilities of commercial lithium-ion batteries for use in battery electric vehicles (BEV's). The evaluation criteria are based on a newly developed experimental methodology which describes the performance characteristics of different batteries of various chemistries. This methodology primarily permits the user to obtain the most important battery characteristics for charging and discharging, internal resistance, efficiency, Peukert constant, thermal stability during charge and discharge phases.**

The presented test data of the lithium-ion batteries are based on the nickel cobalt manganese ($NiCoMnO_2$), iron phosphate and nickel cobalt aluminum oxide in the positive electrode. The energy density of the batteries using nickel manganese cobalt oxide have the highest energy density in the range of 120 -150 Wh/kg compared to iron phosphate being in the range of 70 – 115 Wh/kg.

Further, from the point of view of the charge&discharge capability and energy efficiency, the first mentioned chemistry of batteries show the best performances.

However, the situation regarding the thermal stability indicates that nickel manganese cobalt oxide based batteries have less favorable performances.

Regarding the situation to the cost of the batteries, indicates that nickel manganese cobalt oxide based batteries are too expensive (400 – 800 $/kWh) compared to iron phosphate batteries (300 $/kWh). However, the cycle life of $NiCoMnO_2$ batteries is higher than the iron phosphate batteries.

Finally, special related attributes to the battery pack in battery electric vehicle have been analysed such as internal resistance and the variation between the battery cells, which are necessary for the development of a battery management system.

I. Introduction

As the global economy begins to strain under the pressure of rising petroleum prices and environmental concerns, research have spurred into the development of various types of Hybrid Electric Vehicles (HEV), Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV). HEVs and PHEVs usually require more than one energy source to provide more efficient propulsion. The energy sources should satisfy the following basic operational requirements [1][2]:

- Sufficient power capabilities, so that the necessary power required for propulsion can be supplied to the motor in any reasonable driving condition;
- Quick charging time, in order to increase vehicle availability;
- Sufficient life time, both in terms of calendar life and number of charge/discharge cycles;
- Cost [3]

The most promising battery technology which can fulfill all these requirements as mentioned above are the Lithium-ion batteries [1] [3]. Although various type of lithium battery can be found on the market, the performance characteristics of these batteries are not always specified in a clear and comparable way. This paper presents the performance characteristics of nine battery brands as can be seen in table 1. The batteries have been tested based on a new test methodology which is derived from the draft international standards IEC 62660-4 and ISO 12405-NP [4][5].

II. Methodology

In the literature various analyses are available for investigating the battery performances [6][7][8]. These analyses are often only suited for one type of hybridization topology as BEV, HEV or PHEV. Due to the fact that several Li-ion chemistries are commercialized, the performance characteristics of these batteries should be related to the application. From this point of view, a new test methodology has been introduced which permits us to characterize the performance of various batteries in terms of energy density, charge and discharge capacity, energy efficiency, Peukert constant, variation between cells, charge and discharge capabilities at different C-rates. The proposed test procedure as can be seen in Fig. 1 consists of equal charge and discharge C-rates.

In the literature, one can find several battery testing methods for use in BEV applications [3][7]. But these methods are often based on one discharge and charge rate,

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which are mostly related to the recommended manufacturer C-rate. However in real conditions, the battery package in BEV applications is continuously subjected to variable C-rates. Hereby, the battery performances will differ from the previous scenario. From this standpoint, the test methodology as can be seen in Fig.1, is developed at the Vrije Universiteit Brussel and the research institute VITO based on the draft international standards IEC 62660-4 and ISO 12405-NP [4][5].

