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COMPARISON OF MATERIALS USED FOR ELECTRICAL BATTERY COMPONENTS WITH LOW ENVIRONMENTAL IMPACT

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Batteries used for electrical vehicles contain different material combinations: Lead-Acid (Pb-Ac); Nickel-Cadmium (NiCd); Nickel-Metal-Hybrid (NiMH); Lithium-ion (Li-ion); Nickel-Manganese-Cobalt (NMC). These materials and their impact on environment are analyzed. We choose Analytic Hierarchy Process to apply for decision making, according to the most important criteria (safety, environmental impact, energy density) used to compare vehicle battery types. Based on our analysis, we conclude that NiMH and NMC are leading contenders for batteries used nowadays by automotive industry.

Keywords: Li-ion; NMC; NiMH; NiCd; Pb-Ac; electric vehicle batteries; environmental impact; vehicle safety

1. Introduction

Battery is an essential component of full electric vehicles (EV) or hybrid-electric vehicles (HEV) from the environmental friendly and non-polluting point of view [1].

Materials used in the battery of an electric vehicle are a very important and sensitive issue in terms of impact of environment and pollution because this type of batteries has a harder experience than the battery used in a small device, such as a phone or a laptop both during functioning and the moment of disposal, when its life cycle ends [2].

Consistent of different materials with various physical and chemical properties that decisively influence their functional parameters, vehicle batteries are difficult to compare and it is an actual and future challenge to decide which battery type is a better choice for the next generation of electric vehicles [3].

Vehicle batteries contain different material combinations [4]:

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- Lead-Acid (Pb-Ac);
- Nickel-Cadmium (NiCd);
- Nickel-Metal-Hybrid (NiMH);
- Lithium-ion (Li-ion);
- Nickel-Manganese-Cobalt NMC).

Comparison of all these types of vehicle batteries is made. Analytic Hierarchy Process is an efficient tool applied for decision making, and we use it to compare vehicle batteries according to the most important criteria [5]. Safety, environmental impact and energy density represent some of the criteria used to decide which material is the most appropriate for electric vehicle batteries [6], [7]. Main characteristics of electrical vehicle batteries based on material properties are presented in Section 2. Different electric vehicle battery types and their physical and chemical performances are described in Section 3. In Section 4, the analysis of material impact on battery performances using Analytic Hierarchy Process is made. Finally, conclusions of the analysis are presented and the list of references ends the paper.

2. Main characteristics of electrical vehicle batteries

Materials used in the battery of an electric vehicle are a very important and sensitive issue in terms of impact of environment and pollution because this type of batteries has a harder experience than the battery used in a small device, such as a laptop both during functioning and the moment of disposal, when its life cycle ends. In a vehicle, the power train includes all the components that generate power and deliver it to the road surface. Mainly, it includes the engine and transmission of the vehicle. It is critical the choice of the vehicle battery based on the functional parameters of its material components for HEV or EV if we want power and autonomy, as well as lower negative influence on the environment.

The energy supply for an electric powertrain has to be made with a battery described by the following characteristics [1]:

1. High *specific energy* – it is the energy amount a battery can store (Wh/kg) and it has to be high enough to offer an increased autonomy.
2. High *capacity* - it represents the specific energy expressed as ampere-hour (Ah) and expresses the discharge current the battery can deliver over time.
3. High *specific power* or power-to-weight – it is important that the battery produces an increased power for electric power trains (W/kg).
4. Increased *safety* or low fire risk, in terms of the temperature at which the thermal runaway occurs – this is the goal of any vehicle battery designer because the battery, as any energy storage device carries a fire risk. The vehicle battery can overheat and, finally, catch fire, so it is important to reduce the fire risk of each type

of vehicle battery which is anyway much greater than for a small cell phone battery. Bigger current rate increases the risk of thermal runaway.

5. Low *toxicity* (the battery must be environmental friendly) – in terms of environmental impact (EI99), it is expressed as a number of points which must be low for a “green” battery. It is an important goal of the battery design process [2].
6. Wide *operating temperature range* – it is important to have the same performance at low temperature and also at high temperature, because a vehicle is operating outside, on cold or hot weather.
7. Fast *charging* (as a number of hours) represents the preference of any EV owner ensuring the availability of the EV.
8. Low *self-discharge* to provide long storage and an instant start-up when needed.
9. Long *Life Span*, meaning a large number of cycles of one battery pack.
10. Affordable *price*, relative to the battery life.
11. Low *fuel consumption*, if the battery is used by a HEV.

