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Multi-Objective Optimization in Battery Selection for Hybrid Electric Vehicle Applications

This paper proclaims the battery selection for hybrid electric vehicle applications using multi-objective optimization techniques. Ashby s methodology, Technique for Order Preferences by Similarity to an Ideal Solution (TOPSIS) and VIse Kriterijum-ska Optimizacija Komprominsno Resenje (VIKOR) methods are employed here for the assessment. Various attributes considered for analysis are specific energy, energy density, electrical efficiency, self-discharge rate, nominal cell voltage, energy, cost and durability. The batteries considered for analysis are Li-ion, Ni-MH, Ni-Cd and Pb-acid. Based on the performance indices and battery attributes, selection charts and tables are presented here. It is observed that Li-ion batteries are most suitable for hybrid electric vehicle applications followed by Ni-MH batteries. The outcomes of all methods considered are uniform and promising. The results obtained are also matched up with actual practices in automotive industries. Alike results confirm the validity of this study.

Keywords: Hybrid electric vehicle, battery, Li-ion battery, VIKOR, Ashby's method, TOPSIS

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1. Introduction

Decreasing level of liquid fuel and increasing concern for environment are motivating the world to move towards hybrid vehicles. The combustion engine based vehicles use petroleum to propel it and are major source of pollution causing imbalance in atmosphere. The hybrid vehicles with good fuel efficiency and better performance are replacing combustion engine based vehicles [1].

Hybrid vehicles use two power sources in its architecture [2] to power the vehicle; one is ICE and another is battery. In HEVs, ICE works as primary power source and battery as secondary power source. But other configurations like Electric Vehicle (EV) and Plug-in Hybrid Electric Vehicle (PHEV) use a battery as primary power source and ICE as secondary power source. Longer electric range with good fuel efficiency of EVs and PHEVs are advantages over HEVs. The batteries used in EVs and PHEVs can be charged through mains plug at home, offices and parking stations and through regenerative braking whereas HEVs can be charged either through regenerative braking or engine. EVs, HEVs and PHEVs should use efficient, high power and reliable batteries to minimize the liquid fuel consumption and fulfil the expectations of greener tomorrow. The following section briefs about literature available related to battery technology for HEVS.

Automotive battery technologies and its future are discussed in [3]. The commercially available battery technologies for the HEV applications are investigated in [4]. They compared various batteries analytically. Energy storage system selection should be performed to benefit the environment in the long term [5]. For HEV applications, a battery type should be chosen wisely to make a compromise between high power, low weight, good performance, high energy storage capability, small volume, long life time and low

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price. Alamgir and Sastry [6] discusses about the efficient batteries for transportation purpose and compares Li-ion and Ni-MH battery analytically but does not produce any quantitative analysis.

Selection of a battery is very important to attain good fuel economy, reliable performance and durability in hybrid vehicles. Different types of batteries are available in market so one needs some potential techniques to identify the best. Literature shows that Li-ion battery is better option in comparison to others. But no particular technique has been used to choose the same.

Some battery parameters like energy density, durability, Wh/cycle, specific energy, nominal voltage and efficiency are maximization type issues whereas, self discharge rate and cost are minimization type attributes. So it's required to use multi objective techniques to select the best suitable battery for HEV applications. Few multi objective optimization techniques are proposed by Ashby in 1993 [7], Yoon and Hwang [8], Yoon [9] and Opricovic [10-12]. These approaches are implemented here to find out the best battery from different materials namely Lithium (Li), Nickel (Ni) and lead (Pb). Various battery attributes like energy density, specific energy, electrical efficiency, durability, self discharge rate, energy/cycle and cost are considered here to rank the batteries.

This paper presents the battery selection for hybrid vehicle applications. Section 2 and 3 describe the role of batteries in HEVs and type of batteries existing in the market respectively. Section 4 describes about battery attributes considered in selection method. Section 5 details about the various multi-objective optimization techniques used in the paper i.e., Ashby's methodology, TOPSIS and VIKOR. Section 6 discusses about the calculations and results, section 7 gives insights of existing Li-ion battery technologies and section 8 concludes the paper.

2. Notation

The notation used throughout the paper is stated below.

Nomenclature:

w_e	engine speed	*PGS*	Planetary gear set
w_m	motor speed	*ICE*	Internal combustion engine
w_g	generator speed	*HEV*	Hybrid electric vehicle
N_r	tooth number in ring gear	*Pb-acid*	Lead-acid battery
N_s	tooth number in sun gear	*Ni-Cd*	Nickel-Cadmium
$I_{(s\text{-}d)}$	self discharge current	*Ni-Zn*	Nickel-Zinc
C_p	battery capacity	*Ni-MH*	Nickel metal hydride
K_0	prefactor	*Li-on*	Lithium-ion
T	battery temperature	$LiCoO_2$	Lithium Cobalt Oxide
$LiNiCoAlO_2$	Lithium Nickel Cobalt Aluminium Oxide	$LiMn_2O_4$	Lithium Manganese Oxide
$Li_4Ti_5O_{12}$	Spinel Lithium Titanate	$LiFePO_4$	Lithium Iron Phosphate
		$LiNiMnCoO_2$	Lithium Nickel Manganese Cobalt Oxide

3. Role of batteries in HEVs

In hybrid vehicles two power sources i.e., engine and battery, motor/generator set and PGS are present. PGS is a speed coupler which transmits the power from/to motor, generator, engine and front wheels. PGS have sun gear, ring gear and carrier gear. Carrier is connected to the engine, sun to generator and ring gear is connected to motor. Since no clutch is present in THS, PGS is always running if the vehicle is moving. Relationship between $\omega_{e,}$ ω_m and ω_g can be predicted as eq. (1).

$$\frac{N_r}{N_s + N_r} * \omega_m + \frac{N_s}{N_s + N_r} * \omega_g = \omega_e \qquad (1)$$

N_r and N_s are tooth number in ring and sun gear respectively. Through PGS, generator charges the battery from engine or through regenerative breaking. When sufficient charge is present in the battery, motor propels the vehicle by utilizing battery power.