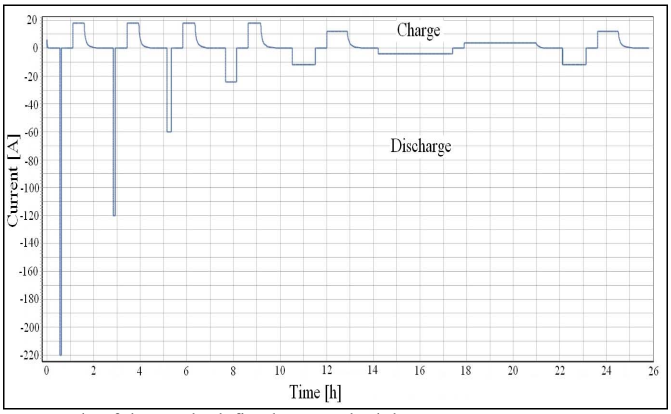

Fig. 1. An example of the newly defined test methodology

Table 1. CHARACTERISTICS OF THE SELECTED LITHIUM-ION BATTERIES FOR BATTERY ELECTRIC VEHICLE APPLICATIONS

Battery	Chemistry Anode/cathode	Shape	Voltage [V]	Capacity [Ah]	Peukert [-]	Resistance [mΩ]
A	Graphite/ iron phosphate	Cylinder	2 - 3.6	2.3	1.03	7.5
B	Graphite/ iron phosphate	Cylinder	2 - 3.65	2.5	1.03	15
C	Graphite/ iron phosphate	Cylinder	2 - 3.8	10	1.01	4
D	Graphite/ NiCoMnO2	Pouch	2.7 - 4.2	12	1.05	1.1
E	Graphite/ iron phosphate	Pouch	2 - 3.6	40	1.01	1.5
F	Graphite/ NiCoAlO2	Cylinder	2.7 - 4.2	27	1.03	0.4
G	Graphite/ iron phosphate	Prismatic	2.5 - 4.24	90	1.32	1
H	Graphite/ iron phosphate	Prismatic	2 - 3.65	45	1.02	0.9
I	Graphite/ NiCoMnO2	Pouch	2.7 - 4.2	70	1.03	0.3

III. RESULTS

In the framework of this study, the performance characteristics of different lithium-ion batteries of various chemistries have been investigated. The characteristics of these batteries are summarized in table 1.

A. Capacity and efficiency performances

The selection criterion of the different batteries remains a complicated process and depends on many factors. The first parameter which has been investigated for the BEV applications is the energy density. In Fig. 2, one can see that the batteries nickel manganese cobalt oxide ($LiNiCoMnO_2$) based D&E show the highest energy density in the range of 120 – 150 Wh/kg. While cells using iron phosphate and nickel cobalt aluminum oxide in the positive electrode have the energy density being in the range of 70 – 115Wh/kg.

The high values of the energy densities for the $LiNiCoMnO_2$ batteries are due to the high cell voltage and good electrode specific capacities [8][9].

These batteries indicate also a high energy efficiency values around 90 – 95%, which prove their suitability for BEV applications.

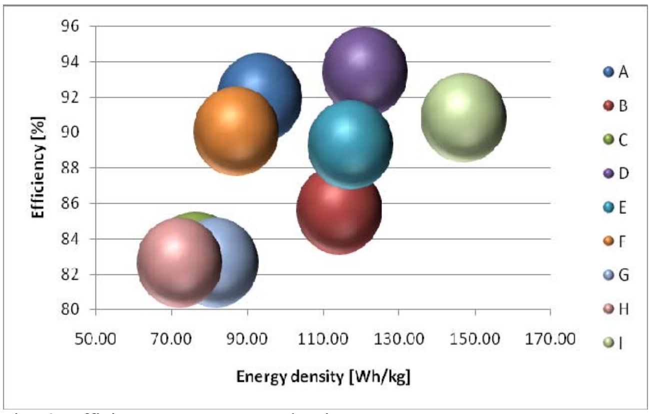

Fig. 2. Efficiency versus energy density

It should be pointed out that the energy density of the batteries has been calculated based on 2C discharge rate. However, in [10] is clearly stated that lead-acid batteries show that the available capacity heavily depends on the discharge C-rates. In BEV applications, the C-rate changes between 0 and 4.

We have further investigated this effect and we found that this effect does not exist for lithium-ion batteries as can be seen in table 1. Table 1 indicates that the Peukert constant is close to 1 with exception of battery G which is much higher

(1.32). The available capacity does not decrease significantly with higher discharge rates as presented in Fig. 3.

Further, the energy efficiency at different discharge C-rates has been investigated. This aspect can be considered as a key issue in BEV applications due to the fact that the losses in the internal resistance will cause the temperature of the battery to rise.

Fig. 4 clearly shows that the LiNiCoMnO and LiNiCoAlO2 batteries (D, F and I) have the highest energy efficiency at different discharge rates around 90% in comparison to 85% for the iron phosphate in the positive electrode with exception of the batteries A and E (90%).