It is important to analyze all these aspects both in terms of technical gains based on the physical and chemical properties of the materials that are used in the batteries and their impact on the living environment but it is difficult to use all of them to compare the available EV and HEV battery types. Usually it is impossible for a battery type to achieve all the desired characteristics thus it must be chosen the best available option.

3. Electric vehicle battery types

The most used types of batteries for HEV and EV have various material components, with different properties which affect either the performances of the battery or the medium, or both: lead-acid, nickel-cadmium, nickel-metal-hybrid and lithium-ion [1].

Lead-acid (Pb-ac) is the oldest rechargeable battery used for vehicles but it has the lowest energy density and a high environmental impact. It is inexpensive and reliable but thermal runaway can occur if improperly charged and lead content and electrolyte make this battery very environmentally unfriendly.

Nickel-cadmium (NiCd) is a well-known enduring, long life and low stress vehicle battery, and it is also used in aviation. But NiCd batteries are exposed to “thermal runaway” phenomenon. It also must be mentioned that cadmium is a toxic heavy metal and therefore requires special care during battery material disposal. “Automotive and industrial batteries and accumulators used in vehicles should meet the requirements of Directive 2000/53/EC, in particular Article 4 thereof. Therefore the use of cadmium in industrial batteries and accumulators for electrical vehicles should be prohibited, unless they can benefit from an exemption on the basis of Annex II to that Directive.” [3] This fact is specified by Directive 2006/66 of the

European Council, which also imposes that more than 75% of Nickel-Cadmium batteries must be recycled instead of simply disposing them in special dumps.

Nickel-metal-hybrid (NiMH) represents a better material mix and is seen as a replacement for NiCd, it offers both higher specific energy and it is as well more environmental friendly. Due to its material properties is also less exposed to thermal runaway phenomenon.

Lithium-ion (Li-ion) battery type is preferred in many applications having a long-life span, high specific energy and low environmental impact. Another argument to use lithium-ion technology is the fact that the known global lithium material resources are sufficient to support the estimated demand for lithium-based vehicle batteries until 2100 [4]. On the other hand, they are more expensive than other types of batteries and the safety of lithium-ion batteries is considered critical because of some events that occurred in the past years. Therefore, researchers looked for new materials with comparable physical and chemical properties which can improve the Li-ion battery technology.

A comparison of these battery models is given in Table 1.

Table 1

Parameters of four classic types of HEV and EV batteries

Battery Type	Energy Density (Wh/kg)	Energy efficiency (%)	Specific Power (W/kg)	Number of cycles of one battery pack	Environmental impact: EI99 (points)
Pb-Ac	40	82.5	180	500	503.37
NiCd	60	72.5	120	1350	543.52
NiMH	70	70.0	200	1350	491.56
Li-ion	125	90.0	430	1000	278.00

Now there are many models of vehicle batteries, derived from Li-ion technology, in combination with different active metals (nickel, manganese, cobalt), with superior performance (enhanced capacity, load capability, safety and longevity) than the traditional vehicle batteries [1]:

- Lithium Manganese Oxide or LMO;
- Lithium Nickel Manganese Cobalt Oxide or NMC;
- Lithium Nickel Cobalt Aluminum Oxide or NCA;
- Lithium Titanate or LTO.

We will use the short form to address types of batteries based on these materials which are described in Table 2, by those elements which make the difference between them:

1. Specific energy or energy density;
2. Number of cycle life per battery pack;
3. Thermal runaway at 1.0 C discharge current.

Table 2

Parameters of four types of batteries derived from Li-ion technology

Battery Type	Energy Density (Wh/kg)	Number of cycles of one battery pack	Thermal Runaway (ºC)
LMO	100-150	300-700	250
NMC	150-220	1000-2000	210
NCA	200-260	500	150
LTO	70-80	3000-7000	180

The highest specific energy is obtained using a NCA battery that means the electric vehicle will have a large autonomy using this battery.

LTO has the longest cycle life so it should not be replaced often.

In the same time, LMO seems to be the safest one.

The battery designers are first of all interested in vehicle safety than in any other characteristic of an EV battery.

4. Analysis of material impact on battery types using Analytic Hierarchy Process

We have presented many types of EV batteries and also many characteristics of importance as a result of various materials used in manufacturing them and the interaction between these materials.

Our goal is to make an objective and systematic comparison of these battery types, in order to decide which one is the best choice both in terms of technical performance and impact on the living environment

Analytic Hierarchy Process (AHP) is the mathematic tool that we use to make the decision [5].

Case 1

First, we analyze the impact of four material combinations used in battery manufacturing derived from the lithium-ion technology based on the criteria given in Table 2.

