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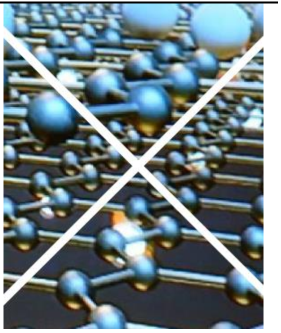

COMPARISON OF AN INTERVAL TYPE-2 FUZZY SETS AND AHP METHODS FOR MATERIAL SELECTION PROBLEM ON LİTHİUM-ION BATTERIES

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Abstract

Lithium-Ion batteries have become one of the most commercially preferred energy storage devices because of their high energy density, low self-discharge rate, and the ability to be cycled many times with slow capacity fading in comparison with other rechargeable batteries. They have been applied on a wide variety of electrical devices and systems such as consumer electronics, power tools, electric vehicles and aerospace equipment. The characteristics of Lithium-Ion batteries are mainly determined by the materials used for its components which can be categorized into four parts: anode and cathode electrodes, separator, and electrolyte. Over the last decade, there has been a significant increase in the number of studies evaluating battery performance based on various materials used in each battery component. However, few attempts have been made to evaluate materials of Lithium-Ion batteries. Thus, in this study, it is aimed to evaluate different materials for cathode electrode in terms of four main criteria: cost, performance, safety and service life using two methods; AHP and interval type-2 fuzzy sets. It is shown that more reliable results are obtained for selecting the best cathode material of Lithium-Ion battery and based on comparison of two methods; same rank is achieved for both approaches.

Keyword: Material selection problem, AHP, Fuzzy Logic, Interval type-2 fuzzy sets, Lithium-Ion battery.

1. Introduction

In view of the current and predictable energy needs, the utilization of Lithium-Ion batteries has become more essential because of its accommodation of high energy and power density, with a low self-discharge rate [1]. In addition, one of remarkable features is able to work under wide temperature range of operation [2]. The high energy efficiency of Lithium-Ion batteries also makes them the leading source of energy storage in many application areas such as renewable sources, the electronic device and electric vehicle industry [3]. Thus, researches on Lithium-Ion batteries have become a critical and essential issue in both industry and government agencies [1].

Lithium-Ion batteries comprise of the anode and cathode electrodes, separator, and electrolyte and these components determine the characteristics of Lithium-Ion batteries [4]. In order to increase the performance of a Lithium-Ion battery along with a decrease on cost, most of researches have focused on electrode materials which provide higher rate capability and higher charge capacity [1]. There are several commercially available electrode materials that can be found in different works which compare them based on their performance, power, weight, energy storage capability, volume, life time and cost. However, in this study, we will focus on five cathode electrodes namely; lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), nickel manganese cobalt (NMC) and, nickel-cobalt-Al (NCA).

Selection of appropriate materials is a challenging task for researchers. Materials are evaluated for two purposes; either the design of a new product or the improvement of an existing product. A number of methods have been developed to select the right materials with a higher performance [5]. According to Scallan [5], there are various features considered to evaluate materials and they all depend on the user preference. For instance, mechanical and physical properties could be one attribute to select the right material, while manufacturing process and cost could be another attribute. Selection of proper materials for sustainable energy has become a significant place among studies. Ahmad and Tahar [6] pointed out that renewable resources should be investigated and evaluated in order to formulate a long term energy policy. In their work, AHP is used to assess potential renewable sources and to find out the most suitable policy for Malaysia. Okokpujieet al. [7] addressed a material selection problem for wind turbine blade to improve sustainable energy generation. In this study, firstly, criteria are decided by materials engineers and renewable energy professionals. Then, four alternatives are investigated in terms of these criteria. Based on performance of alternatives, the decision-makers recommended the best alternative to manufacturers. In addition, Gil et al. [8] tested thermal energy storage for solar cooling applications using different materials in a plot plant built.

Due to the complexity of the material selection problem, there has been a range of studies applying multi-criteria decision making methods which provide a structure to solve a problem considering multiple criteria at the same time. Panday and Bansal addressed a battery selection problem for hybrid electric vehicle applications using TOPSIS and VIKOR [9]. Kaa et al. pointed out that the factors affecting technology success in the residential grid storage market could be related to success in battery technologies. The problem is solved using the best worst method (BWM) evaluating five battery materials: lithium, lead, nickel, sodium and flow batteries [10]. Sangwan and Jindal proposed an integrated fuzzy multi-criteria decision model to evaluate different recycling alternatives for Lithium-Ion batteries to show the importance of recycling processes [11].

Based on the literature, it is clearly revealed that although multi-criteria decision making methods are used in many engineering applications to select the most suitable materials, few attempts have been made to evaluate materials of Lithium-Ion batteries and to the authors' knowledge, there is no research found on material selection on cathode materials with considering variety of criteria selected at the same time.

The aim of this study is to select the best materials for cathode electrodes of Lithium-Ion batteries used in electric scooter battery system using both Analytic Hierarchy Process (AHP) and interval type-2 fuzzy sets. Because of being easy to understand and successfully applied to different decision making problems in literature, AHP is selected to solve this problem. Because of the uncertain nature of material selection problems of Lithium-Ion batteries, in the study, a fuzzy approach is preferred as a second method to apply to the problem evaluating alternatives proposed for cathode electrodes. First, the problem is solved using AHP and then in order to see the impact of uncertainties revealed into the linguistic evaluation of decision makers, the same problem is solved using interval type-2 fuzzy sets. Finally, the results of two methods are compared to conclude with more reliable results.

2. Background

This section introduces basic concepts of Lithium-Ion batteries and the fundamentals of the techniques used in this work with an overview of related work in the area.

