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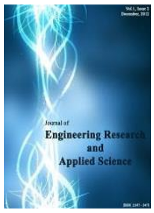

Evaluation of the performance of batteries used in electric vehicles using TOPSIS method

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Abstract

Today, the increasing level of awareness on the environmental damage of fossil fuel use and the decrease in these fuel reserves increase the interest in clean transportation. From this point of view, electric vehicles (EV) are important alternatives for clean transportation and their market share is expected to increase in the near future due to zero CO_2 emissions, lower operating costs, noiseless operation and lower maintenance costs. One of the most important components of EVs is the battery. Because the performance of the battery directly affects the performance of the EVs. Therefore, it is important to evaluate the performance of the batteries to be used in these vehicles and to choose the most suitable battery after this evaluation. In this study, TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) which is one of the multi-criteria decision-making methods (MCDM) is used to evaluate the performance of batteries used in EVs. Six batteries used in EVs are evaluated according to the criteria of nominal voltage, maximum energy density, maximum power density, operating temperature, number of cycles and cost. At the end of the study, it is determined that the Li-ion battery had the best performance according to the evaluation criteria.

Keywords: Electric vehicles, electric vehicle battery, TOPSIS.

1. Introduction

In order to ensure energy security, countries make new regulations to minimize their dependence on foreign sources and to increase their energy efficiency. In addition, new technologies are encouraged due to climate change and environmental issues and measures are taken to limit carbon emissions. Studies on this subject have focused on both increasing the efficiency of traditional engine technology and alternative fuel technologies such as electric vehicles [1]. Today, the automotive market is dominated by conventional internal combustion vehicles and there are very few hybrid/electric vehicles on the market [2]. Both the concern about the depletion of fossil fuels and the environmental damage caused by the emissions of internal combustion engines, the emission-based taxation system implemented in the European Union has made it mandatory for vehicle manufacturers to work on hybrid and/or electric vehicles [3]. The interest in EVs is increasing day by day due to the limited fuel reserves of internal combustion engine vehicles working with fossil fuels and the damage these vehicles cause to the environment [4]. The main advantages of EVs are zero CO2 emissions, lower operating costs, noiseless operation and lower maintenance costs [5]. EVs are a more attractive and powerful alternative to petroleum-derived vehicles, as they are environmentally friendly vehicles with zero emissions. The energy cycle of these vehicles, which provides 60% more road driving for the same amount of primary energy source, is also very impressive [6]. Therefore, it is estimated that the market shares of these vehicles will increase in the near future [2].

The mechanical propulsion that EVs need to move is provided by electric motors. Electric motors convert electrical energy into mechanical energy and generally obtain the necessary electrical energy from batteries. Therefore, the batteries used in EVs are of great importance for the vehicle. The efficient and reliable use of EVs is directly related to the use of batteries [4]. The most important limiting component in front of the widespread use of EVs is battery technology, which has become a priority study for commercial applications in recent years [2,3].

Therefore, in this study, the batteries used in EVs were evaluated in terms of performance. Since there is more than one criterion in the evaluation of

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batteries, the TOPSIS method is used in the evaluation phase.
In the next section of the study, information about EV batteries is given, in the 3rd section the material and method are explained, in the 4th section the findings obtained from the study are given, and in the last section the results and evaluations are made.

2. Electric vehicle batteries

Since EV systems do not use fossil fuels and do not require an internal combustion engine to burn the fuel, these systems are both more economical and more environmentally friendly. However, in order to compete with vehicles using internal combustion engine technology, low cost and full charging range features must reach the desired level. One of the most important components of EVs is the battery. Because the performance of the battery directly affects the performance of EVs. Battery full charge time, battery life, range etc. criteria that users give the most importance are directly related to the battery system. One of the biggest barriers to the widespread use of EVs is production costs. Therefore, efforts are being made to reduce the cost of EVs. One of the most important factors that make up the cost is the batteries. Therefore, studies on EVs have mostly focused on batteries [7]. A wide variety of EV battery technologies are available today. Lead-Acid (Pb) batteries have been used for years to supply the electricity needs of vehicles [8, 9]. Lead acid batteries have a share of around 50% in the world battery market. However, due to the increasing need for portable and mobile systems and the low energy and power densities of lead acid batteries, it prevents the increase in its market share [3]. With the introduction of the first modern EVs in the 1980s, the need for more powerful batteries increased [8]. Thus, Nickel-Cadmium (NiCd) batteries were developed first, and then Nickel-Metal-Hydride (NiMH) batteries were developed for use in hybrid electric vehicles (HEV) [8-11]. The most important and most defining characteristics of batteries are energy density, power density, durability, discharge rate, nominal voltage, price, size and service life [7, 9, 11-13]. Power density and energy density are external parameters. For this reason, a battery with short full charge and full discharge times cannot have adequate energy storage capacity. The service life also depends on the usage and charging style [7]. Increasing battery energy density has been a core in the development of better batteries as it essentially determines EV driving range, manufacturing cost and consumer preference [13].