The high energy efficiency values of the batteries D, F and I are due to the higher nominal voltage [8].

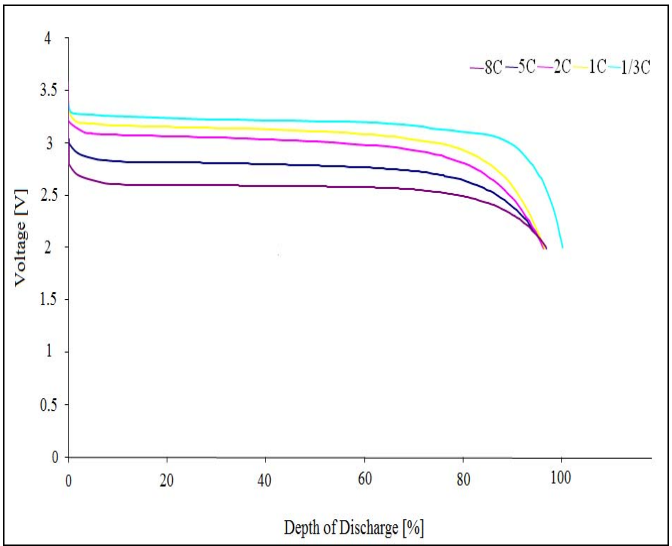

Fig. 3. Example of capacity performance of lithium-ion battery at different discharge rates

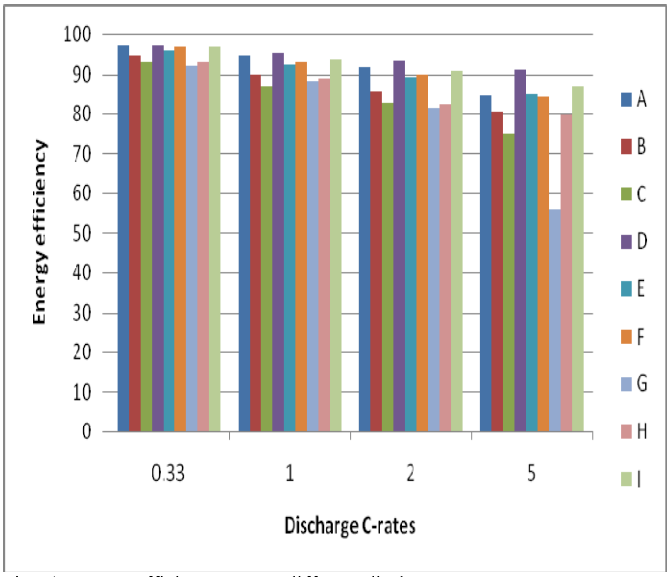

Fig. 4. Energy efficiency versus different discharge rates

B. *Charge capabilities*

It is generally known that battery electric vehicles are an important factor for improvement of traffic and more particularly for a healthier living environment. The operation of these vehicles is dependent on the availability of efficient electric energy storage devices. However, most of the commercial battery electric vehicles can be charged up to 16A. This yields that the charge process for BEV applications will take several hours (around 10 to 15) until the battery has been full charged. In order to enhance the suitability of battery electric vehicles, the charge current limit should be increased.

Van den Bossche defined three charging speed levels [11]:

- Normal charging: 3.7kW
- Semi-fast charging: 22.2kW
- Fast charging: 250kW

It is well documented in [11] that the charging process of a battery typically involves two phases:

- The main charging phase, where the bulk of energy is recharged into the battery,
- The final charge phase, where the battery is conditioned and balanced,

Most chargers in use today use the so-called IU characteristics, where a constant current I is used for the main charge and a constant voltage U for the final charge (Fig. 5).

The duration of the main charge phase is dependent on the available current, whileas the final charge , which only needs a small current [12].

In this study, the charging capabilities of the different batteries for the main charging phase have been analyzed based on charging rates from 1/3C to 3C. The results in Fig. 6 indicate generally that the NiCoMnO2 and NiCoAlO2 batteries at 3C-rate are most suited for fast charging. The charging capacity up to Vmax is around 88% of the mentioned manufacturer capacity. However, the batteries using iron phosphate in the positive electrode (E, G and H) show as well good charging capabilities around 90%.