2.1. Basic concepts of Lithium-Ion batteries

A Lithium-Ion battery is a general term used to refer to the batteries of various chemistry with different performance and characteristics [12]. Lithium-Ion batteries are composed of positive (cathode) and negative (anode) electrodes, and an ionically conductive and electrically insulating electrolyte and a separator. The electrolyte containing lithium conductive salt connects the positive and negative electrodes. The anode and the cathode are electrically isolated by the separator consisting of a microporous polymer membrane. This membrane allows the movement of Lithium-Ions between the anode and the cathode, but does not allow electron movement. During the charge / discharge process, aluminium acts as a current collector on the cathode side and copper on the anode side [13, 14]. The operating principle of Lithium-Ion batteries is as the following: During charging Lithium-Ion batteries, two electrodes are first connected to an external power source. Thus, the electrons released from the cathode move towards the anode through the external circuit, the positively charged Lithium-Ion move through the electrolyte towards the anode and intercalation of Lithium-Ion into active material takes place in anode side. After the intercalation process is completed, the external electrical energy is chemically stored in the battery [14]. The discharge process is in the opposite direction of the charging process. Lithium ions de-intercalated from the anode move through the electrolyte and electrons move through the outer circuit towards the cathode. Due to the electron movement, the external circuit becomes a usable electrical circuit [13, 14].

Although this study focuses on the evaluation of fully commercialized cathode materials, before clear understanding of the cathode, it is useful to give brief information about anode and electrolyte materials used in Lithium batteries. The anode is the negative terminal of the battery cell and is usually coated on current collectors such as aluminium and copper. Today, a mixture of graphite and soft or hard carbons are generally used to form anode for Lithium-Ion batteries [12].

One of the outstanding features of the graphite anode is that it has a specific capacity of 300–350 $mAhg^{-1}$[15]. Another remarkable anode material is lithium titanite due to its low temperature operation and high power density. Batteries using this anode material are called Lithium-Ion titanite cells (LTO). The LTO cell operates between -40 and + 60 °C and has the advantage of having a good power density of 1400 WL^{-1} , but the nominal voltage is between 2.2 V and 2.3 V and is low. Another vital part of Lithium batteries is the electrolyte, which plays a crucial role in electrochemical behavior and ion transfer between the two electrodes [16]. In view of their advantages and disadvantages, liquid, gel and solid electrolytes are selected by the manufacturers for different purposes. Although liquid electrolytes cause safety concerns such as solid electrolyte interphase (SEI), dendrite growth, leakage and thermal runaway, it has high ionic conductivity, making it attractive. Compared to liquid electrolytes, the gel-polymer electrolytes have lower ionic conductivity but offer improved safety. Due to the suppression of dendrite growth and higher electrochemical and thermal stability, solid electrolyte is safer than the other two electrolytes. The disadvantage of solid electrolyte is that it has lower ionic conductivity compared to liquid and gel electrolyte [16, 17].

Cathode is an electrode that accepts electrons during cell discharge [18]. In order to benefit from the advantages of different chemistries and to achieve significant performance results, cathode materials containing different chemistries in various proportions are preferred by cell manufacturers. In this study, five of the most commercially accepted cathode materials are evaluated to be used in electric scooter battery system. These cathode materials can be listed as lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), nickel manganese cobalt (NMC) and, nickel cobalt aluminium (NCA) [12]. Due to good cycling performance, low self-discharge rate, high theoretical specific capacity of 274 $mAhg^{-1}$, high theoretical volumetric capacity of 1363 $mAhcm^{-3}$, and high discharge voltage, the layered $LiCoO_2$ has been a revolutionary part of Lithium-Ion batteries used in portable electronics for decades. However, due to chemical and thermal instability, high cost and safety concerns, the use of this cathode material in electrical vehicles and energy storage of renewable energy sources is quite low. In addition, only 50% of the theoretical capacity can be utilized using this cathode material [19, 1, 20]. Furthermore, the LCO cathode experiences severe capacity fading at high current rates and deep cycles. The main reason why LCO cathode material is expensive is the high cost of Cobalt. Because of using $LiCoO_2$cathode with low thermal stability, the cell may be at risk of thermal runaway and consequently explosion due to exothermic oxygen release after heating the cell above certain point [1]. In order to achieve a more affordable cost and higher energy density, efforts have been made to replace cobalt with cheaper nickel. As a result, a $LiNiO_2$ cathode material with similar theoretical specific capacity of 275 $mAhg^{-1}$, higher reversible capacity of 200 $mAhg^{-1}$, and layered structure was formed [1, 13, 18]. During the production of NCO, Nickel ions substitute some of the lithium positions. Ni^{2+} ions, which have similar radii with the Li^{+} ions, are the main cause of this mixed occupation, and the Ni^{2+} ions block lithium diffusion, resulting in an irreversible capacity loss in the cathode material. Basically, LNO is more thermally unstable than LCO due to Ni^{3+} ions and the safety concerns as a result of oxygen release persist in this cathode material [13].