Studies on batteries have focused on li-ion technology [2]. Lithium-ion batteries are now used in the majority of EVs [11]. It predicts that lithium-based batteries will dominate the rechargeable battery market [3]. Especially its high-power density characteristic has made it attractive in EV applications. Therefore, battery packs formed with lithium-based battery cells are widely used in systems that require high energy capacity and are designed to operate with battery support [11]. In addition, lithium-ion or lithium polymer batteries are increasingly used in portable electronic systems, electric vehicles, linear generators, aerospace and aircraft power systems, thanks to their high rated voltage, long shelf life, low weight and smaller size advantages [9, 14, 15]. Recently, Lithium-ion polymer (LiPo), Sodium Nickel Chloride (NaNiCl), Lithium iron phosphate (LiFePO4), Nickel Metal Hydride (NiMH), Zinc air (Zn-air), Lithium sulphide (LiS), Lithium air (Li- air) have begun to be used in EVs. Lithium batteries containing silicon, sulphur and air (oxygen) are seen as the most promising batteries in the future. In addition, developments in nano-technology play an important role in battery development [8].

As electric mobility has been identified as the key to improving urban air quality and reducing reliance on fossil fuels, many efforts are being made in academia and industry to drive global adoption of EVs [16]. In some industrial situations, the consequences of bad or conflicting decisions will lead to unsafe situations. Similarly, the evaluation and selection of safe battery technology is a critical task in the production of EVs. In this respect, EV manufacturers prefer the battery not only by considering a single factor, but also by considering other important criteria such as energy density, specific power, safety, reliability (faultless operation) and cost for the optimal solution. In this respect, battery selection emerges as an MCDM problem involving the selection of the best among various alternatives based on various qualities [5]. The evaluation and selection process of batteries to be used in EVs is a suitable area for MCDM. Because battery systems contain many factors and variations. For this reason, MCDM methods are preferred in battery selection in EVs to evaluate more than one purpose together and to analyze complex processes in a more understandable way.

3. Material and Method

In the study, TOPSIS method was used for the evaluation and selection of EV batteries. The methods and steps are briefly explained below.

3.1. TOPSIS Method

TOPSIS method is one of the important MCDM methods introduced by Hwang and Yoon [17] in 1981. The basic principle of the TOPSIS method is that the chosen alternative should be the closest to the positive ideal solution and the farthest from the negative ideal solution [18-20]. In other words, it is based on the concept that the selected factors should have the shortest geometric distance to the positive ideal solution and the longest geometric distance to the negative ideal solution [19, 21]. TOPSIS selects the best alternative from a finite collection of homogeneous alternatives evaluated under a finite set of decision features (or criteria) [22, 23]. The positive ideal solution maximizes the maximization seeking criteria (or benefit criteria) and minimizes the minimization seeking (or cost criteria). In contrast, the negative-ideal solution maximizes the cost criteria while minimizing the benefit criteria [24]. In the TOPSIS methodology, the numerical scores of each alternative from all attributes/criteria are used to develop a decision matrix and a normalized decision matrix. Positive and negative ideal solutions are found according to the characteristics of the attributes/criteria, and the order of preference of the alternatives becomes definite according to the closeness coefficient of each alternative [18]. The TOPSIS method includes simple calculation, easy understanding, and a strong capacity to integrate other methods. Therefore, it is an effective decision-making approach used in various applications [25]. The steps of the TOPSIS method are described below [17].

Step 1: Construct the decision matrix (A): Alternatives and criteria are listed on the rows and columns, respectively.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

where a_{ij} is the real value of the alternative i according to the criteria j.

Step 2: Construct the normalized decision matrix using eq. (1).

$$r_{ij} = \sqrt{\sum_{i=1}^{m} a_{ij}^{2}}$$

$i = 1, 2, ..., m$ and $j = 1, 2, ..., n.$ (1)

Step 3: Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as follows:

$$v_{ij} = r_{ij} . w_j \quad (2)$$

where w_j is the weight of the j^{th} criterion or attribute and $\sum_{j=1}^{n} w_j = 1$.

Step 4: Determine the positive ideal A^* and negative ideal A^- solutions.

$$A^* = \left\{ (\max_i v_{ij} \,\middle|\, j \in B), (\min_i v_{ij} \,\middle|\, j \in C \right\} \quad (3)$$

$$A^- = \left\{ (\min_i v_{ij} \,\middle|\, j \in B), (\max_i v_{ij} \,\middle|\, j \in C \right\} \quad (4)$$

Where B and C are the benefit and cost criteria, respectively.