Battery pack should get charged quickly but discharge rate should be less. Basically Li-ion, Ni-MH, Ni-Cd and Pb-acid batteries are used for high power applications. To identify the suitable battery for hybrid vehicle applications several battery attributes like energy density, specific energy, electrical efficiency, durability, energy/cycle, self-discharge rate and cost are considered here and using Asbhy's approach, TOPSIS and VIKOR methods, a better option in terms of battery is chosen.

Batteries are categorized into two types, Primary and Secondary. Primary batteries produce current immediately and are most commonly used in portable devices with lower current drawn. Primary cells cannot be reliably recharged, since the chemical reactions are not easily reversible and active. These batteries have high energy density but are expensive in terms of cost per kilowatt hour [13]. Secondary batteries are also known as rechargeable batteries. They are composed of active materials. These are (re)charged by applying electric currents. The chemical reactions are reversible hence battery can be charged and recharged subsequently. The oldest type of rechargeable battery is Pb-acid battery. Ni-Cd, Ni-Zn, Ni-MH and Li-on cell are most commonly used secondary cells. Ni-MH replaced the Ni-Cd in most applications due to its higher capacity. Li-ion batteries are utilized nowaday in high power applications. The market has shifted towards secondary cells because of its lower unit price, useable time and repetitive charging/discharging capability.

3.1. Types of batteries

3.1.1. Lead acid battery

Pb-acid batteries are designed for high power applications and are inexpensive, safe and reliable [14]. They have low specific energy, short calendar life and temperature sensitive performance. Pb-acid cell contains electrodes of Pb metal and lead oxide (PbO_2) in the electrolyte of sulphuric acid (H_2SO_4). Following reactions occur at electrodes like eqs. (2) and (3).

At anode: $\mathrm{Pb + HSO_4{}^- + H_2O \rightarrow PbSO_4 + H_3O^+ + 2e^-}$ (2)

At Cathode: $\mathrm{PbO_2 + 3H_3O^+ + HSO_4{}^- + 2e^- \rightarrow PbSO_4 + 5H_2O}$ (3)

3.1.2. Nickel-Cadmium Battery

Ni-Cd battery has significantly higher energy density than Pb-acid battery. It contains Nickel oxide cadmium hydroxide as positive electrode, Cadmium (Cd) as negative electrode and potassium hydroxide as electrolyte. Reactions are metioned as eqs. (4) and (5). Potassium hydroxide is not consumed in the reaction. Cd is heavy metal and is highly toxic. Ni-Cd batteries are costlier that Pb-acid batteries and have negative temperature coefficient [15]. These exhibit thermal runaway hence avoided by car manufacturers.

At anode: $2\ \mathrm{NiO(OH)} + \mathrm{Cd} + 2\mathrm{H_2O} \rightarrow 2\mathrm{Ni(OH)_2} + \mathrm{Cd(OH)_2}$ (4)
At Cathode: $2\ \mathrm{NiO(OH)} + 2\mathrm{H_2O} + 2\mathrm{e^-} \rightarrow 2\mathrm{Ni(OH)_2} + 2\mathrm{OH^-}$ (5)

3.1.3. Nickel-Metal Hydride Battery

Ni-MH batteries have 2-3 times higher capacity than equivalent Ni-Cd cell and have much higher life than Pb-acid batteries. Metal hydride as anode, $Ni(OH)_2$ as cathode and potassium hydroxide as electrolyte are used in Ni-MH cell. The issues with Ni-MH are high self discharge rate, heat generation at higher temperature and higher cost. The chemical reactions are given as eqs. (6) and (7).
At anode: $\mathrm{OH^-} + \mathrm{MH} \rightarrow \mathrm{H_2O} + \mathrm{M} + \mathrm{e^-}$ (6)
At cathode: $\mathrm{Ni(OH)} + \mathrm{H_2O} + \mathrm{e^-} \rightarrow \mathrm{Ni(OH)_2} + \mathrm{OH^-}$ (7)

3.1.4. Lithium ion battery

Li-ion batteries with higher energy per unit mass, high energy efficiency, better performance at all temperatures and low self discharge rate are dominating the current market. These batteries use carbon anode and oxides of cobalt, manganese and nickel as cathode. The chemical equation reactions are as given in eqs. (8) and (9).

At
anode: $\mathrm{Li_xC_6} \rightarrow \mathrm{xLi^+} + \mathrm{xe^-} + 6\mathrm{C}$ (8)
At cathode: $\mathrm{Li_{1-x}CoO_2} + \mathrm{xL^+} + \mathrm{xe^-} \rightarrow \mathrm{LiCoO_2}$ (9)

4. Battery indices

The performance indices of batteries vary with respect to a range of variables as described here.

