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Triangular Intuitionistic Fuzzy Aggregating and Ranking Function Approach for the Rating of Battery 'End-of-Life' Handling Alternatives

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Abstract: The increased adoption of intermittent renewable sources in the energy sector has also increased the use of battery storage systems. However, the negative impact which the improper disposal of batteries has on the environment has stirred debates on its sustainability. To ensure the proper disposal of battery waste, there is a need to identify and rank the most preferred battery 'end-of-life' handling alternatives. This paper focuses on identifying the most preferred 'end-of-life' handling alternatives for batteries using a modified triangular intuitionistic fuzzy aggregating and ranking function (TIFARF) model. To test the proposed modified TIFARF model, opinions from experts in the Nigerian renewable energy sector were collected, and the results show that the most preferred alternative is incineration, with a closeness coefficient of 0.130, while the least preferred alternative is recycling, whose closeness coefficient is 0.112. The results are an indication of a lack of facilities needed for the proper recycling of battery remains after their lifetime; if adequate facilities are available, the opinion of experts may be biased towards other alternatives. Future studies should focus on more battery 'end-of-life' handling alternatives and on countries with adequate facilities that can be used to manage batteries at the end of their lifespan.

Keywords: battery storage system; TIFARF; TOPSIS; environmental impact

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1. Introduction

Over the last two decades, the renewable energy industry has experienced outstanding successes with respect to efficiency, durability, and the extent of its penetration in the energy mix. Many countries such as Denmark have included and or committed to the inclusion of large-scale renewable energy technologies (especially wind turbines and solar-based technologies) in the national grid. Using the bottom-top approach to electrification, many developing countries have also committed to the development of micro-grids to support off-grid and remote communities where grid connection is either impossible or not viable. Individuals and business corporations who are able to afford off-grid energy systems also adopt the use of nano-grids to meet their energy requirements. Some of the factors responsible for the increased penetration of these technologies include attempts to decarbonize the electricity sector, environmental impact reduction, and the continued decline in the cost of renewable energy technologies. The reduction in the cost of electricity from renewable energy technologies has made it more competitive with the traditional methods of electricity generation. For instance, between 2009 and 2020, the cost of wind turbines has gone down by at least 55%, while that of solar photovoltaic modules has tumbled by approximately 90% [1]. It is reported that between 2010 and 2019, the global weighted-average levelized cost of electricity (LCOE) for utility-scale solar photovoltaics (PV) fell by 82%, while that of concentrating solar power (CSP) and onshore wind technology fell by 47% and 39%, respectively [1].

Thanks to these declining costs, the uptake in renewable energy technologies in the energy sector is now on the rise. However, intermittent energy sources such as solar irradiation and wind usually require back-ups in the form of energy storage or conventional power plants. The former is usually preferred because of negligible operation and maintenance costs and low environmental impact during its operational lifespan. Although the cost of intermittent renewable energy is decreasing, the same cannot be said of the energy storage system, which is an essential part of the renewable energy structure [2]. Based on a review conducted by Babatunde et al, it is reported that for most micro- and nano-grid energy systems, the battery storage system usually returns a high life cycle cost compared to other components of the system [3] because they need to be changed periodically throughout the project lifespan. An energy storage system (ESS) is used to harvest energy in the periods of sufficiency for the purpose of suppling demands at the time of insufficiency or peak loads. Energy storage can, therefore, offset any imbalances that may be experienced in an energy system. ESS serves the purposes of flexibility, load smoothing, peak shaving, and power reservoirs.

ESS are generally classified based on time scale of discharge (short-, medium-, and long-term) and storage medium (chemical, electrical, electrochemical, thermal, and mechanical) [3–5]. Mechanical energy storage makes use of forced springs, pressurized gas, potential energy, and kinetic energy as a storage medium. The most common forms of mechanical energy storage include pumped hydro, flywheels, and compressed air energy storage [6]. As for thermal energy storage, energy is stored either in the form of cold or heat. Thermal energy storage usually finds application in residential and industrial settings. The thermal energy system consists of latent heat storage and sensible heat storage. Electrical energy storage systems usually store electrical energy in electrostatic or magnetic form and include superconducting magnets, capacitors, and supercapacitors [2,6,7]. Electro-chemical energy storage media allows energy conversion from chemical to electrical energy through the flow of electrons. Electrochemical energy storage includes electrochemical capacitors and every form of battery. To generate energy, battery storage systems (BSS) convert the chemical energy in their active elements into electricity through an electrochemical process known as oxidation-reduction reverse reaction [8]. Based on their principle of operation, batteries can be classified as primary cell and secondary cell. The working principle of a fuel cell is also similar to that of batteries, and some literature studies classify it as a battery [6], however, fuel cells do not run down or need recharging. The chemical materials from electrochemical energy storage systems have the tendency to cause pollution of the environment; thus, they must be properly disposed of [7].