We have to decide on the best option from this set considering these comparing criteria.

AHP is used for decision but we have to express our judgment by means of intervals for two parameters: energy density and number of cycles [6].

The set of alternatives has four components:

{LMO, NMC, NCA, LTO}

The first comparison criterion is the energy density which is specified by intervals of values instead of precise values.

We have to express our preference according to these intervals, based on specified minimum and maximum values of a specific parameter. In fact, a linear optimization problem must be solved, to deduce the corresponding weight vector.

The vector of values for the energy density is given below:

$$d = ([100,150], [150, 220], [200, 260], [70, 80])$$

Comparison of two intervals can be made using different strategies. The strategy adopted by us consists in a polygonal modeling of the bounded constraint intervals and finding the weight center of it [7].

In 2D, the polygon is a rectangle and the method is equivalent to computing the arithmetic mean of the limit values for each interval which are the coordinates of the weight center of the rectangle (Fig. 1).

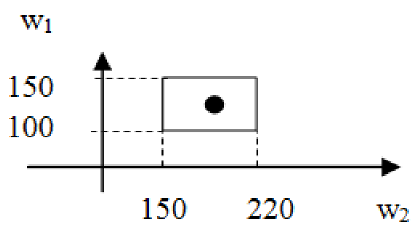

Fig. 1 Constraint polygon for two intervals of values

In 4D space, we generalize the previous idea and we deduce the weight vector for the polytope defined by the vector of constraint intervals as the weight center coordinates which are computed by arithmetic mean of the bounds on each space dimension.

We write the following vectors for the energy density, for the number of cycles per battery pack and for the thermal runaway:

$$e = [125, 185, 230, 75]$$

$$n = [500, 1500, 500, 5000]$$

$$t = [250, 210, 150, 180]$$

The corresponding pairwise comparison matrices are:

$$A^{e} = \begin{pmatrix} 1.0000 & 0.6757 & 0.5435 & 1.6667 \\ 1.4800 & 1.0000 & 0.8043 & 2.4667 \\ 1.8400 & 1.2432 & 1.0000 & 3.0667 \\ 0.6000 & 0.4054 & 0.3261 & 1.0000 \end{pmatrix}$$

$$A^{n} = \begin{pmatrix} 1.0000 & 0.3333 & 1.0000 & 0.1000 \\ 3.0000 & 1.0000 & 3.0000 & 0.3000 \\ 1.0000 & 0.3333 & 1.0000 & 0.1000 \\ 10.000 & 3.3333 & 10.000 & 1.0000 \end{pmatrix}$$

$$A^{t} = \begin{pmatrix} 1.0000 & 1.1905 & 1.6667 & 1.3889 \\ 0.8400 & 1.0000 & 1.4000 & 1.1667 \\ 0.6000 & 0.7143 & 1.0000 & 0.8333 \\ 0.7200 & 0.8571 & 1.2000 & 1.0000 \end{pmatrix}$$

Applying the geometric mean method on these pairwise comparison matrices, the preferences vectors are deduced:

$$w_e = [0.2033 \quad 0.3008 \quad 0.3740 \quad 0.1220]$$

$$w_n = [0.0667 \quad 0.2000 \quad 0.0667 \quad 0.6667]$$

$$w_t = [0.3165 \quad 0.2658 \quad 0.1899 \quad 0.2278]$$

Each preference vector contains only positive real numbers and the sum of all components is equal to 1, verifying the normalizing condition.

But battery designers are more interested to offer safety and higher energy storage capacity than a longer battery life. Let us express a hierarchy of these criteria:

- 5 (maximum) for safety;
- 3 (medium) for specific energy;
- 1 (minimum) for longevity.

We use the following normalized weight vector to quantify the design goals and compute a weighted average of the preferences vectors:

$$p = [1/3, 1/9, 5/9]$$

The new global preference vector is:

$$w' = [0.2510 \quad 0.2702 \quad 0.2376 \quad 0.2413]$$

The maximum preference corresponds to the second alternative in the set, NMC, meaning Lithium Nickel Manganese Cobalt Oxide and we can decide this is the best material choice for batteries based on Lithium-ion technology.

Case 2

The second analysis case takes into account another set of alternatives which includes the materials used in classical vehicle batteries and NMC:

$$\{Pb\text{-}ac, NiCd, NiMH, NMC\}$$

A description of these battery types can be made based on Table 3. We express the safety of these batteries using fuzzy numbers.