4.1. Specific Energy and energy density

Energy density of a fuel per unit mass is known as specific energy of that fuel. Specific energy is the amount of electrical energy stored for every kilogram of battery mass. More the energy can be stored or transported for the same amount of volume, it is said to be high energy density. Watt-hour/litre energy density is the amount of electrical energy stored per cubic metre of battery volume. To maximize energy density and specific energy, specific energy density can be calculated as eq. (10) and higher value shows the efficient energy storage [16].

$$\text{Specific Energy} = \frac{\text{Rated Wh capacity}}{\text{Battery mass in kg.}} \tag{10}$$

4.2. Electrical efficiency

This is another very important parameter and it is defined as the ratio of electrical energy supplied by a battery to the amount of electrical energy required to return it to the state before discharge. Higher efficiency will prove a better battery type.

4.3. Self discharge rate

The batteries discharge when not in use, this phenomenon is called self discharge. This reduces the charge level of battery without any use even. The discharge rate varies with battery type and temperature. The self discharge rate is a measure of how quickly a cell will lose its energy while sitting on the shelf due to unwanted chemical actions within the cell [17]. These side reactions can be reduced up to some extent by storing battery at lower temperature [18]. Self discharge rate and temperature are related as in eq. (11) [19].

$$I_{(s-d)} = \frac{1}{C_p} K_0(T) e^{-\ln 2 * \left(\frac{R}{10}\right) * (T*(T+10))} \tag{11}$$

4.4. Energy/cycle

Energy delivered per cycle has a significant impact on choosing battery. The amount of energy in every discharge cycle should be high and it should be continued for larger numbers of cycles with repetition.

4.5. Cost

Initial cost and life time cost of batteries may vary. The installation and initial purchase of Li-ion battery is high as compared to the other batteries of same capacity but durability and high performance of Li-ion battery repay it back in terms of good performance. Different chemistries need a different type of charger to charge it; this also leads to the cost raise.

4.6. Durability

Number of charge/discharge decides the durability of battery. It varies with type of battery and how it has been used in past. This is a very important attribute of battery which decides the life of battery and performance duration. Good durability with high installation cost may repay back to customer in terms of economy. Table 1 shows the numerical values of different attributes of the related battery [20-21].

Table 1: Attributes of different material battery

Battery attributes	Unit	Li-ion	Ni-MH	Ni-Cd	Pb-acid
Specific energy	Wh/Kg	180	70	50	35
Energy density	Wh/l	180	140	100	70
Electrical efficiency	Percent	85	66	90	90
Self-discharge rate	Percent/month	5	30	10	20
Nominal voltage	Volts	3.6	1.2	1.2	2.0
Energy /cycle	Wh	8.6	7.5	4.5	24
Cost	$	24	18.5	11	8.5
Durability	Cycles	1200	1000	2000	800

5. Different methods used for Battery selection

To select an alternative for the application with various conflicting criteria, multiple criteria decision making (MCDM) method is used. It has been extensively used in various areas like industries, food quality decision making, economics, material selection, investment decision, project evaluation and staff appraisal, etc. To choose a best fit alternative according to the goal or objective is the key to decision making. [22] have done an exhaustive review of the recent efforts and developments of MCDM with various categories. This method is utilized in various literatures as for food products [23], to improve airline service quality [24] and to develop a decision support system [25]. Vucijak et al. [26] and Supriyasilp et al. [27] used MCDM for hydro power generation with economic and environmental criteria consideration. MCDM application for site selection for waste management, transshipment and macro-site selection for wind/solar hybrid power stations is given in [28], [29] and [30] respectively. MCDM is used widely in various areas but somehow has not been used to choose an appropriate battery for HEV applications. This paper utilizes MCDM technique and implemented TOPSIS and VIKOR method to perform the battery selection. Multiple methods are used to verify the selection.

5.1. ASHBY's method

To meet the product performance and minimize the cost, Ashby presented a novel method for selection of materials in different application. According to Ashby's approach; the desired objective function is minimized/maximized to optimize the performance under the influence of the constraints. Ashby's approach is used here to determine the optimal performance battery for hybrid vehicle applications. A novel material selection approach to optimize the multiple criteria is developed in [7]. Wood et al. [31] selected materials for high field pulsed magnets using Ashby's approach. To select blade and tower material for the wind turbines, Ashby's approach is used [32]. Ashby selected the insulating material for the refrigerators to reduce the environmental hazards by his own selection method [33]. Ashby proposed to make hybrid materials to improve the behaviour of the materials with the detailed study [34]. Selection of material for the microsystems designers from the vast set of materials is performed in [35]. Hard coating materials are selected using multi criteria decision technique and used Ashby's approach for preparing a material selection chart [36]. This approach optimizes a performance index P_j based on objective functions and is used here to apply in battery selection as in eq. (12).

$$P_j = f_j(F, P, M) \tag{12}$$

5.2. TOPSIS

Technique for order preferences by similarity to an ideal solution (TOPSIS) is MADM instrument for measuring relative efficiency of alternatives. Yoon and Hwang [8] and Yoon [9] introduced the TOPSIS method based on the idea that the best alternative should have the shortest distance from an ideal solution. They assumed that if each attribute takes a monotonically increasing or decreasing variation, then it is easy to define an ideal solution. Such a solution is composed of all the best attribute values achievable, while the worst solution is composed of all the worst attribute values achievable [37]. The goal is to propose a solution which has the shortest distance from the ideal solution in the Euclidean space. Such a solution may need to simultaneously have the farthest distance from a negative ideal solution [38-39]. The TOPSIS method, by considering both the above distances, tries to choose solutions that are simultaneously close to the ideal solution. Jee and Kang used TOSIS method to select the optimal material for the flywheel [40]. Shanian and Savadogo used Topsis method to select the suitable material for the metallic bipolar plate to be used in polymer electrolyte fuel cell [41]. Shanian and Savadogo recommended TOSIS method for the material selection of highly sensitive components [42]. Zanakis et al. compared different MCDM methods and proved TOSIS a considerable method for selection of an alternative [43]. Rao et al. uses TOPSIS along with AHP method to select a suitable material for the engineering design problem from among the various available alternatives [44]. Thakker et al. performed selection of material for wave energy extraction turbine blade with TOPSIS along with adapted value engineering technique and Cambridge material selector based technique [45]. Gupta chose the best suitable material for the absorbent layer in thin film solar cells [46]. The TOPSIS method, by considering both the above distances, tries to choose solutions that are simultaneously close to the ideal solution. The procedure can be categorized in six steps:

1) Construct of the decision matrix: the decision matrix is expressed as eq. (13).

$$D=\begin{pmatrix} d_{11} & \cdots & d_{1m} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nm} \end{pmatrix} \tag{13}$$

dij is the rating of the alternative Ai with respect to the criterion Cj.

2) Construct the normalized decision matrix: Each element r_{ij} is obtained by the Euclidean normalization as eq. (14).

$$r_{ij=}\frac{d_i}{\sqrt{\sum_{i=1}^{m} d_{ij}^2}}\ , i = 1, \ldots\ldots m \text{ and } j = 1, \ldots\ldots n. \tag{14}$$

3) Construct the weighted normalized decision matrix: The weighted normalized decision matrix vij is computed as eq. (15).

$$V_{ij} = w_i * r_{ij} \text{ where } \sum_{i=1}^{m} w = 1 \tag{15}$$

4) Determination of the ideal solution A* and the anti-ideal solution A- as eq. (16).

$$A^* = [V_1^*, \ldots\ldots, V_m^*] \text{and } A^- = [V_1^-, \ldots\ldots, V_m^-] \tag{16}$$

For desirable criteria

$$V_i^* = \max\{v_{ij}, j = 1, \ldots\ldots, n\}$$
$$V_i^- = \min\{v_{ij}, j = 1, \ldots\ldots, n\}$$

For undesirable criteria

$$V_i^* = \min\{v_{ij}, j = 1, \ldots\ldots, n\}$$
$$V_i^- = \max\{v_{ij}, j = 1, \ldots\ldots, n\}$$

5) Seperation of each alternative from ideal and negative ideal solution as eq. (17).

$$\left.\begin{aligned} S_i^* &= \sqrt{\sum_{i=1}^{m}(V_i^* - V_{ij})^2}, j = 1, \dots\dots, n \\ S_i^- &= \sqrt{\sum_{i=1}^{m}(V_i^- - V_{ij})^2}, j = 1, \dots\dots, n \end{aligned}\right\} \tag{17}$$

6) Ranking (Calculate the relative closeness to the ideal solution of each alternative as eq. (18)).

$$C_j^* = \frac{S_i^-}{S_i^- + S_i^*}, j = 1, \dots\dots, n. \tag{18}$$

A set of alternatives can be ranked according to the decreasing order of C_j *.

5.3. VIKOR

The VIKOR (Vlse Kriterijum-ska Optimizacija Kompromisno Resenje) which means multi-criteria optimization (MCO) and compromise solution method was mainly developed by Opricovic and Tzeng [10-12]. The method can be defined as a multi-criteria optimization of complex systems and it is based on ranking and selecting from a set of alternatives under conflicting criteria. Assuming that each alternative is evaluated according to each criterion function, the compromise ranking could be performed by comparing the measure of closeness to the ideal alternative. The compromise solutions could be the basis for negotiations, involving the preference of decision makers by criteria weights [47].The VIKOR algorithm also determines the weight stability intervals for the obtained compromise solution with the input weights given by the expert. This method focuses on ranking and selecting from a set of alternatives in the presence of conflicting criteria. It introduces the multicriteria ranking index based on the particular measure of ‘‘closeness’’ to the ‘‘ideal’’ solution [12]. Heydari et al. extended the concept of VIKOR method for decision making [48]. Jha et al. used VIKOR method to select the appropriate material for engineering problem to avoid unnecessary cost involvement and premature product failure [25]. VIKOR method is used to rank various alternatives, including site selection, technical and operational parameters for sustainable hydropower [49]. Jahan et al. used a modified VIKOR to overcome the errors of the traditional VIKOR method for the material selection to be used in biomedical engineering applications [50]. Fallah et al. calculate the Malmquist productivity number using VIKOR method to calculate progress or regression [51]. Bondor et al. used VIKOR method to calculate the risk factor in case of diabetic kidney disease [52]. For multi-criteria group decision makers, used extended VIKOR method for the project selection [53]. Penga et al. used VIKOR method for the optimization of multi-response problems in institutionistic fuzzy environment [54]. Developing of the VIKOR method started with the following form of Lp-metric [55]:

1) Determine the normalized Decision Matrix: The normalized decision matrix can be expressed as in eq. (19).

$$\left.\begin{aligned} F &= \left[f_{ij}\right]_{m\times n} \\ f_{ij} &= \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}}, i = 1, \dots\dots, m, \text{and } j = 1, \dots. n; \end{aligned}\right\} \tag{19}$$

and x_{ij} is the performance alternative with respect to the jth criteria.