Although BSS offer a cost-effective way of harnessing power (when compared to operating a captive generator for the same period), its investment cost is usually a bottleneck. Apart from high investment cost, another aspect of BSS usually overlooked by researchers and practitioners is waste management after its operational life cycle. If not well managed, some, BSS technologies could have adverse environmental and health impacts after their operational lifespan [7]. The waste management of BSS 'scraps' involves the process of collection, transportation, treatment, recycling, and waste disposal [5]. The majority of BSS wastes are not properly handled, with some discarded in landfills, incinerated, or carelessly dumped in open places, while only some end up being recycled [9]. Some BSS wastes, if not properly disposed of, can contaminate the ground water, agricultural processes, the food chain, and therefore, affect human and animal health [10]. Consequently, it is essential that future research place a greater priority on the proper handling of BSS waste management that may have a negative impact on health and the environment. This would not only ensure the minimization of negative environmental impacts, but also reduce health risks and enhance the sustainability of the energy sector. The choice of battery waste handling techniques depends on various aspects related to economic, environmental, technical, and social factors. To address the handling of battery scraps after their lifetime has ended, this study presents a modified triangular intuitionistic fuzzy aggregating and ranking function

(TIFARF) model that integrates the environmental, social, and economic perspectives into the ranking of BSS 'after life' waste handling approach. The developed framework is based on the rich knowledge of experts in renewable energy adoption. The main contributions of this paper include the following:

- This paper focused, for the first time, on identifying the most preferred 'end-of-life' handling alternatives for batteries.
- The study extends the fuzzy aggregating and ranking function (TIFARF) method proposed by Ref [11] for the evaluation of the 'end-of-life' handling alternatives for batteries.

1.1. Environmental Impacts of BSS

As the world scrambles to substitute fossil fuels with green energy to mitigate climate change, the environmental impact of deploying batteries to alleviate the intermittency of renewable energy is a major concern. Typically, the environmental impact of batteries is minimal, or most of the time inert, during their life spans; most of the environmental impact attributed to batteries occurs during their production and more specifically, at the end of their life [12]. These environmental impacts can affect the food chain, agriculture, and the health of humans; therefore, various literature has been dedicated to discussing and evaluating the environmental impact of batteries at the end of their lifespan [6,9,13–16]. From these studies, it is evident that for small-scale energy applications, decision makers are of the opinion that lead–acid batteries are the most preferred option for energy storage [15,16]. The major reason is that lead–acid batteries can be recycled with an efficiency of up to 99% [17]. With regard to largescale applications, pumped hydro storage is identified as the best las-stage option in terms of environment friendliness; however, the land requirement is a major disadvantage [18,19]. Many of the batteries available for both domestic and commercial-scale renewable energy applications contain significant traces of heavy metals such as lithium, cadmium, nickel manganese, and other emerging contaminants associated with high ecotoxicity [20]. Improper handling of batteries after their lifespan can result in contamination of the surface and groundwater, which when ingested by humans and animals, have adverse health effects. Some of the contaminants from batteries and their adverse effects are given in Table 1.

1.2. Battery 'End-of-Life' Handing Alternatives

This section presents the four main methods of battery disposal identified in the literature; these include landfill deposit, incineration, stabilization, and recycling [9].

Table 1. The adverse environmental effects of the contaminants from batteries.

Contaminant	Effects	Reference
Cadmium	As a simple chemical element, it is impossible to break down cadmium to less noxious constituents when it is released to the environment. When released to the environment, it can be absorbed by plants, and if such plant is consumed by animals or humans, the element is accumulated in the vital organs of the body. The accumulation of cadmium can damage the liver, bones, and kidney. cadmium is carcinogenic in nature.	[21,22]
Cobalt	If an environment is exposed to cobalt, humans can come in contact with it through drinking contaminated water, eating contaminated crops (especially fruits), and by breathing contaminated air. When the skin is in contact with a contaminated surface, the probability of exposure is high. Humans and animals may accumulate cobalt in their bodies if they consume contaminated foods (plants or animals). High concentration of cobalt may lead to thyroid damage, heart related problems, vomiting and nausea, and vision problems. Cobalt contamination also has a negative effect on biomass.	[22]
Copper	When exposed to the soil, copper can interfere with soil activity and consequently, affect the activities of earthworms and other microorganisms, thereby slowing down the decomposition of organic matter. Ingestion of Copper can result in gastric-related medical challenges, liver damage, and some neurological difficulties.	[22]