Step 5: Calculate the separation measures using the m-dimensional Euclidean distance. The separation measures of each alternative from the positive ideal solution (S_i^*) and the negative ideal solution (S_i^-), respectively, are as follows:

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2} \quad (5)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \quad (6)$$

Step 6: Calculate the relative closeness to the ideal solution.

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*} \qquad 0 \le C_i^* \le 1 \qquad (7)$$

Step 7: Rank alternatives by the relative closeness (C_i^*) to the ideal solution.

4. Result

In the study, first of all, based on the literature study on batteries used in EVs, the criteria that are effective in the evaluation and selection of batteries and battery types commonly used in existing EVs were determined and the hierarchical evaluation model given in Fig. 1 was created.

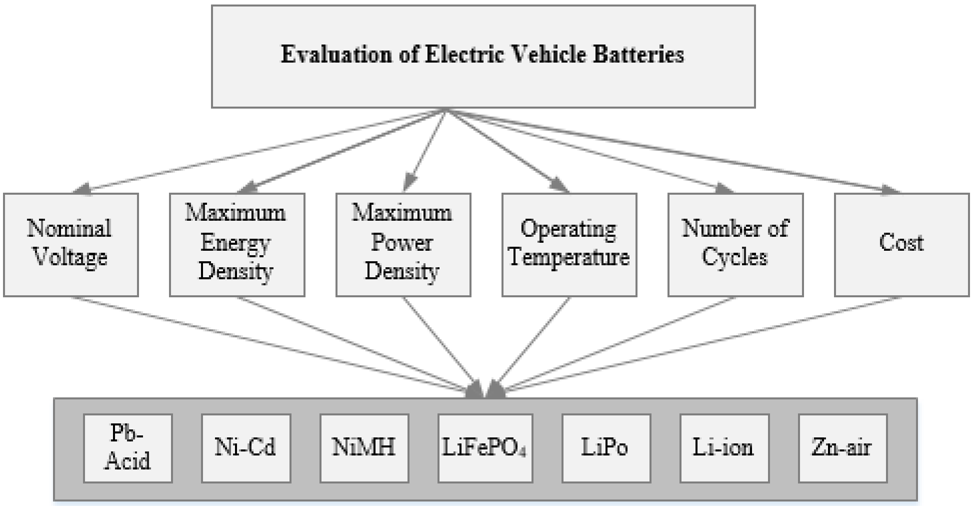

Fig. 1. EV battery evaluation model

After the evaluation model is created, the evaluation criteria values of each battery are determined depending on the literature and given in Table 1.

Table 1. Evaluation criteria values for EV batteries

Battery Type	Nominal Voltage (V)	Maximum Energy Density (Wh/kg)	Maximum Power Density (W/kg)	Operating Temperature (^{0}C)	Number of Cycles (at 80% Discharge)	Cost ($/kW/h)
Pb-Acid	2	35	150	-15 - +50	1000	60
Ni-Cd	1,2	50	200	-20 - +50	2000	300
NiMH	1,2	70	200	-20 - +60	2000+	250
$LiFePO_4$	3,2	150	300	-20 - +70	1000	200
LiPo	3,7	150	350	-20 - +60	1000	150
Li-ion	3,6	180	220	-20 - +60	2000	150
Zn-air	1,65	200	140	-10 - +55	200	100

When the criteria in Table 1 are examined, it has been determined that the criteria apart from the cost criterion are the benefit criteria. At the same time, these numerical values were taken into account in the evaluation of the batteries according to these criteria, since the ones apart from the operating temperature criteria have a certain numerical value. However, a weight scale in the range of 1-9 was used in the evaluation of batteries according to the operating temperature criterion (1: very low in weight, 9: very heavy in weight), and batteries were evaluated according to this criterion in line with the common opinion of 3 experts in electric vehicles. In addition, the importance weights of the criteria used for the evaluation of the batteries were determined and the decision matrix in Table 2 was created.

Table 2. Decision matrix

Battery Type	Nominal Voltage	Maximum Energy Density	Maximum Power Density	Operating Temperature	Number of Cycles	Cost
Pb-Acid	2	35	150	6	1000	60
Ni-Cd	1,2	50	200	7	2000	300
NiMH	1,2	70	200	8	3000	250
$LiFePO_4$	3,2	150	300	9	1000	200
LiPo	3,7	150	350	8	1000	150
Li-ion	3,6	180	220	8	2000	150
Zn-air	1,65	200	140	6	200	100
Criteria Importance Weight	0,12	0,24	0,18	0,14	0,15	0,17

Then, the data in the decision matrix are normalized with the help of eq. (1) and the normalized matrix is given in Table 3.