2) Determine the ideal and negative ideal solutions: The ideal solution S* and negative ideal solutions S^- are as in eqs. (20) and (21).

$$\left.\begin{aligned} S^* &= \{(\max f_{ij} I\, j \in J) or (= \{(\min f_{ij} I\, j \in J\,) Ii = 1, \dots\dots, m\} = \{f_1^*, f_2^*, \dots\dots, f_n^*)\} \\ S^- &= \{(\min f_{ij} I\, j \in J) or (= \{(\max f_{ij} I\, j \in J\,) Ii = 1, \dots\dots, m\} = \{f_1^-, f_2^-, \dots\dots, f_n^-)\} \end{aligned}\right\} \tag{20}$$

$$\left.\begin{aligned} J &= \{j = 1,2, \dots. n\ I\ f_{ij}, \text{a larger response is desired}\} \\ J' &= \{j = 1,2, \dots. n\ I\ f_{ij}, \text{a smaller response is desired}\} \end{aligned}\right\} \tag{21}$$

3) Calculate the Utility and the Regret measure: The utility measure and the regret measure for each alternative are given as eq. (22).

$$\left.\begin{aligned} S_i &= \sum_{j=1}^{n} w_j \times (f_j^* - f_{ij})/(f_j^* - f_j^-) \\ R_i &= \max_j [w_j \times (\frac{f_j^* - f_{ij}}{f_j^* - f_j^-})] \end{aligned}\right\} \tag{22}$$

S_i represents utility measure, $R_i$represents the regret measure and w_j is the weight of the criteria j.

4) Calculate the VIKOR index: The VIKOR index can be as eq. (23) using eq. (24).

$$Q_i = v\left[\frac{S_i - S^*}{S^- - S^*}\right] + (1 - v)\left[\frac{R_i - R^*}{R^- - R^*}\right] \tag{23}$$

Q_i represents the ith alternative VIKOR value i=1,....,m.

$$\left.\begin{aligned} S^* &= \min_j S_i \\ S^- &= \max_j S_i \\ R^* &= \min_j S_i \\ R^- &= \max_j S_i \end{aligned}\right\} \tag{24}$$

v is the weight of maximum group utility and usually set to 0.5 [56-57].

6. Result and Discussion

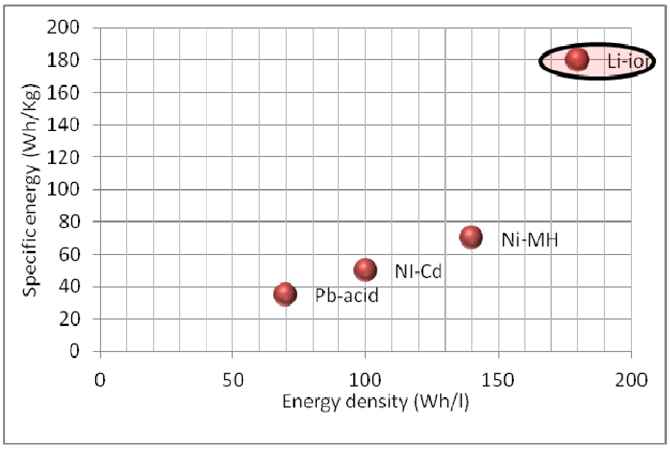
The primary requirement to use an HEV is a large driving range with minimum liquid fuel consumption over the roads. The optimal performance of hybrid vehicle varies with the batteries used during propulsion. From different type of batteries available; the battery selection is made based on various attributes for HEV applications. The Selection chart and calculations obtained from various methods are presented in this section below.

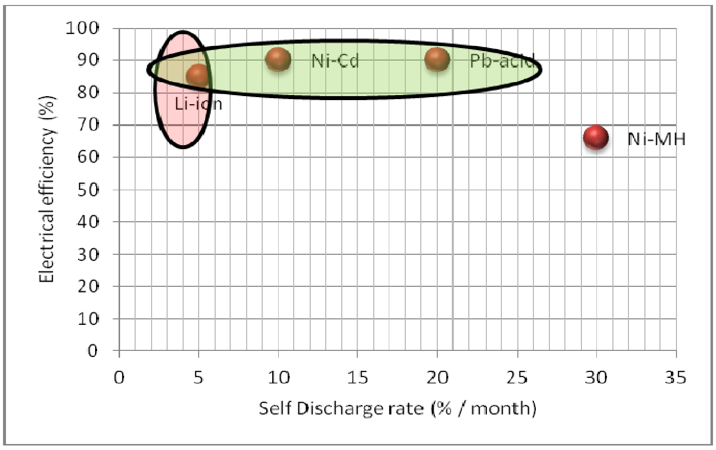
6.1. The Ashby's Methodology

The basic performance index for battery is higher open circuit voltage (OCV) which can maintain a good state of charge (SOC) throughout the operation [18]. Higher OCV also results in high peak power. The high peak power and OCV should be available for several numbers of discharge cycles to optimize the cost and performance of hybrid vehicles. Specific peak power also called as gravimetric power, is amount of power a battery can store is and the same is given by eq. (25).

$$\text{Specific power} = \frac{\text{Rated peak power}}{\text{Battery mass in kg.}} \tag{25}$$

These battery performance indices affect the overall fuel economy of hybrid vehicles and performance. The optimal battery is selected here by placing the battery attributes in battery selection map. Fig. 1 (a) shows the variation of specific energy and energy density. It is considered that specific energy density should be high to store more energy. From the fig. 1 (a), it is clear that Li-ion battery has significantly higher specific density and specific energy, both as compared to others.