It was found that the partial substitution of Ni with Co is a more effective method, thereby avoiding the negative effects of complete mixing. Adding a small amount of Al to this partial substitution both improves electrochemical performance and leads to a more thermally stable cathode. $\mathrm{LiNi_{0.8}Co_{0.15}Al_{0.05}}$ (NCA) cathode material formed by the addition of a small amount of Al has become commercially widespread. NCA batteries manufactured by Panasonic are used in Tesla electric vehicles. Compared to the other four batteries, NCA batteries have a high usable discharge capacity of 200 $\mathrm{mAhg^{-1}}$. However, Due to the formation of SEI and micro-crack growth at the grain boundaries, they suffer from significant capacity loss even at temperatures between 40 and 70 °C[1]. The reason for using manganese (Mn) in the batteries is that it is cheap, environmentally friendly, has high electronic and ionic conductivity, excellent rate capability and offers an ideal level in terms of safety [19]. Spinel $\mathrm{LiMn_2O_4}$ cathode has been considered one of the serious options by the electric vehicle industry and has been used in Chevy Volt. Disadvantages of batteries using $\mathrm{LiMn_2O_4}$ cathode are that it has a severe capacity loss at temperatures exceeding 55 °C; it has a short cycle life [19, 1]. In addition, it has a gravimetric energy density of 410-492 $\mathrm{Whkg^{-1}}$, which is less than the energy density of other four cathode materials [18]. The short cycle life is mainly because of irreversible reactions with electrolyte, oxygen loss due to de-lithiation of $\mathrm{LiMn_2O_4}$, dissolution of Mn and formation of $\mathrm{Li_2Mn_2O_4}$ at high discharge rates [1]. Oxygen production does not occur in cells where $\mathrm{LiFePO_4}$ cathode material is used, even at high temperatures and as a result of fully decomposition. For this reason, this cathode material provides a vital safety advantage with the lowest heating rate during thermal runaway. In LFP cells, thermal runaway is dominated by the anode and electrolyte pair [21]. $\mathrm{LiFePO_4}$ with olivine structure is non-toxic, has excellent safety and is cost-effective. LFP batteries which have these features have become one of the most prominent candidates for transport applications. The LFP battery manufactured by A123 was used in Chevrolet Spark EV for transportation purposes [22]. On the other hand, low ionic and electronic conduction are an obstacle to be overcome for $\mathrm{LiFePO_4}$ cathode materials. Electronic and ionic conductivity are generally enhanced by making $\mathrm{LiFePO_4}$ as nanoparticles and coating these particles with conductive carbons. The processes for making nanoparticle and coating carbon cause extra processing costs [19]. Current batteries using $\mathrm{LiFePO_4}$cathode are only able to deliver garvimetric energy density of 90-110 $\mathrm{Whkg^{-1}}$, and in this respect, it lags behind competitors like NCA and NMC [23]. Also, LFP has lower energy density than the other four chemistries on the market which means larger volume is needed to fit battery pack into vehicles [21].Although different NMC cathode materials can be formed using cobalt, nickel and manganese in various proportions, the most common NMC in the market is in the form $\mathrm{LiNi_{0.33}Co_{0.33}Mn_{0.33}O_2}$ (NMC-111) [1]. Compared to LiCoO2, The $\mathrm{LiNi_{0.33}Co_{0.33}Mn_{0.33}O_2}$ cathode, which offers improved thermal, structural and chemical stability and has more satisfactory electrochemical properties, has become an attractive option [18]. NMC batteries have good cycle stability even at 50 °C. As it has an average specific capacity of 160-170 $\mathrm{mAhg^{-1}}$and 1000-2000 charge/discharge cycles, the interest in NMC batteries increases over time and NMC has a growing market share [18, 23]. Cylindrical and prismatic NMC batteries produced by different companies are used in the electrical vehicles of various brands such as Nissan, Renault, Chevrolet, Honda and Volkswagen [22].

Based on literature, it could be said that each material has some advantages and disadvantages. Thus, in order to evaluate them, considering several criteria at the same time could be the best way to provide fair evaluation.

2.2. Multi-criteria decision making

Conflicting criteria are evaluated in order to make decisions with a consideration of different objectives such as minimizing the cost of Lithium-Ion battery while maximizing specific capacity. The multi-criteria decision making (MCDM) is widely used method to evaluate explicitly multiple conflicting criteria in the discrete decision spaces. In a MCDM problem, alternatives proposed are examined to compare, rank and order them based upon criteria [24]. In literature, a number of MCDM methods can be found as Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Multi Attribute Utility Technique (MAUT), Fuzzy set theory. Analytic Hierarchy Process (AHP) is one of the most outstanding MCDM approaches to solve complex decision problems using hierarchical levels along with a process of paired comparison [25]. However, this method is not capable where imprecise human thinking is present in linguistic judgment [26, 27]. In order to cope with these types of uncertainty, fuzzy sets are preferred by researchers [28, 29]. Thus, in this study, we used both AHP and interval type-2 sets to handle a material selection problem for Lithium-Ion batteries.

2.2.1. Analytic Hierarchy Process

Saaty introduced the AHP method which compares alternatives in a hierarchical structure with respect to perception and thinking of decision makers [30]. AHP uses pairwise comparison of elements in the same hierarchy for both criteria and alternatives giving different weight for each element [31]. In literature, the AHP method has been used in many different real-word problems. In addition, some researchers have applied in material selection problems owing to a number of conflicting criteria affecting decision makers. For instance, Dweiri and Al-Oqla stated that the AHP method is useful to evaluate materials under competition on quality and cost [31]. In addition, Kiong et al. addressed a material selection problem in screw manufacturing to minimize environmental impacts using AHP and pairwise comparison among materials provided useful information to decrease harmful environmental impact of screw manufacturing [32]. Kühn et al. proposed an AHP approach to select materials for automated dry fiber placement and this method helps to minimize cost and preparation time decreasing iterative manufacturing trials [33]. Through the review of several papers chosen, it is clearly seen that AHP is applied into a number of material selection problems and it is capable of providing useful information for decision makers. For this reason, in this work, an AHP approach is used to deal with cathode materials for Lithium-Ion batteries. In addition, due to ambiguity in subjective judgments and the lack of information, the same problem proposed is solved using interval type-2 fuzzy sets and results of two methods are compared in order to obtain more reliable result.

2.2.2. Interval Type-2 Fuzzy Sets

Zadeh introduced fuzzy set theory which allows varying degrees of membership values in a given set to consider both tangible and intangible knowledge [34]. Zadehalso proposed type-2 fuzzy sets to handle problems which type-1 fuzzy sets cannot cope with [35]. According to Hagras, the wider coverage of uncertainties are provided using type-2 fuzzy sets while using less rules [36].

However, due to the computational complexity on type-reduction and defuzzification processes of type-2 sets, the most researchers have focused on interval type-2 fuzzy sets [37]. Thus, in this study, we preferred to use interval type-2 fuzzy sets.