Due to the higher charge current, the charge time can be reduced with a factor 3 (270A) in the case of G and H. However, in Table 1, we have seen that the battery G has very poor discharge capabilities, where the Peukert constant is 1.32 and energy efficiency about 70%.

As reported in [12], the time duration in the final charge phase for the most battery technologies takes several hours, typically values for lead-acid batteries is around 5 to 8 hours.

As presented in Fig. 7, the time duration during constant voltage charging is for the analysed batteries in the range of 0.3 – 1.5 hours. In this analysis, the same criterion has been used as for lead-acid batteries, whereby charging is terminated when the current is below 0.01C.

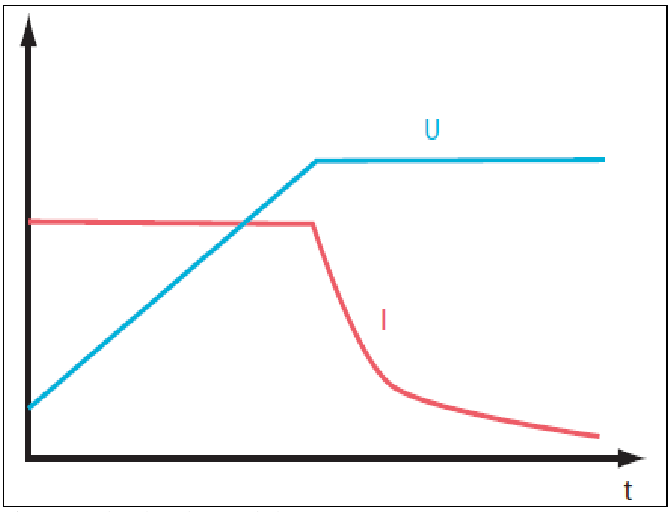

Fig. 5. IU charging characteristics

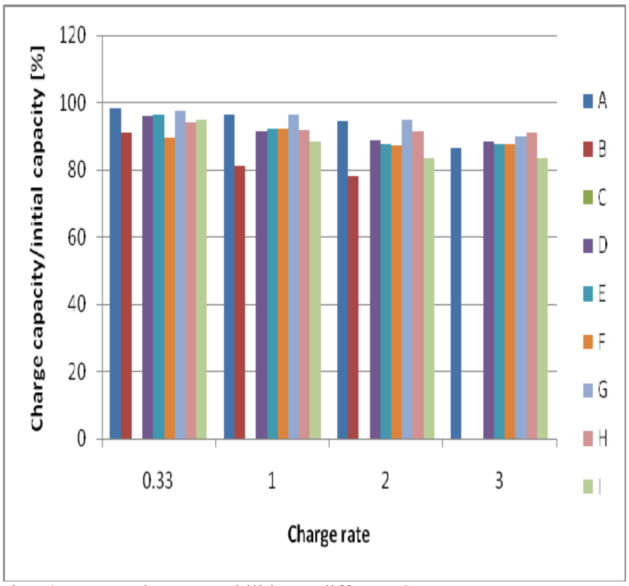

Fig. 6. Battery charge capabilities at different C-rates

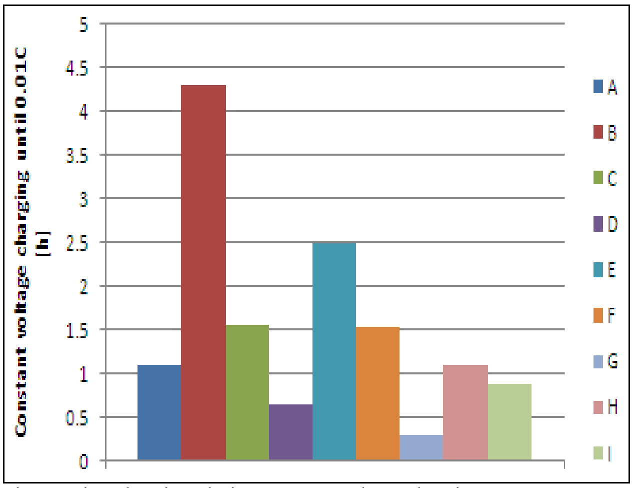

Fig. 7. Time duration during constant voltage charging

C. *Butler-Volmer phenomenon*

In Fig. 4 and Fig. 6, we have seen that the energy efficiency is decreasing as C-rates increases. However, it is in several works well documented [13][14] that the decreasing of the energy efficiency is related to the increasing of the internal resistance. However, Fig. 8 indicates that the calculated internal resistance values are decreasing with increased C-rates.