(a) (b)

Fig. 1. (a) Specific energy versus energy density variation for considered batteries, (b) Electrical efficiency versus Self discharge plot of different batteries

A good battery should have high electrical efficiency and low self discharge rate. Fig. 2(b) infers that, Ni-Cd, Pb-acid and Li-ion have a trade off in terms of its electrical efficiencies Ni-Cd and Pb-acid battery shows higher efficiencies with higher self discharge rate whereas Li-ion battery with very low self discharge rate exhibit good percentage of electrical efficiency. Fig. 3 exhibits the energy drawn from the battery in every discharge cycle. The Pb-acid battery has a highest Watt hour energy per cycle but lowest durability. As durability reduces the running cost of hybrid vehicles increases, hence Pb-acid battery will not be suitable for this application. Ni-Cd has higher durability among all but has very low energy delivery in every cycle. Hybrid vehicles demand high energy out of battery; thus Ni-Cd is also not suitable for hybrid vehicle applications. Ni-MH and Li-ion batteries have a trade off in this case with very close values. But from fig. 1(b) and fig. 2, it is clear that Li-ion batteries have a high specific energy and higher power than Ni-MH batteries; hence choosing here Li-ion battery over Ni-MH will not lead to the wrong decision for vehicle manufactures. On the basis of the selection charts plotted, Li-ion battery is found to be most promising and Ni-MH rank as second.

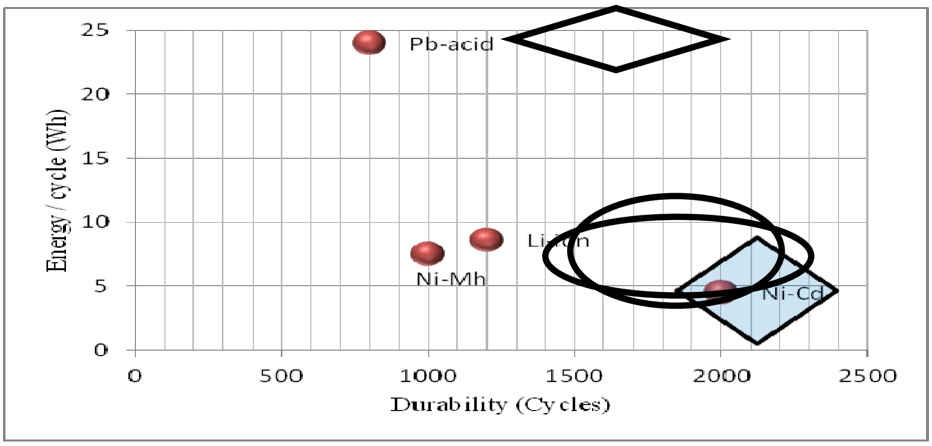


Fig. 2. Energy/cycle versus durability plot for various batteries

6.2. TOPSIS method

The various available batteries and their attributes are given in table 2. Here, self discharge rate and cost are minimization type and rest others are maximization type attributes. The normalized decision matrix is formed using (14) and the same is given in Table 3.

Table 2: Batteries and Attribute

Parameter / Battery	Energy density	Specific energy	Cell voltage	Electrical efficiency	Self discharge rate	Cost	Energy/cycle
Li	180	180	3.6	85	5	24	8.6
Ni-Mh	140	70	1.2	66	30	18.5	7.5
Ni-Cd	100	50	1.2	90	10	11	4.5
Pb acid	70	35	2	90	20	8.5	24

Table 3: Normalized decision matrix

Parameter / Battery	Energy density	Specific energy	Cell voltage	Electrical efficiency	Self discharge rate	Cost	Energy/cycle
Li	0.69592	0.888685	0.808223	0.509970	0.86754	0.28012	0.319074
Ni-Mh	0.54127	0.34560	0.26940	0.395977	0.205280	0.4450	0.27826
Ni-Cd	0.38662	0.24685	0.26940	0.53996	0.73509	0.67005	0.16695
Pb acid	0.27063	0.17280	0.44901	0.53996	0.470187	0.74504	0.89044

Weighting factors of various attributes are computed using ratio method and listed in table 4. Weighted normalized decision matrix is obtained using (15) and presented in table 5. Ideal and negative ideal solutions are estimated using (16) and presented in table 6. Distances of each alternative from the ideal and negative ideal solution are listed in table 7 using (17).

Table 4: Weighting factors of different attributes

Parameter	Energy density	Specific energy	Cell voltage	Electrical efficiency	Self discharge rate	Cost	Energy/cycle
Weighting factor	0.3668763	0.25082	0.005989	0.24782869	0.0486672	0.04642	0.033393

Table 5: Weighted normalized decision matrix

Parameter / Battery	Energy density	Specific energy	Cell voltage	Electrical efficiency	Self discharge rate	Cost	Energy/cycle
Li	0.255316	0.22290	0.004841	0.126385	0.042221	0.0130	0.010654
Ni-Mh	0.198579	0.08668	0.001613	0.098134	0.009990	0.0206	0.009292
Ni-Cd	0.141842	0.06191	0.001613	0.133819	0.035774	0.0311	0.005575
Pb acid	0.099289	0.04334	0.002689	0.133819	0.022882	0.0345	0.029734

Table 6: Ideal and negative ideal solution

Parameter	Energy density	Specific energy	Cell voltage	Electrical efficiency	Self discharge rate	Cost	Energy/ cycle
A*	0.255316	0.222903	0.004841	0.133819	0.009990	0.013003	0.02973
A-	0.099289	0.043342	0.001613	0.098134	0.042221	0.034585	0.00557

Table 7: Seperation of each alternative from ideal and negative ideal solution

Battery	Li	Ni-Mh	Ni-cd	Pb-acid
S+	0.038185416	0.153411313	0.200946167	0.23921363
S-	0.240596446	0.113945285	0.059015989	0.047246682

The ranks of batteries are calculated using (18) and the same is shown in table 8. The table shows that highest score is achieved by Li-ion battery which makes it a best suitable option to use in hybrid vehicle applications. Similarly, Ni-MH ranks second, Ni-Cd ranks third and fourth position is occupied by Pb-acid battery.