For type-2 fuzzy systems, a membership function (the degree of membership) shown as $\mu_{\widetilde{A}}(x,u)$ characterized as fuzzy set $\widetilde{A}$ and this fuzzy sets are shown as:

$$\widetilde{A} = \{(x,u),\ \mu_{\widetilde{A}}(x,u) \mid \forall x \in X, \forall u \in\ J_x \subseteq\ [0;1]\} \tag{1}$$

where $x \in X$ and $u \in J_x \subseteq [0;1]$ in which $0 \leq \mu_{\widetilde{A}}(x,u) \leq 1$. If all $\mu_{\widetilde{A}}(x,u) = 1$ then $\widetilde{A}$ is named as an interval type-2 fuzzy set [38]. In addition, membership functions can have different shapes such as triangular, trapezoidal, Gaussian and in this study, trapezoidal interval type-2 fuzzy sets (IT2FSs) are used and shown as follows:

$$\tilde{A}_i = \left(\tilde{A}_i^U, \tilde{A}_i^L\right) = \left(\left(\tilde{a}_{i1}^u, \tilde{a}_{i2}^u, \tilde{a}_{i3}^u, \tilde{a}_{i4}^u; h_1\left(\tilde{A}_i^U\right), h_2\left(\tilde{A}_i^U\right)\right), \left(\tilde{a}_{i1}^l, \tilde{a}_{i2}^l, \tilde{a}_{i3}^l, \tilde{a}_{i4}^l; h_1\left(\tilde{A}_i^L\right), h_2\left(\tilde{A}_i^L\right)\right)\right) \tag{2}$$

where $\widetilde{A}_i^U$ and $\widetilde{A}_i^L$ are type-1 fuzzy sets while $\tilde{a}_{i1}^u, \tilde{a}_{i2}^u, \tilde{a}_{i3}^u, \tilde{a}_{i4}^u, \tilde{a}_{i1}^l, \tilde{a}_{i2}^l, \tilde{a}_{i3}^l$ and $\tilde{a}_{i4}^l$ represent the reference points of the interval type-2 fuzzy set, $\widetilde{A}_i$ [38]. The height of each constituent membership function shown as $h_k(\widetilde{A}_i^U), h_k(\widetilde{A}_i^U)$ for $1 \leq k \leq 2$ is assumed to be equal to 1. Thus, it is not explicitly defined. Algebraic operations used in this work are addition and multiplication as depicted respectively as follows [38]:

$$\widetilde{A}_1 \oplus\ \widetilde{A}_2 = \left(\widetilde{A}_1^U, \widetilde{A}_1^L\right) \oplus\ \left(\widetilde{A}_2^U, \widetilde{A}_2^L\right) \tag{3}$$

$$\widetilde{A}_1 \otimes\ \widetilde{A}_2 = \left(\widetilde{A}_1^U, \widetilde{A}_1^L\right) \otimes\ \left(\widetilde{A}_2^U, \widetilde{A}_2^L\right) \tag{4}$$

3. Methodology

This study aims to provide an evaluation of five cathode materials for Lithium-Ion batteries namely $LiCoO_2$(LCO), $LiMn_2O_4$(LMO), $LiMn_2O_4$(LFP), $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$(NMC), $LiNi_{0.8}Co_{0.15}Al_{0.05}$ (NCA) with respect to 9 criteria under 4 main criteria as shown in Table 1. The performance of 5 alternatives are investigated using two different methods; AHP and interval type-2 fuzzy sets. In AHP, the problem is solved considering 9 criteria that have same importance weight for decision maker while in fuzzy approach, the problem is examined using 4 main, 9 sub-criteria. Thus, although thermal abuse and thermal stability is similar in general, in this study, thermal stability is considered under safety while thermal abuse is examined under service life in order to obtain more reliable results.

3.1. Definition of Criteria

For decades, there has been a growing interest on Lithium-Ion battery systems. Since the first launch of lithium batteries, it has always been a key objective to obtain high-performance, inexpensive, perfectly safe and durable batteries. Obtaining desirable cathode materials and using these cathodes in the cell play a significant role to achieve this key objective.

Table 1. Main and Sub-criteria used for evaluation of alternative cathode materials

Main Criteria	Abb.	Sub-criteria	Abb.
Performance	M_1	Specific Capacity	C_1
		Gravimetric Energy Density	C_2
		Discharge (C- Rate)	C_3
		Working Voltage	C_4
Cost	M_2	Cell Cost	C_5
Safety	M_3	Cathode Safety	C_6
		Thermal Stability	C_7
Service Life	M_4	Cycle Life	C_8
		Thermal Abuse	C_9

Table 2. Criteria for Cathode materials and their changes based on five materials namely $LiCoO_2$(LCO), $LiMn_2O_4$(LMO), $LiMn_2O_4$(LFP), $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$(NMC), $LiNi_{0.8}Co_{0.15}Al_{0.05}$ (NCA), respectively.

Criteria	LCO	LMO	LFP	NMC	NCA
Specific Capacity [18]	140	100-120	150-170	160-170	180-200
Gravimetric Energy Density [18]	546	410-492	518-587	610-650	680-760
Discharge (C- Rate) [23]	<1C	1C	1C-3C	0.7-1C	1C
Working Voltage [13]	3.9	4.1	3.4	3.7	3.7
Cost [39,40]	High	Low	Low	Low	Low
Safety [19,13]	Very Low	Medium	Very High	High	Low
Thermal Stability [19,41]	Very Low	Medium	High	Medium	Low
Cycle Life [41,23]	500-1000	300-700	1000-2000	1000-2000	500
Thermal Abuse [9 ,41]	High	Low	Low	Medium	High

Nowadays, cathode materials consisting of different chemistries, having various performances and varying costs are frequently encountered in commercial Lithium-Ion batteries as seen in Table 2. Therefore, it has become extremely important to select proper Lithium-Ion batteries that use different cathode materials depending on the place of use. In this study, in order to select cathode suitable for electric scooter battery system, nine criteria are taken into consideration as explained in the followings:

1. Specific Capacity; is defined as the amount of charge the cathode contains per unit weight and is expressed as $mAhg^{-1}$ or $Ahkg^{-1}$. Also, it is a measure of how long the energy can be supplied to a device under a certain discharge current. Materials with higher specific capacity are often preferred because they provide energy for longer [18].