Table 1. *Cont.*

Contaminant	Effects	Reference
Lead	Lead released from batteries that are not properly disposed of finds its way into the environment through water, soil, and air. Lead poisoning is reported to have carcinogenic effects and is a major cause of cardiovascular diseases, nervous system complications, and some kidney problems.	[21,22]
Lithium	It has been reported that the extraction of lithium impairs the soil and causes air contamination. There have been many reports of dead animals and ruined farms in the areas surrounding where lithium is mined. Although lithium is not as toxic as lead and cadmium, lithium causes changes in the growth of invertebrates and interferes with nucleic acids synthesis. Lithium is a phytotoxin that causes acute phytotoxicity.	[23]
Nickel	There are various environmental concerns linked with nickel; some of these include the pollution of soil, air, and water, the destruction of habitats, and greenhouse gas emissions.	[24]

1.2.1. Landfill (LF)

Landfills are designated sites for the disposal of solid wastes and garbage. This method is the most common means of disposing batteries used in household applications. Batteries from residential applications are usually disposed of as public solid waste by users and sent to landfill. While landfills in some developing and developed counties are properly managed and integrated into the waste management system, the presence of illegal dump sites is still a matter of concern to environmentalists [25].

1.2.2. Incineration (IN)

When batteries are sent to landfills after the end of their lifespan, they are either left idle or incinerated. When these batteries are burnt, several dangerous chemical elements are released into the environment either in liquid, gaseous, or solid forms. Some of these chemical elements include lead, cadmium, mercury, and dioxins.

1.2.3. Stabilization (SN)

Although it comes with a high cost, the stabilization process is a preliminary step often used in the treatment of batteries to minimize or totally prevent the metals from batteries from contaminating the environment.

1.2.4. Recycling (RG)

Because various battery technologies are emerging, a number of recycling methods are continuously being developed to handle the remains of batteries at the end of their lifespan. Based on the literature, the battery recycling processes that are presently being explored are either hydrometallurgical or pyrometallurgical [26].

2. Materials and Methods

This section presents the methodological approach adopted in this study. The triangular intuitionistic fuzzy aggregating and ranking function (TIFARF) model proposed for the development of a fixable model for the evaluation of the reliability and safety of the components of a commercial lithium-ion battery was modified and adopted for this study.

2.1. Concept of the TIFARF Model

The TIFARF model was first developed and presented by Aikhuele, 2020 [11] for the evaluation of the reliability and safety of lithium-ion battery components. It consists of a triangular intuitionistic fuzzy set (TIFS), a triangular intuitionistic fuzzy (TIF) aggregating operator, and a ranking function. The model, which derives its computing data from expert opinions, uses specialized linguistic terms and the triangular intuitionistic fuzzy number (TIFN) for its data collection and simulations.

The TIFN, which can be expressed in the form $\acute{\delta} = ([e, f, g]; \mu_\delta, v_\delta)$, consists of a triangular fuzzy number $[e, f, g]$, membership function $\mu_\delta(x)$, and a non-membership function $v_\delta(x)$ of the intuitionistic fuzzy set (IFS). In applying the model for decision-making, the collected data from the experts are aggregated using the induced triangular intuitionistic fuzzy (TIF) aggregating operator and then ranked with the ranking function, comprised of the Hamming distance and the value-index ranking method. In this paper, however, the TIFARF model has been improved by using a much easier method—the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method—for the ranking.

2.2. Definition 1

If a TIFN is expressed in form $\acute{\delta_i} = ([e, f, g]; \mu_\delta,\ v_\delta)$, such that $i = 1, 2, 3, \ldots, n$, then the induced triangular intuitionistic fuzzy ordered weighted geometric (I-TIFOWG) operator is given a mapping of $\Omega^n \rightarrow \Omega$ [27] The weighting vector of the I-TIFOWG operator is given as $w = (w_1, w_2,\ w_3, \ldots, w_n)^v$, such that $w_i \in [0,\ 1]$, and $\sum_{i=1}^{n} w_i = 1$. Another weighting vector $\omega = (\omega_1, \omega_2,\ \omega_3, \ldots, \omega_n)^v$, which is also associated with the I-TIFOWG operator, is given an output of $\omega_i \in [0,\ 1]$, $\sum_{i=1}^{n} \omega_i = 1$. The I-TIFOWG operator is expressed as:

$$\begin{aligned} \mathrm{I-TIFOWG}_{\omega,W}(\langle x_1, \delta_1\rangle,\ \langle x_2, \delta_2\rangle, \langle x_3, \delta_3\rangle, \ldots, \langle x_n, \delta_n\rangle) \\ = \omega_1(\delta_1) \otimes \omega_2(\delta_2) \otimes \omega_3(\delta_3) \ldots \otimes \omega_n(\delta_n) \\ = \left(\left[\prod_{i=1}^{n} (e_i)^{\omega_i},\ \prod_{i=1}^{n} (f_i)^{\omega_i},\ \prod_{i=1}^{n} (g_i)^{\omega_i} \right]; \prod_{i=1}^{n} (\mu_{\delta_i})^{\omega_i},\ 1 \right. \\ \left. - \prod_{i=1}^{n} (1 - v_{\delta_i})^{\omega_i} \right) \end{aligned} \tag{1}$$

where the TIFOWG pair $\langle x_i, \delta_i\rangle$ is the order-inducing variable and δ_i is the triangular intuitionistic fuzzy argument variable.

2.3. TOPSIS Method

TOPSIS is a multi-criteria decision-making method that is based on the idea that whenever an alternative is chosen from among a finite set, the alternative should be the one with the shortest distance from the positive ideal solution (PIS) and the longest from the negative ideal solution (NIS) [28,29]. It has found application in several areas of engineering and management [30–32]. In Figure 1, the computational algorithm of the TOPSIS model is presented.

2.4. Algorithm of the TIFARF Model

In the development of the algorithm for the modified TIFARF model, a number of factors and parameters have been considered; among these are the linguistic terms and TIFN used for data collection, the aggregation operator, and finally, the TOPSIS method used for the ranking of the alternatives. The proposed algorithms for the evaluation of battery 'end-of-life' handling strategies are given in the following steps:

Step 1: Design a template, clearly state the alternatives (A) and criteria (C), and then, in the instructions, discuss what the study intends to evaluate. Invite experts with a subject knowledge of the problem to give their expert opinions on the alternatives with respect to the criteria. The opinions of the individual experts, which are obtained using specialized linguistic terms, can be converted into their TIFN equivalent as shown in Equation (2); the linguistic scale and their corresponding TIFN for the data collection have been given in Table 2.

$$\begin{matrix} \\ A1 \\ A2 \\ \vdots \\ \vdots \\ Am \end{matrix} = \begin{bmatrix} C1 & & & & Cn \\ ([e_{11}, f_{11}, g_{11}]; \mu_{11}, v_{11}) & \cdots & & \cdots & ([e_{1n}, f_{1n}, g_{1n}]; \mu_{1n}, v_{1n}) \\ ([e_{21}, f_{21}, g_{21}]; \mu_{21}, v_{21}) & \cdots & & \cdots & ([e_{2n}, f_{2n}, g_{2n}]; \mu_{2n}, v_{2n}) \\ \vdots & \vdots & \ddots & \vdots & \\ \vdots & \vdots & \ddots & \vdots & \\ \vdots & & & & \vdots \\ ([e_{m1}, f_{m1}, g_{m1}]; \mu_{m1}, v_{m1}) & \cdots & & \cdots & ([e_{mn}, f_{mn}, g_{mn}]; \mu_{mn}, v_{mn}) \end{bmatrix} \quad (2)$$

where μ is the membership function, and v is the non-membership function, while e, f, and g are the triangular values related to the intuitionistic fuzzy set in the model.