Table 8: Battery Ranking

Battery	Li	Ni-Mh	Ni-cd	Pb-acid
Ci	0.863027617	0.426192156	0.227017618	0.164932733

6.3. VIKOR method

Normalized decision matrix table has been used for step 1 matrix formation. Determination of ideal and negative ideal solution is presented in table 9 using (20). Utility and regret measures are collected in table 10 using expression given in (22).

Table 9: Determination of ideal and negative ideal solution

Parameter	Energy density	Specific energy	Cell voltage	Electrical efficiency	Self discharge rate	Cost	Energy/cycle
A*	0.695920	0.8886857	0.8082238	0.5399686	0.1324532	0.25495	0.8904414
A-	0.270635	0.1728000	0.2694079	0.3959770	0.7947194	0.71987	0.1669577

Table 10: Calculation of utility and regret measure

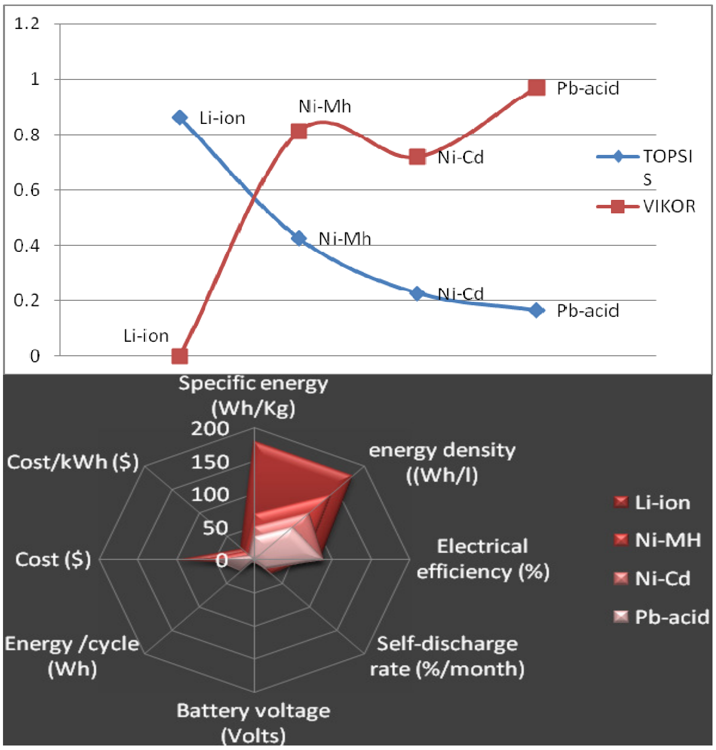
Battery	Si	Ri
Li	0.124424152	0.051630977
Ni-Mh	0.684380212	0.247828691
Ni-Cd	0.548299239	0.266819135
Pb acid	0.650893481	0.36687631

It finds the ideal and negative ideal solutions as S*=0.124424152; S-=0.684380212; R*=0.051630977 and R-=0.36687631. The VIKOR index for all the batteries are calculated in table 11 using eq. (23). The minimum value set of the desired alternative by VIKOR method is for Li-ion battery type. Hence Li-ion battery will be the best alternative to choose for the application with minimum cost and self discharge rate while maximizing other attributes.

Table 11: VIKOR index

Battery	Li	Ni-Mh	Ni-Cd	Pb acid
Qi	0	0.811182583	0.719792283	0.970098787

Ranking outcomes of TOPSIS and VIKOR methods are put together in fig. 3 (a). TOPSIS and VIKOR methods also rank Li-ion battery as fist option. TOPSIS ranks batteries in the order: Li-ion>Ni-Mh>Ni-Cd>Pb-acid whereas VIKOR ranks like Li-ion> Ni-Cd > Ni-Mh >Pb-acid. From the Ashby's approach, Li-ion battery proves to be best option for hybrid vehicle operation. Including Ashby's approach, it becomes clear that Li-ion battery ranks first followed by Ni-Mh in the list.



(a) (b)

Fig. 3. (a) Comparison of TOPSIS and VIKOR, (b) Spider web plot for attributes of the different batteries

The spider web plot in fig. 3 (b) summarizes all parameters mentioned in table 1 which also shows that Li-ion battery is covering wide range of battery attributes.

Aforementioned discussions recommend Li-ion battery as the best suitable option for hybrid vehicle applications followed by Ni-Mh. It is also investigated that absence or presence of any attribute in any decision making method affects the ranking order. Many combinations are tried here but in all the cases Li-ion battery proves to be best except one case. In this particular case, energy density and specific energy are ignored which leads to lower ranking of Li-ion battery. The sequence of ranking in such a case is Pb-acid > Ni-Cd > Li-ion > Ni-Mh. In hybrid vehicle applications, battery with high energy density is appreciated as it provides a large mileage in one charge cycle. High energy density and high specific energy allow vehicle to perform satisfactorily in case of acceleration and energy regeneration. Hence Li-ion battery and Ni-Mh battery are proved to be descent options for use. The table 12 below summarizes the usage of these battery technologies in various hybrid vehicles applications. Li is an alkali metal with the very light weight and Ni is in fourth period of periodic table with iron and is quite dense. So for the same energy storage capacity, Li-ion battery size will be bigger but it will weigh lighter. Weight is very important parameter to be analyzed in HEVs. Memory effect is worth considerable phenomenon to keep in mind. It is observed that batteries forget their maximum energy capacity if they are often discharged/charged partially. Ni-MH battery suffers with the memory effect, whereas Li-ion batteries don't. Due to this Ni-MH energy storage capacity decrease and Li-ion battery can be charged/discharge faster. This concludes that in hybrid vehicles applications Li-ion battery will be an appropriate choice with respect to good mileage, reliability and durability.