2. Gravimetric energy density; is described as the energy density of a material's unit weight and expressed as $Whkg^{-1}$. Energy density is the common product of specific capacity and voltage. Cathode materials generally have a lower specific capacity than graphite, the most commonly used anode material and the energy density of the cell is determined by the electrode having a lower energy density. Therefore, the main determinant of the energy density of the cell is cathode. As a result, selecting cathode material with a high gravimetric energy density is extremely important as it will increase the energy density of the cell and provide more energy per unit weight [18].
3. Discharge (C-Rate); is a term used to refer to the rate at which a battery can discharge all its energy or power. The 1C discharge rate delivers the nominal capacity of the battery within 1 hour. In other words,1C rate means that a battery can discharge in one hour and 3C rate means that the same battery can discharge in 20 minutes (60 min / 3C = 20 min). High C-rate is a desirable feature since cells with high C-rate rates can provide higher discharge current [12].
4. Working Voltage (V); is the potential difference between the anode and cathode during the operation of the cell and it is called either working voltage or operating voltage. In addition, it varies with the state of charge. Since the energy density of the cell is determined by capacity and voltage, it is important to select cathode material that can provide higher voltage [39].
5. Cell Cost; is the sum of cost of battery components and processing cost. Obviously, the cost of cells using various cathode chemistries will be different than each other. In addition, some cathode materials need to undergo extra processing to perform at the desired level, which results in extra processing costs [19].Low-cost cathode materials are preferable to create cheaper cells.
6. Cathode Safety; concerns include thermal instability, chemical instability, toxicity, and short circuit caused by various reasons. The safety is one of the key factors in determining the areas where different Lithium-Ion batteries can be applied. As a component of the cell, the choice of safer cathode material is advantageous for whole cell [20].
7. Thermal Stability; specifies to what extent the battery loses its stability with increasing or decreasing temperature. Thermal instability of the cathode material causing overheating, thermal runaway and even explosion can be said to be the main safety problem in the cell. Therefore, the thermal properties of the cathode material must be carefully examined to ensure that the cell remains thermally stable as desired [20].
8. Cycle Life; is defined as the total number of cycles that can the battery reach. One time discharging and then charging the battery is called a cycle. The cycle can be carried out at various power and voltage ratings or at constant charge or discharge rates as required. Cathode materials capable of reaching higher number of cycles will lead to cells with long cycle life [12].

9. Thermal Abuse; relates to thermal stability and examines how cells with different cathode materials behave over a wide temperature range. Cells are more prone to thermal abuse may encounter different modes of failure such as thermal runaway due to internal gas and heat generation, short-circuit due to electrode displacement and contact of two electrodes. It is obvious that thermal abuse shortens the life of the cell due to failures it may cause. Therefore, it has become essential to select thermally stable cathode materials to create cells that resist thermal abuse [21].

3.2. Applying AHP method

Table 3. Numerical Scale for Pairwise Comparison [42].

Linguistic variable	Numeric value
Extremely important	9-8
Very strongly more important	7-6
Strongly more important	5-4
Moderately more important	3-2
Equally important	1

The basic concept of AHP is to decide objective, alternatives that we evaluate and criteria used for evaluation of alternatives. After deciding all constraints and objective, a pairwise comparison matrix is generated to compare alternatives over criteria for all alternatives. As a next step, a numeric scale shown in Table 3 is used to calculate the relative importance of two criteria and it is carried on with until all criteria are compared to each other to generate the matrix. For instance, if C1 is compared to C2 and it is assigned as 5, the comparison of C2 to C1 becomes 1/5 as its reciprocal. After that, in order to obtain the required relative criteria weights, the matrix is normalised. And then, percentage importance distribution of the alternatives is calculated to get a 1×m matrix where m is the number of alternatives. Finally, to achieve the rank of alternatives, the matrix of option scores (n×m) is computed where n is the number of criteria (detailed in [43]).

3.3. Applying Interval Type-2 Fuzzy Sets

In this study, the decision maker selected four main, nine sub-criteria. After that, all criteria are defined in a linguistic way such as “very high” in order to represent the importance of each criterion. Linguistic weights of attributes are shown in Table 4. Then, the linguistic definitions for all criteria are converted into fuzzy weights using fuzzy membership functions. For example, let one criterion defined as “Medium”, it is assigned as ((0.3, 0.5, 0.5, 0.7) (0.4, 0.5, 0.5, 0.6)) as shown in Table 4. Next, cathode materials are identified in the same manner using linguistic terms such as ‘very good’, ‘good’, ‘poor’. Linguistic terms and their corresponding fuzzy sets are demonstrated in Table 5. After that, these terms are converted into fuzzy performance rating. And then, the aggregate fuzzy score is calculated using Centroid type-reduction and defuzzification methods and the rank of materials are obtained as shown in Table 11 (detailed in [43]).

Table 4. Linguistic variable to evaluate each criterion [44].