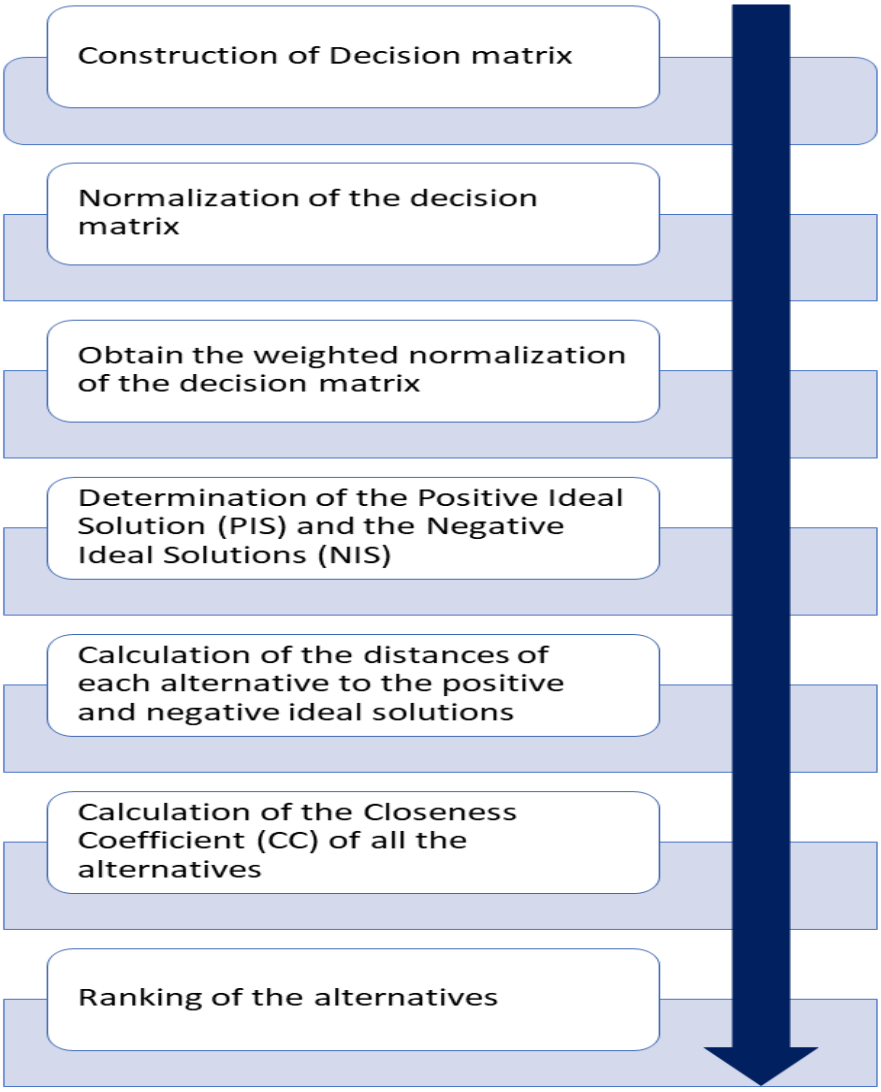

Figure 1. The main implementation steps for TOPSIS.

Table 2. The linguistic scale and its TIFN equivalent used for data collection.

S/N	Linguistic Terms	TIFN
1	Moderately Low (ML)	([0.25, 0.35, 0.55]; 0.20, 0.60)
2	Low (L)	([0.40, 0.50, 0.65]; 0.20, 0.65)
3	Moderately High (MH)	([0.55, 0.60, 0.70]; 0.30, 0.70)
4	High (H)	([0.60, 0.65, 0.75]; 0.45, 0.75)
5	Extremely High (EH)	([0.70, 0.75, 0.85]; 0.55, 0.80)

Step 2: With the individual experts' opinions in place, the I-TIFOWG operator, as shown in Equation (1) above, is applied to aggregate the different opinions and to construct a comprehensive decision matrix $(Y_{ij} = [D]_{m*n})$. This is achieved, however, by first rating the expert's knowledge on the subject (education qualification) and then using their weight vector (ω_i) in the evaluation.

Step 3: From the comprehensive decision matrix (aggregated opinions), construct a weighted normalization matrix using the predetermined weight vector of the criteria.

$$Z_{ij} = [D]_{m*n} * W_j \tag{3}$$

Step 4: Determine the intuitionistic fuzzy positive and negative ideal solutions (IFPIS and IFNIS) for the alternatives. With the ideal solutions, calculate the closeness coefficient (cc_i) of all the alternatives using the Equation (4).

$$cc_i = \frac{S^-}{(S^- + S^+)} \tag{4}$$

where, S^- and S^+ are the separation measures from the negative and positive ideal solution, respectively.

Step 5: Finally, rank the alternatives in descending order.

3. Numerical Illustration

In this section, the modified TIFARF model algorithm presented in the method section is implemented for the evaluation and ranking of the battery end-of-life handing strategies. This is achieved by prioritizing the disposal strategy using the following criteria: investment cost (IC), environmental cost (EC), air pollution (AP), land and water contamination (LWC), job opportunities (JO), and visual inspection (VI). The different battery disposal strategies and their impacts have been discussed in the previous section, and the various criteria are presented in Table 3. In the implementation of the model, it is assumed that all related information in regard the battery disposal strategies are known by the experts invited for the assessment. It is also assumed that the evaluation model for the battery disposal strategies can be applied to any other decision-making project.

In implementing the model, a total of five experts (E), with at least ten years of experience in renewable energy resources and management were invited to evaluate the battery "end of life" handling strategies. Out of the ten experts that were contacted, only five returned the questionnaires. One of them has a BSc degree as his/her highest qualification, three of them have MSc degrees, and one has a PhD; they were assigned the following weight vectors 0.15, 0.20, 0.20, 0.20, and 0.35 respectively, which are used in the simulation. With respect to years of experience in renewable energy, three of the experts have between 11–15 years of experience, while two of them have between 6–10 years of professional experience (Figure 2).