Table 3. Normalized matrix

Battery Type	Nominal Voltage	Maximum Energy Density	Maximum Power Density	Operating Temperature	Number of Cycles	Cost
Pb-Acid	0,293	0,099	0,242	0,302	0,223	0,120
Ni-Cd	0,176	0,141	0,323	0,353	0,447	0,599
NiMH	0,176	0,197	0,323	0,403	0,670	0,499
$LiFePO_4$	0,469	0,423	0,485	0,453	0,223	0,399
LiPo	0,543	0,423	0,566	0,403	0,223	0,299
Li-ion	0,528	0,507	0,355	0,403	0,447	0,299
Zn-air	0,242	0,563	0,226	0,302	0,045	0,200

The values in the normalized matrix are multiplied by the criterion importance weights using eq. (2) and the weighted normalized matrix given in Table 4 is obtained.

Table 4. Weighted normalized matrix

Battery Type	Nominal Voltage	Maximum Energy Density	Maximum Power Density	Operating Temperature	Number of Cycles	Cost
Pb-Acid	0,035	0,024	0,044	0,042	0,034	0,020
Ni-Cd	0,021	0,034	0,058	0,049	0,067	0,102
NiMH	0,021	0,047	0,058	0,056	0,101	0,085
$LiFePO_4$	0,056	0,101	0,087	0,063	0,034	0,068
LiPo	0,065	0,101	0,102	0,056	0,034	0,051
Li-ion	0,063	0,122	0,064	0,056	0,067	0,051
Zn-air	0,029	0,135	0,041	0,042	0,007	0,034

With the help of the values in the weighted normalized matrix, positive ideal solutions (A^*) are calculated using eq. (3) and negative ideal solutions (A^-) are calculated using eq. (4) and given in Table 5.

Table 5. Positive and negative ideal solutions

	Nominal Voltage	Maximum Energy Density	Maximum Power Density	Operating Temperature	Number of Cycles	Cost
(A^*)	0,065	0,135	0,102	0,063	0,101	0,020
(A^-)	0,021	0,024	0,041	0,042	0,007	0,102

After calculating the positive and negative ideal solutions, separation measures of each alternative from the positive ideal solution (S_i^*) and the negative ideal solution (S_i^-) are calculated using equations (5) and (6). In addition, closeness (C_i^*) of the batteries to the ideal solution is obtained using eq. (7) and as shown in Table 6, batteries are ranked according to these closeness values.

Table 6. S_i^*, S_i^-, C_i^* values and ranking of batteries

Battery Type	S_i^*	S_i^-	C_i^*	Ranking
Pb-Acid	0,147	0,087	0,371	6
Ni-Cd	0,149	0,064	0,301	7
NiMH	0,126	0,101	0,445	5
LiFePO4	0,090	0,108	0,545	3
LiPo	0,081	0,123	0,603	2
Li-ion	0,061	0,136	0,690	1
Zn-air	0,120	0,131	0,521	4

When Table 6 is examined, the Li-ion battery ranks first with a closeness coefficient of 0.690. LiPo battery (0.603) the second and Ni-Cd ranks the last.

Considering these results, it is seen that the use of Li-ion batteries in electric vehicles is more advantageous. According to the literature, it is seen that Li-ion batteries are used more in existing vehicles. In this context, it can be said that the result obtained from the method coincides with the real situation.

5. Conclusions

Along with the effects of worldwide economic expansion and growing population, efforts to improve society's welfare, advanced industry and technology are causing a global increase in energy demand. The accumulation of greenhouse gases in the atmosphere, mainly originating from the industry, transportation and electricity sectors, is the main cause of global warming and climate change. In order to reduce global warming and its environmental effects, different measures are proposed and implemented around the world. In order to contribute to the solution of this problem, the use of environmentally friendly and efficient EVs is encouraged instead of existing vehicles using fossil fuels. It is estimated that the sales of electric and hybrid vehicles will reach 15% to 20% of the total new vehicle sales in 2035, especially due to the legal obligations that will be brought by countries that consume large amounts of oil.

Batteries are the main energy source in EVs and the motion energy of the vehicle is provided by the propulsion batteries. In EVs, the battery is the most expensive, heaviest and most bulky part of the vehicle. The fact that the most important component of EVs is the battery forces designers to choose the best battery. In battery selection, many different parameters such as energy density, power density, self-discharge rate, charging time, ampere-hour efficiency, energy efficiency, cost, commercial availability, operating temperature and lifetime are taken into account.

In this study, the batteries used in EVs were evaluated according to the TOPSIS method. Six batteries commonly used in EVs were evaluated according to the criteria determined according to the literature review. As a result of the evaluation, the Li-ion battery was determined as the most suitable battery for EVs. Li-ion battery's features such as maximum energy density, maximum power density and nominal voltage have been the prominent features of being the best battery. The fact that Li-ion batteries are mostly used in EVs today also shows

that the result obtained from the method is reliable.
In future studies, batteries can be evaluated by adding criteria such as self-discharge, efficiency, fast charging time, maintenance and safety requirements to the evaluation model and with different MCDM methods.

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