Trapezoidal ITFSs	$\tilde{a}_{i1}^{u}$	$\tilde{a}_{i2}^{u}$	$\tilde{a}_{i3}^{u}$	$\tilde{a}_{i4}^{u}$	h_1	h_2	$\tilde{a}_{i1}^{l}$	$\tilde{a}_{i2}^{l}$	$\tilde{a}_{i3}^{l}$	$\tilde{a}_{i4}^{l}$	h_1	h_2
Very Low (VL)	0	0	0	0.1	1	1	0	0	0	0.05	0.9	0.9
Low (L)	0	0.1	0.1	0.3	1	1	0.05	0.1	0.1	0.2	0.9	0.9
Medium Low (ML)	0.1	0.3	0.3	0.5	1	1	0.2	0.3	0.3	0.4	0.9	0.9
Medium (M)	0.3	0.5	0.5	0.7	1	1	0.4	0.5	0.5	0.6	0.9	0.9
Medium High (MH)	0.5	0.7	0.7	0.9	1	1	0.6	0.7	0.7	0.8	0.9	0.9
High (H)	0.7	0.9	0.9	1	1	1	0.8	0.9	0.9	0.95	0.9	0.9
Very High (VH)	0.9	1	1	1	1	1	0.95	1	1	1	0.9	0.9

Table 5. Linguistic variable to evaluate each alternative [44].

Trapezoidal ITFSs	$\tilde{a}_{i1}^{u}$	$\tilde{a}_{i2}^{u}$	$\tilde{a}_{i3}^{u}$	$\tilde{a}_{i4}^{u}$	h_1	h_2	$\tilde{a}_{i1}^{l}$	$\tilde{a}_{i2}^{l}$	$\tilde{a}_{i3}^{l}$	$\tilde{a}_{i4}^{l}$	h_1	h_2
Very Poor (VP)	0	0	0	1	1	1	0	0	0	0.5	0.9	0.9
Poor (P)	0	1	1	3	1	1	0.5	1	1	2	0.9	0.9
Medium Poor (MP)	1	3	3	5	1	1	2	3	3	4	0.9	0.9
Fair (F)	3	5	5	7	1	1	4	5	5	6	0.9	0.9
Medium Good (MG)	5	7	7	9	1	1	6	7	7	8	0.9	0.9
Good (G)	7	9	9	10	1	1	8	9	9	9.5	0.9	0.9
Very Good (VG)	9	10	10	10	1	1	9.5	1	1	10	0.9	0.9

4. Results and Discussion

4.1. Results of AHP

In Table 6, the pairwise comparison matrix filled by a decision maker is demonstrated. After that, matrices are generated and normalised as shown in Table 7 which gives only one criterion as an example because of the page restriction.

Table 6. Pairwise comparison matrix for Lithium-Ion cathode materials.

Comparison	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
LCO/LMO	7	7	1	1/3	1/7	1/5	1/5	3	1/3
LCO/LFP	1/3	1	1/3	7	1/7	1/7	1/5	1/7	1/5
LCO/NMC	1/5	1/7	1	3	1/7	1/7	1/3	1/7	1/5
LCO/NCA	1/9	1/9	1	3	1/7	1/3	1	3	1/3
LMO/LFP	1/5	1/7	1/3	9	1	1/5	1	1/9	1
LMO/NMC	1/7	1/7	1	5	1	1/3	3	1/9	1
LMO/NCA	1/9	1/9	1	5	1	3	5	1	3
LFP/NMC	1/3	1/3	3	1/5	1	1	3	1	1
LFP/NCA	1/5	1/7	3	1/5	1	5	5	9	3
NMC/NCA	1/3	1/5	1	1	1	5	3	9	3

Table 7. Matrices for materials of Lithium-Ion cathode in terms of the Specific Capacity (C1).

	Matrix generalised					**Matrix normalised**					
Comparison	**LCO**	**LMO**	**LFP**	**NMC**	**NCA**	**LCO**	**LMO**	**LFP**	**NMC**	**NCA**	**Mean**
LCO	1	7	0.33	0.20	0.11	0.06	0.24	0.03	0.04	0.06	**0.088**
LMO	0.14	1	0.20	0.14	0.11	0.01	0.03	0.02	0.03	0.06	**0.031**
LFP	3	5	1	0.33	0.20	0.17	0.17	0.10	0.07	0.11	**0.126**
NMC	5	7	3	1	0.33	0.28	0.24	0.31	0.21	0.19	**0.247**
NCA	9	9	5	3	1	0.5	0.31	0.52	0.64	0.57	**0.508**

At the same time, the performance importance of each criterion is compared to each other and demonstrated as seen in Table 8. Finally, the location is ranked by calculating the score matrix and results are shown in Table 11. Based on the results, it is clearly seen that NMC is the best material among five alternatives by a small margin while NCA is placed as the second preferable material.

Table 8. Percentage importance of potential criteria.

Criteria	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**Mean**
C1	1	3	1	1	1	3	5	1	5	**0.186**
C2	0.33	1	3	1	1	1	3	1	5	**0.125**
C3	1	0.33	1	0.33	0.33	0.33	1	0.20	1	**0.054**
C4	1	1	3	1	1	1	5	1	3	**0.141**
C5	1	1	3	1	1	1	3	1	5	**0.137**
C6	0.33	1	3	1	1	1	1	1	3	**0.107**
C7	0.20	0.33	1	0.20	0.33	1	1	3	3	**0.085**
C8	1	1	5	1	1	1	0.33	1	5	**0.133**
C9	0.20	0.20	1	0.33	0.20	0.33	0.33	0.20	1	**0.032**

4.2. Results of interval type-2 fuzzy sets

In order to rank cathode materials, interval type-2 fuzzy sets are also used. First main and sub-criteria are defined as shown in Table 1. Their importance is decided as depicted in Table 9. The main criterion and its corresponding sub-criterion are multiplied to convert linguistic terms to fuzzy sets and this is done for each sub-criterion. Let consider C1 as an example:

$$C1 = MH \otimes VH = \big((0.5,0.7,0.7,0.9;1,1),(0.6,0.7,0.7,0.8;0.9,0.9)\big)$$
$$\otimes \big((0.9,1,1,1;1,1),(0.95,1,1,1;0.9,0.9)\big)$$
$$=\big((0.45,0.7,0.7,0.9;1,1),(0.57,0.7,0.7,0.7;0.9,0.9)\big) \qquad (5)$$

The linguistic terms for performance of alternatives are determined as shown in Table 10. These terms are converted into fuzzy sets in the same manner as explained for importance of criteria. Then, aggregate fuzzy scores are calculated by multiplying each performance by fuzzy importance weight of criteria. In order to obtain crisp scores, fuzzy set values are converted into crisp values using Centroid type-reduction and defuzzification. Finally, these crisp values are ranked to obtain the rank of alternatives as depicted in Table 11 .