The linguistic results of the experts have been presented in Table 4, along with the aggregate of the experts' opinions, which was obtained using the equivalent of the linguistic terms (TIFN) and the weight vectors of the experts in the I-TIFOWG operator. The aggregated result is referred to the comprehensive decision matrix.

Table 3. The battery disposal strategies.

Factor	Criteria	Definition	Direction
Economic	Investment cost	This is the starting/capital cost of each alternative, including land, equipment, and other assets.	Non-beneficial
	Environmental cost	The associated cost invested in cleaning up the environmental pollution caused by the processes of each alternative.	Non-beneficial
Environmental	Air pollution	Emissions and air pollutants associated with each alternative.	Non-beneficial
	Land and water contamination	The effects of the pollution on the surrounding land and the contamination of the surrounding water bodies or water table.	Non-beneficial
Social	Job opportunities	The number of employment opportunities associated with each alternative.	Beneficial
	Visual impression	A reflection of the public's perception of the visual impact of each alternative.	Non-beneficial

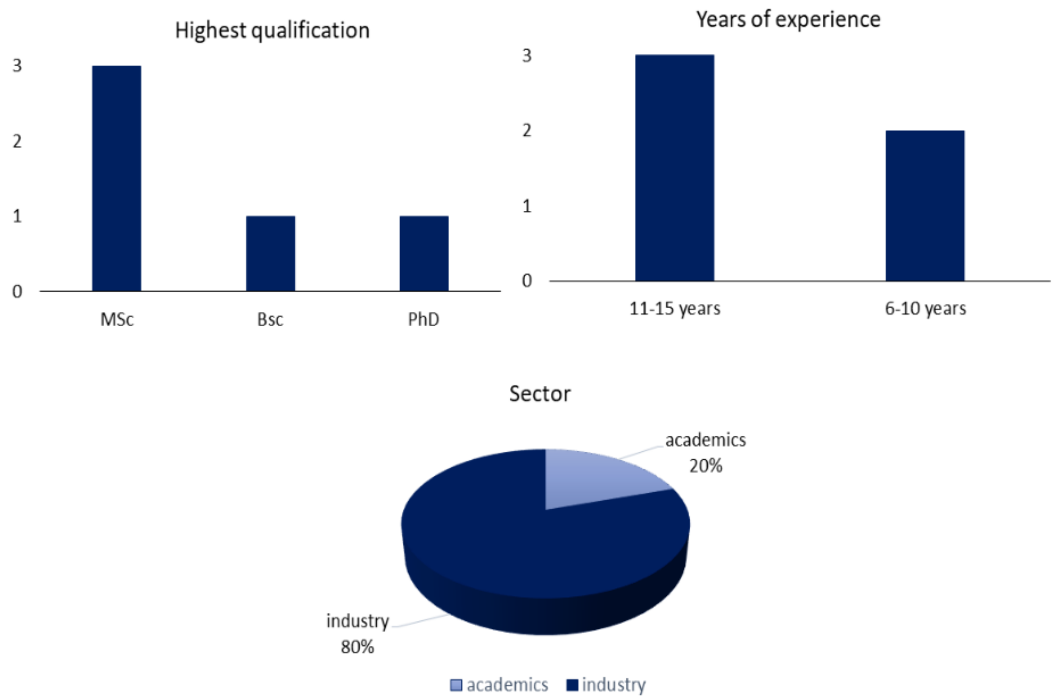

Figure 2. The professional and educational details of experts.

Table 4. The intuitionistic fuzzy decision matrix and the aggregated experts' opinions and judgments.

Criteria / Alternative	IC	EC	AP	LWC	JO	VI
LF	E1-(L), E2-(L), E3-(L) E4-(L) and E5-(MH)	E1-(H), E2-(H), E3-(H) E4-(MH) and E5-(MH)	E1-(H), E2-(H), E3-(H) E4-(H) and E5-(H)	E1-(H), E2-(H), E3-(H) E4-(H) and E5-(L)	E1-(H), E2-(MH), E3-(H) E4-(L) and E5-(EH)	E1-(L), E2-(H), E3-(L) E4-(ML) and E5-(EH)
IN	E1-(MH), E2-(ML), E3-(MH) E4-(ML) and E5-(MH)	E1-(MH), E2-(H), E3-(MH) E4-(EH) and E5-(EH)	E1-(MH), E2-(H), E3-(MH) E4-(EH) and E5-(MH)	E1-(L), E2-(MH), E3-(L) E4-(H) and E5-(ML)	E1-(MH), E2-(MH), E3-(MH) E4-(L) and E5-(MH)	E1-(MH), E2-(L), E3-(MH) E4-(ML) and E5-(MH)