Table 3

Performance and environmental impact of materials used in four types of HEV and EV batteries

Battery Type	Energy Density (Wh/kg)	Specific Power (W/kg)	Number of cycles of one battery pack	Environmental impact: EI99 (points)	Safety Degree
Pb-Ac	40	180	500	503.37	3
NiCd	60	120	1350	543.52	1
NiMH	70	200	1350	491.56	5
NMC	185	430	1500	278.00	1

According to this table, NMC battery seems to be the best choice for a vehicle battery if we want high specific energy, high energy efficiency, high specific power and low environmental impact. But safety is the most important goal for a vehicle battery and NMC is not the safest one. Let us find out how safety level influences the decision.

We have to decide objectively which the best choice is according to five comparison criteria.

We order these criteria by their importance, expressed by a weight (9 – maximum importance; 1 – minimum importance):

- safety (9)
- environmental impact (7)
- specific power (5)
- energy density (3)
- number of cycles of one battery pack (1)

The corresponding weight vector to their importance is:

$$p_5 = [0.36 \quad 0.28 \quad 0.2 \quad 0.12 \quad 0.04]$$

We should mention that the comparison of materials based on the environmental impact must be differently made because the maximum preference corresponds to the minimum number of points of EI99. Based on values given in Table 3, five pairwise comparison matrices are computed:

$$A^s = \begin{pmatrix} 1.0000 & 3.0000 & 0.6000 & 3.0000 \\ 0.3333 & 1.0000 & 0.2000 & 1.0000 \\ 1.6667 & 5.0000 & 1.0000 & 5.0000 \\ 0.3333 & 1.0000 & 0.2000 & 1.0000 \end{pmatrix}$$

$$A^e = \begin{pmatrix} 1.0000 & 1.0798 & 0.9765 & 0.5523 \\ 0.9261 & 1.0000 & 0.9044 & 0.5115 \\ 1.0241 & 1.1057 & 1.0000 & 0.5655 \\ 1.8106 & 1.9550 & 1.7683 & 1.0000 \end{pmatrix}$$

$$A^p = \begin{pmatrix} 1.0000 & 1.5000 & 0.9000 & 0.5294 \\ 0.6667 & 1.0000 & 0.6000 & 0.3529 \\ 1.1111 & 1.6667 & 1.0000 & 0.5882 \\ 1.8889 & 2.8333 & 1.7000 & 1.0000 \end{pmatrix}$$

$$A^d = \begin{pmatrix} 1.0000 & 0.6667 & 0.5714 & 0.2162 \\ 1.5000 & 1.0000 & 0.8571 & 0.3243 \\ 1.7500 & 1.1667 & 1.0000 & 0.3784 \\ 4.6250 & 3.0833 & 2.6429 & 1.0000 \end{pmatrix}$$

$$A^n = \begin{pmatrix} 1.0000 & 0.3704 & 0.3704 & 0.3333 \\ 2.7000 & 1.0000 & 1.0000 & 0.9000 \\ 2.7000 & 1.0000 & 1.0000 & 0.9000 \\ 3.0000 & 1.1111 & 1.1111 & 1.0000 \end{pmatrix}$$

For each matrix, a preference vector is deduced using the geometric mean method:

$$w_s = [0.3000 \quad 0.1000 \quad 0.5000 \quad 0.1000]$$

$$w_e = [0.2101 \quad 0.1945 \quad 0.2151 \quad 0.3803]$$

$$w_p = [0.1935 \quad 0.1290 \quad 0.2151 \quad 0.4624]$$

$$w_d = [0.1127 \quad 0.1690 \quad 0.1972 \quad 0.5211]$$

$$w_n = [0.1064 \quad 0.2872 \quad 0.2872 \quad 0.3191]$$

Computing the weighted average of these vectors, according to the importance of the criteria, the global preference vector results:

$$w_g = [0.2233 \quad 0.1480 \quad 0.3184 \quad 0.3103]$$

The maximum preference corresponds to the third material option, which is NiMH, closely followed by NMC.

6. Conclusions

Automotive industry needs better battery types for electric vehicles and hybrid electric vehicles. Battery technology is continuously evolving and new battery types are produced with mix of materials involving different active metals. There are many criteria used to compare them but, nowadays, safety and the environmental impact are the most important ones. Using AHP, we compare four material combinations used in Li-ion batteries and then we compare the best of them with materials used in classical battery types. We conclude that NiMH and NMC material combinations are leading contenders for automotive applications. NiMH is safe but not as environmentally friendly as Li-ion batteries are. Strict rules should be imposed for disposal and recycling process of all types of vehicle batteries. For NMC batteries, special care measures must be taken to avoid catching fire.

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