Table 12: Overview of battery technology used in several vehicles

Company	Vehicle model	Battery technology
GM	Chevy-Volt	Li-ion
	Saturn Vue Hybrid	Ni-MH
Ford	Escape	Ni-MH
	Fusion	Ni-MH
	MKZ HEV	Ni-MH
	Escape PHEV	Li-ion
Toyota	Prius	Ni-MH
	Lexus	Ni-MH
Honda	Civic	Ni-MH
	Insight	Ni-MH
Hyundai	Sonata	Lithium Polymer
Chrysler	Chrysler 200C EV	Li-ion
BMW	X6	Ni-MH
	Mini E	Li-ion
BYD	E6	Li-ion
Daimler Benz	ML450	Ni-MH
	S400	Ni-MH
	Smart EV	Li-ion
Mitsubishi	iMiEV	Li-ion
Nissan	Altima	Ni-MH
	Leaf EV	Li-ion
Tesla	Roadster	Li-ion
Think	Think EV	Li-ion, Sodium/Metal chloride

7. Overview of existing Li-ion battery technologies

It is uncovered that depending on the type of technology used in Lithium ion batteries, specifications of the batteries change significantly. These uses Lithium as basic component like Lithium cobalt oxide, Lithium Manganese Oxide, Lithium Iron Phosphate, Lithium Nickel Manganese Cobalt Oxide, Lithium Nickel Cobalt Aluminium Oxide and Lithium Titanate are discussed in detail below [58-62] .

7.1. Lithium Cobalt Oxide ($LiCoO_2$)

$LiCoO_2$ batteries offer high specific energy (1.1 kWh kg−1) and capacity. It consists of a cobalt oxide cathode and a graphite carbon anode. During discharge Li-ions move from anode to cathode and vice-versa on charge. It has limited load capabilities (specific power) and relatively short life span. These batteries, however, cannot be charged and discharged at a higher current rating.

7.2. Lithium Manganese Oxide ($LiMn_2O_4$)

$LiMn_2O_4$ are fast charging batteries. They have high-current discharge capability. Its architecture forms a three-dimensional spinel structure that improves ion flow on the electrode. Hence, have lower internal resistance with superior current handling. They offer more energy than nickel-based chemistries (approximately 50 percent) and have design flexibilities. Hence life span, specific power and specific energy can be maximized by manufacturers.

7.3. Lithium Iron Phosphate ($LiFePO_4$)

$LiFePO_4$ offers good electrochemical performance with low resistance. Nano-scale phosphate cathode material is used which brings enhanced safety, good thermal stability, high current rating and long cycle life features. Specific energy is lower than Li-manganese.

7.4. Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)

$LiNiMnCoO_2$ can have either high specific energy or high specific power. Acquiring both at the same time is quite tough. Cathode has combination of one-third nickel, one-third manganese and one-third cobalt which offers a unique blend. And lower down the cost due to reduced cobalt content.

7.5. Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$)

$LiNiCoAlO_2$ offer high specific energy and power densities with admirable life span. These batteries have lower safety and higher cost than others.

7.5. Spinel Lithium Titanate ($Li_4Ti_5O_{12}$)

$Li_4Ti_5O_{12}$ replaces the anode graphite of Li-on battery. Spinel structure offers fast-charging and delivers a high discharge current of 10C, or 10 times the rated capacity. These batteries are safe and have excellent low-temperature discharge characteristics; however, specific energy offered is low.

Table 13 comprises various parameter values of Lithium based batteries which may help to choose a battery for the desired operational area. Various battery technologies tried to improve the Li-based batteries with reduced operating cost.

Table 13: Lithium based batterie's Specifications

Specifications	$LiCoO_2$	$LiMn_2O_4$	$LiFePO_4$	$LiNiMnCoO_2$
Voltage	3.60V	3.80V	3.30V	3.60/3.70V
Charge limit	4.20V	4.20V	3.60V	4.20V
Durability (cycles)	800	300-700	2000	1000–2000
Operating temperature	Average	Average	Good	Good
Specific energy (Wh/kg)	150–190	100–135	90–120	140-180
Energy density (Wh/kg)	300	280	170	160
Thermal runaway (°C)	150	250	270	210
In use since	1994	1994	1999	2003

8. Conclusion

The optimal battery selection for hybrid vehicle applications using Ashby's approach, TOPSIS and VIKOR are presented. The performance indices of battery are optimized against several battery attributes. On the basis of battery selection charts, it is found that Li-ion and Ni-MH batteries outperform and would serve the purpose in hybrid vehicles. Further, very high specific energy and energy density of Li-ion against Ni-MH battery, advises to opt for Li-ion battery. A powerful battery management system can be used to increase the performance and life of Li-ion battery. Li-ion batteries are inviting lot of research attention due to its lower self discharge rate, high specific energy density and high specific power. Various technologies are being explored by researchers to manufacture low cost batteries with improved performance. As a result, in near future smaller size, very powerful and long live Li-ion battery will attract not only hybrid vehicle manufacturers but manufacturers of all the relevant disciplines with reduced cost.

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