Table 4. *Cont.*

Criteria / Alternative	IC	EC	AP	LWC	JO	VI
SN	E1-(MH), E2-(H), E3-(MH) E4-(MH) and E5-(MH)	E1-(MH), E2-(MH), E3-(MH) E4-(H) and E5-(MH)	E1-(MH), E2-(MH), E3-(MH) E4-(MH) and E5-(MH)	E1-(L), E2-(L), E3-(L) E4-(MH) and E5-(MH)	E1-(MH), E2-(MH), E3-(MH) E4-(H) and E5-(MH)	E1-(MH), E2-(L), E3-(MH) E4-(MH) and E5-(H)
RG	E1-(H), E2-(ML), E3-(H) E4-(EH) and E5-(L)	E1-(L), E2-(L), E3-(L) E4-(ML) and E5-(MH)	E1-(L), E2-(L), E3-(L) E4-(L) and E5-(ML)	E1-(L), E2-(L), E3-(L) E4-(L) and E5-(ML)	E1-(MH), E2-(H), E3-(MH) E4-(EH) and E5-(MH)	E1-(H), E2-(H), E3-(H) E4-(EH) and E5-(H)
	IC	**EC**	**AP**	**LWC**	**JO**	**VI**
LF	([0.35, 0.45, 0.60]; 0.18, 0.71)	([0.53, 0.58, 0.69]; 0.32, 0.78)	([0.55, 0.60, 0.71]; 0.37, 0.79)	([0.48, 0.56, 0.68]; 0.30, 0.77)	([0.52, 0.59, 0.71]; 0.31, 0.78)	([0.45, 0.54, 0.69]; 0.31, 0.78)
IN	([0.34, 0.43, 0.59]; 0.20, 0.71)	([0.58, 0.64, 0.75]; 0.38, 0.77)	([0.56, 0.62, 0.73]; 0.35, 0.79)	([0.37, 0.46, 0.62]; 0.24, 0.73)	([0.44, 0.52, 0.64]; 0.21, 0.73)	([0.41, 0.49, 0.63]; 0.23, 0.74)
SN	([0.52, 0.57, 0.68]; 0.29, 0.77)	([0.52, 0.57, 0.68]; 0.29, 0.77)	([0.51, 0.56, 0.67]; 0.27, 0.76)	([0.45, 0.52, 0.65]; 0.23, 0.74)	([0.51, 0.56, 0.67]; 0.27, 0.76)	([0.42, 0.49, 0.64]; 0.25, 0.74)
RG	([0.42, 0.51, 0.66]; 0.27, 0.76)	([0.38, 0.47, 0.62]; 0.21, 0.73)	([0.33, 0.43, 0.61]; 0.19, 0.72)	([0.33, 0.43, 0.61]; 0.19, 0.72)	([0.55, 0.60, 0.71]; 0.33, 0.79)	([0.57, 0.63, 0.74]; 0.42, 0.81)

Using the results, the predetermined weight vector of the criteria is used for the construction of the weighted normalization matrix. Additionally, from the weighted normalization matrix, the triangular intuitionistic fuzzy positive and negative ideal solution for the battery disposal strategy is determined. The results of the computation, along with the predetermined weight vector, have been presented in Table 5. Finally, in Table 6, the results of the intuitionistic fuzzy positive and negative ideal solutions for the battery disposal strategy is presented.

Table 5. The weight vector of the criteria and the constructed weighted normalization matrix.

Criteria / Alternative	IC	EC	AP	LWC	JO	VI
Wv	0.42675	0.47125	0.46852	0.53465	0.462257	0.49375
LF	([0.15, 0.19, 0.26]; 0.08, 0.30)	([0.25, 0.27, 0.33]; 0.15, 0.37)	([0.26, 0.28, 0.33]; 0.17, 0.37)	([0.26, 0.30, 0.37]; 0.16, 0.41)	([0.24, 0.27, 0.33]; 0.14, 0.362)	([0.22, 0.27, 0.34]; 0.15, 0.38)
IN	([0.15, 0.18, 0.25]; 0.08, 0.30)	([0.28, 0.30, 0.35]; 0.18, 0.36)	([0.26, 0.29, 0.34]; 0.16 0.37)	([0.20, 0.24, 0.33]; 0.13, 0.39)	([0.20, 0.24, 0.30]; 0.10, 0.34)	([0.20, 0.24, 0.31]; 0.11, 0.36)
SN	([0.22, 0.24, 0.29]; 0.13, 0.33)	([0.25, 0.27, 0.32]; 0.14, 0.36)	([0.24, 0.26, 0.32]; 0.13, 0.36)	([0.24, 0.28, 0.35]; 0.12, 0.40)	([0.24, 0.26, 0.31]; 0.13, 0.35)	([0.21, 0.24, 0.32]; 0.12, 0.37)
RG	([0.18, 0.22, 0.28]; 0.11, 0.32)	([0.18, 0.22, 0.29]; 0.10, 0.34)	([0.15, 0.20, 0.28]; 0.09, 0.34)	([0.18, 0.23, 0.32]; 0.10, 0.38)	([0.25, 0.28, 0.33]; 0.15, 0.38)	([0.28, 0.31, 0.36]; 0.21, 0.40)