Table 9. Importance of main and sub-criteria according to decision maker.

	M1	M2	M3	M4	C1	C2	C3	C4	C5	C6	C7	C8	C9
Decision Maker	MH	VH	M	H	VH	VH	M	VH	VH	H	M	VH	MH

Table 10. Performance of alternatives according to decision maker.

Alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9
LCO	F	MG	F	MG	G	VP	G	MG	P
LMO	MP	MP	F	G	P	F	P	MP	MG
LFP	MG	MG	MG	F	VP	G	P	G	G
NMC	G	G	F	MG	P	MG	MP	G	MG
NCA	VG	VG	F	MG	P	P	MG	F	MP

Based on Table11, it is clearly seen that both methods are achieved same rank of alternatives and NMC is found as the best cathode material for Lithium-Ion batteries used for Scooter. In comparison to examining materials, it is found that the performance of NMC and NCA is quite similar both AHP and fuzzy approaches. Although, AHP assumes that decision makers provide precise information to examine alternatives, ambiguity can arise in judgements of the decision maker. For this reason, comparison of two methods is done and it is found that precise information is provided to examine alternatives according to same results achieved by AHP and interval type-2 fuzzy sets.

Table 11. Results for both AHP and fuzzy approaches.

Materials	Score	Rank	Score	Rank
LCO	0.098	5	11.661	5
LMO	0.180	4	21.374	4
LFP	0.233	3	23.264	3
NMC	0.245	1	24.444	1
NCA	0.243	2	23.342	2

5. Conclusions

As a result of growing concern regarding sustainability, the utilization of Lithium-Ion batteries has been worked by many researchers. To improve their performance, electrode materials have become the most significant component of Lithium-Ion batteries and most of researches have focused on electrode materials. In this study, material selection problem for electrode materials of Lithium-Ion batteries was addressed considering both qualitative and quantitative factors and was solved the problem using two multi-criteria decision making methods; AHP and interval type-2 fuzzy sets. In this study, different cathode materials were examined under variety of criteria selected with respect to both subjective and objective thoughts.

The motivation behind this study was also that there has been a lack of extensive research in the field of material selection for Lithium-Ion batteries considering several criteria at the same time. First, AHP was applied to the problem proposed and then due to uncertainties raised in judgements, interval type-2 fuzzy sets were used to provide more appropriate results. Finally, results obtained by two methods were compared and it was found that both methods achieved same results. All materials for each component of Lithium-Ion batteries can be investigated using different multi-criteria decision making methods, which is also worth studying as a future study.

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References

1. Nitta, N., Wu, F., Lee, J. T., and Yushin, G., Li-ion battery materials: present and future. Materials Today, 2015, 18(5),252–264.
2. Nishi, Y., Lithium ion secondary batteries; past 10 years and the future, Journal of Power Sources, 2001, 100(1-2),101-106.
3. Sarkar, A., Shrotriya, P., Chandra, A., Parametric Analysis of Electrode Materials on Thermal Performance of Lithium-Ion Battery: A Material Selection Approach Batteries and Energy Storage, J. Electrochem. Soc., 2018, 165(9), A1587-A1594.
4. Mishra, A., Mehta, A., Basu, S., Malode, S. J, Nagaraj P. Shetti, N. P., Shukla, S., Nadagouda, M. N., Aminabhavi, T. M., Electrode materials for lithium-ion batteries, Materials Science for Energy Technologies, 2018, 1(2),182-187.
5. Scallan, P.,Material evaluation and process selection, Editor(s): Peter Scallan, Process Planning, Butterworth-Heinemann, 2003, Pages 109-170.
6. Ahmad, S., Tahar, R., Selection of renewable energy sources for sustainable development of electricity generation system using analytic hierarchy process: A case of Malaysia, Renewable Energy, 2014, 63, 458-466.
7. Okokpujie,I.P., Okonkwo, U.C., Bolu, C.A., Ohunakin,O.S., Agboola, M.G., Atayero,A.A., Implementation of multi-criteria decision method for selection of suitable material for development of horizontal wind turbine blade for sustainable energy generation, Heliyon, Volume 6, Issue 1, 2020, e03142, ISSN 2405-8440.