This relationship has been also described by Butler-Volmer [15]. General expression of their equation is presented in (1):

$$I = I_o \cdot \left\{ e^{\left(\frac{\alpha.n.F}{R.T}.(V-V_o)\right)} - e^{\left(\frac{(1-\alpha).n.F}{R.T}(V-V_o)\right)} \right\} \quad (1)$$

Where I_o is the current density, α presents the transfer coefficient, R is the universal gas constant and F is the Faraday constant. While T is the temperature, V and V_o represent the electrode and equilibrium voltages.

As one can see, the equation gives the relationship between the current and the voltage. The voltage can be considered as logarithmically dependent on the current. Hence, the evolution of the battery internal resistance is decreasing in function of decreased C-rates.

While decreasing of the energy efficiency is due to the development of the losses in the internal resistance, which are quadratic in function of the current RI^2.

This phenomenon results that the internal resistance of a battery is not only dependent on the temperature and state of charge as generally is known, but also of the current value.

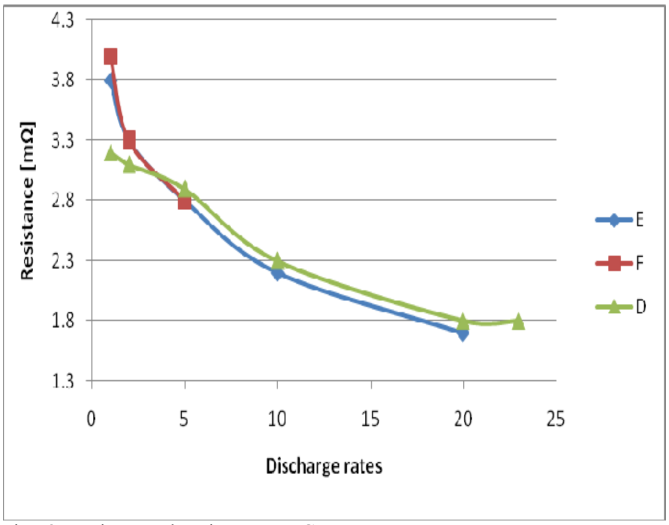

Fig. 8. Resistance duration versus C-rates

D. *Thermal, cycle life and cost evaluation*

In order to complete this analysis, a comparison of the life cycle and cost have been made. In the previous Figures, we have seen that batteries based on $NiCoMnO_2$ in the positive electrode are most appropriate batteries that can be selected for use in BEV applications.

Axsen et al discussed the basic concepts of PHEV and BEV applications, compared three sets of influential technical goals, and explained the trade-offs in PHEV and BEV battery design [1][16]. They mentioned that the battery cost should not be higher than 300$/kWh and the life cycle of the battery should be in the range of 5000 cycles.

However, the cost of the nickel cobalt manages oxide based batteries is still very high in comparison to iron phosphate batteries (B and H). As can be seen in Table 2, the life cycle of a lithium-ion battery is around 1000 – 1200 cycles. These proposed values are derived from the manufacturer data sheet, which are based on 100% DoD. The target of 5000 cycles (70% DoD) cannot be met for the most commercial lithium-ion batteries [1].

Finally, regarding the situation from the point of thermal stability, which is the most important requirement for a battery design in BEV and PHEV applications, shows that the iron phosphate batteries are at the moment most appropriate lithium technology that can be used [17]. Iron phosphate based technology possesses superior thermal and chemical stability which provides better safety characteristics than those of lithium-ion technology made with other cathode materials (especially compared to $NiCoMnO_2$&NiCoAlO2). Lithium iron phosphate batteries are incombustible in the event of mishandling during charge or discharge, they are more stable under overcharge or short circuit conditions and they can withstand high temperatures without decomposing. When abuse does occur, the phosphate iron based batteries will not burn and is not prone to thermal runaway [18][19].

Hence, due to the thermal runway of $NiCoMnO_2$ and NiCoAlO2, the battery pack design of these batteries should be fitted by an active cooling system.

Table 2. COMPARISON OF THERMAL PERFORMANCES, CYCLE LIFE AND COST OF THE VARIOUS BATTERIES

Number	Thermal stability	Cycle life	Cost/kWh
A	most stable	1000	300
B	very stable	1000	310
C	most stable	1000	315
D	least stable	1200	811
E	stable	1000	301
F	stable	1000	823
G	Fairly stable	1000	300
H	stable	1000	304
I	least stable	1200	417

However, Dahn et al concluded that the thermal stability of NiCoMnO2 batteries can be improved by the substitution of aluminum for Co in $Li(NiMnCoAl)O_2$. Dahn called such batteries NMCA. They also concluded that NMCA batteries have larger volumetric and gravimetric energy [20].

E. *Standard deviation*

Series connected cells in a battery pack in battery electric vehicles, require monitoring equipment that is capable of measuring the voltages of individual cells or modules in order to prevent damage and identify defective cells or modules. As discussed in [21][22], all type of lithium-ion batteries can be damaged and in the worst case scenario exploded. As documented in [23], there are various battery management system topologies (such as passive and active BMS) that can be used in function of the variation between the cells or modules in a battery pack.

Fig. 9 represents the standard deviation between the tested batteries. The presented variations have been calculated based on 5 cells for each battery type. As one can see, most of the tested batteries indicate a variation in the range of 0.3 – 0.4%. However, the battery G shows a dispersion of about 2.2%, which results that an active BMS topology will be more than required.

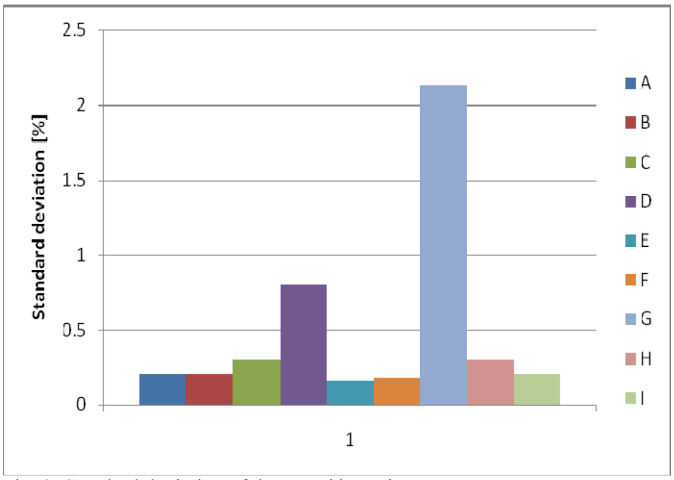

Fig. 9. Standard deviation of the tested batteries

IV. SUMMARY AND CONCLUSIONS

It is well recognized that the key issues in the improvement of the Battery Electric Vehicle is the selection of the battery technology. The selection of best appropriate battery type will depend on a number of factors such as: energy density, energy efficiency, charge and discharge capabilities, thermal stability and life cycle.

In this paper a new test methodology has been introduced which makes it possible to calculate the most important quantifiable battery attributes which are related to the battery for use in BEV applications.

The test results show that nickel manganese cobalt oxide based batteries have the highest energy density in the range of 120 -150 Wh/kg compared to 70 – 115 Wh/kg for iron phosphate and nickel cobalt aluminum in the positive electrode. The high values of the energy densities for the $LiNiCoMnO_2$ batteries are due to the high cell voltage and good electrode specific capacities.

Further, this study showed that $LiNiCoMnO_2$ and NiCoAlO2 batteries have the best charge and discharge capabilities in terms of ampere-hours. Also these batteries indicate an energy efficiency in the range of 90% compared to 85 for iron phosphate batteries.

Regarding the situation from the point of thermal stability, shows that the iron phosphate batteries are at the moment the most appropriate lithium technology for BEV applications. Iron phosphate based technology possesses superior thermal and chemical stability which provides better safety characteristics than those of lithium-ion technology made with other cathode materials (especially compared to $NiCoMnO_2$&NiCoAlO2).

Finally, prices of the nickel manages cobalt oxide based batteries is higher (400 – 800 $/kWh) compared to iron phosphate batteries (300 $/kWh), which is at the moment a serious limitation besides thermal stability for use in BEV applications.

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