8. Gil, A., Oró, E., Peiró, G., Álvarez, S., Cabeza, L. F., Material selection and testing for thermal energy storage in solar cooling, Renewable Energy, Volume 57, 2013, Pages 366-371, ISSN 0960-1481.
9. Panday, A. , and Bansal, H. O. , Multi-Objective Optimization in Battery Selection for Hybrid Electric Vehicle Applications. Journal of Electrical Systems, 2016, 12(2),325–343.
10. Kaa, G., Fens, T., Rezaei, J., Residential grid storage technology battles: a multi-criteria analysis using BWM, Technology Analysis and Strategic Management, 2019, 31(1),40-52.
11. Sangwan, S. K., Jindal, A., An integrated fuzzy multi-criteria evaluation of lithium-ion battery recycling processes, International Journal of Sustainable Engineering, 2013, 6(4): 359-371.
12. Warner, J. T., The Handbook of Lithium-Ion Battery Pack Design: Chemistry, Components, Types and Terminology, Elsevier, Grand Blanck, MI,, 2015, 1–80.
13. Graf, C., Cathode materials for lithium-ion batteries, Lithium-ion batteries: basics and applications. Edited by Korthauer, R., and Wuest, M., Springer, 2018, 29-40.
14. Deng, D., Li-ion batteries: Basics, Progress, and Challenges, Energy Science & Engineering, 2015, 3(5),385–418.
15. Scrosati, B., and Garche, J., Lithium Batteries: Status, Prospects and Future. Journal of Power Sources, 2010, 195(9),2419–2430.
16. Gwon, H., Hong, J., Kim, H., Seo, D.-H., Jeon, S., and Kang, K., Recent Progress on Flexible Lithium Rechargeable Batteries. Energy Environ. Sci., 2014, 7(2),538-551.
17. Yuan, M., Erdman, J., Tang, C., and Ardebili, H., 2014, “High Performance Solid Polymer Electrolyte with Graphene Oxide Nanosheets,” RSC Adv., 4(103), 59637–59642.
18. Doeff, M. M., Chapter 2: Battery Cathodes. Batteries for Sustainability: Selected Entries from the Encyclopedia of Sustainability Science and Technology. Edited by Brodd J. R., Springer, New York, NY, 2013, 5–49.
19. Manthiram, A., Materials Challenges and Opportunities of Lithium Ion Batteries. The Journal of Physical Chemistry Letters, 2011, 2(3),176–184.
20. Wang, Y., and Huang, H.-Y. S., An Overview of Lithium-Ion Battery Cathode Materials. MRS Proceedings, 2011, 1363.
21. Doughty, D. H., and Roth, E. P., A General Discussion of Li Ion Battery Safety. The Electrochemical Society Interface, 2012, 21(2),37–44.
22. Schmuch, R., Wagner, R., Hörpel, G., Placke, T., & Winter, M., Performance and cost of materials for lithium-based rechargeable automotive batteries. Nature Energy, 2018, 3(4): 267–278.
23. Al-Hallaj, S., Wilk, G., Crabtree, G., and Eberhard, M., Overview of distributed energy storage for demand charge reduction. MRS Energy & Sustainability, 2018, 5(1),1–18.
24. Lazim, A., Norsyahida Z., Integration of fuzzy AHP and interval type-2 fuzzy DEMATEL: An application to human resource management, Expert Systems with Applications, 2015, 42(9),4397-4409.

25. Ying-Chyi C., Chia-Chi S., Hsin-Yi Y., Evaluating the criteria for human resource for science and technology (HRST) based on an integrated fuzzy AHP and fuzzy DEMATEL approach, Applied Soft Computing, 2012, 12(1),64-71.
26. Marbini A.H. and Tavana M., An extension of the Electre I method for group decision-making under a fuzzy environment, Omega, 2011, 39 (4),373-386.
27. Sen, C. G., Cinar, G., Evaluation and pre-allocation of operators with multiple skills: A combined fuzzy AHP and max–min approach, Expert Systems with Applications, 2010, 37 (3),2043-2053.
28. Ling W., Jian C., Jun W., Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process, International Journal of Production Economics, 2007, 107(1), 151-163.
29. Yeap, J.A.L., Ignatius J., Ramayah, T., Determining consumers' most preferred eWOM platform for movie reviews: A fuzzy analytic hierarchy process approach, Computers in Human Behavior, 2014, 31,250-258.
30. Saaty, R.,The analytic hierarchy process–what it is and how it is used, Math. Model,1987,9,161–176.
31. Dweiri, F., Al-Oqla, F. M., Material selection using analytical hierarchy process. Int. J. Comput. Appl. Technol., 2006, 26 (4),182-189.
32. Kiong, S. C., Lee, L. Y., Chong, S. H., Azlan, M. A., Nor, N. H. M., Decision Making with the Analytical Hierarchy Process (AHP) for Material Selection in Screw Manufacturing for Minimizing Environmental Impacts, Applied Mechanics and Materials, 2013, 315,57-62.
33. Kühn, F., Rehra, J., May, D., Schmeer, S., Mitschang, P., Dry fiber placement of carbon/steel fiber hybrid preforms for multifunctional composites, Advanced Manufacturing: Polymer & Composites Science, 2019,5(1),37-49.
34. Zadeh, L., Fuzzy sets. Information and Control, 1965, 8:338- 353.
35. Zadeh, L., The consept of a linguistic variable and its applications to approximate reasoning. Inform Science, 1975, 8,199- 249.
36. Hagras, H., Type-2 flcs: A new generation of fuzzy controllers. IEEE Computational Intelligence Magazine, 2007, 2,30-43.
37. Greenfield, S., Chiclana, F., John, R., Coupland, S., The sampling method of defuzzification for type-2 fuzzy sets: Experimental evaluation, Information Sciences, 2012, 189,77-92.
38. Mendel, J.M., John, R., Liu, F., Interval type-2 fuzzy logic systems made simple. IEEE T. Fuzzy Systems, 2006, 14,808- 821.
39. Young, K., Wang,, C., Wang, L. Y., and Strunz, K., Electric Vehicle Battery Technologies. Electric vehicle integration into modern power networks. Edited by R. Garcia-Valle, and J.A.P. Lopes, SPRINGER-VERLAG NEW YORK, 2013, 15–56.
40. W. Reaugh, Larry. Re-Cycling Spent Electric Vehicle Batteries Potentially Recovers Significant Amounts of Lithium, Cobalt and Other Cathode Metals. American Manganese Inc., 19 Jan. 2017, https://americanmanganeseinc.com (accessed September 10, 2019).

41. Sen, C. G., Cinar, G., Evaluation and pre-allocation of operators with multiple skills: A combined fuzzy AHP and max–min approach, Expert Systems with Applications, 2010, 37 (3),2043-2053.
42. Bhushan, N., & Rai, K. (2004). Strategic Decision Making: Applying the Analytic Hierarchy Process. Decision Engineering. Springer London.
43. Türk, S. John, R. and Özcan, E., Interval type-2 fuzzy sets in supplier selection, 14th UK Workshop on Computational Intelligence (UKCI), Bradford, 2014, 1-7.
44. Chen, S., Lee, L., Fuzzy multiple attributes group decision-making based on the interval type-2 TOPSIS method, Expert Systems with Applications, 2010,37 (4), 2790-2798.