Table 6. The intuitionistic fuzzy positive and negative ideal solutions.

Alternative	TIFPI Solution	TIFNI Solution
LF	0.806	0.119
IN	0.751	0.112
SN	0.695	0.101
RG	0.668	0.084

Considering the results of the raking presented Figure 3, it is not difficult to see that the alternative (IN) has the highest potential to be adopted when compared to the other alternatives, and thus should be given the utmost priority. The results, which could serve as the basis for a decision-making strategy related to battery disposal, are expected to give battery disposal managers a clue on how to manage their disposal processes. Using the modified TIFARF model, the study has been able to present a much easier approach when compared to the TIFARF model presented in [11].

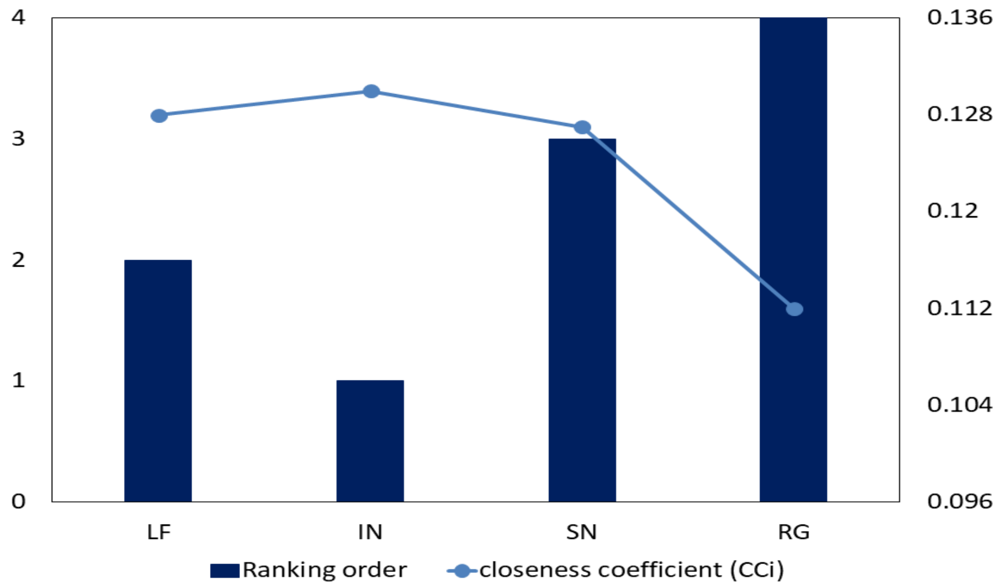

Figure 3. The final ranking of the closeness coefficient of the alternatives.

4. Conclusions

In this paper, a modified TIFARF model has been presented for the evaluation of battery disposal strategies. The modified TIFARF model, which is comprised of an induced triangular intuitionistic fuzzy (TIF) aggregating operator and the TOPSIS method, presents a much easier computational approach as compared to the TIFARF model presented in [11]. The modified TIFARF model, which derives its computing data from expert's opinions, uses specialized linguistic terms and the triangular intuitionistic fuzzy number (TIFN) for its data collection and simulations. Results from the evaluation show that the alternative (IN) has the highest potential to be adopted when compared to the other alternatives, and thus should be given the utmost priority. The proposed framework contributes to battery waste management and would help decision makers in handling battery wastes effectively and efficiently; this would help in the minimization of the environmental impact and hazardous health effects on humans, animals, and plants. Future studies are expected to carry out comparative analyses of the results of this model and similar MCDM models; these studies should also include the effects of uncertainties to ascertain the robustness of the model to changes in weighing parameters.

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References

1. IRENA. Renewable Capacity Statistics 2020, Abu Dhabi. 2020. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_RE_Capacity_Statistics_2020.pdf (accessed on 18 February 2022).
2. Akinyele, D.O.; Rayudu, R.K. Review of energy storage technologies for sustainable power networks. *Sustain. Energy Technol. Assess.* **2014**, *8*, 74–91. [CrossRef]
3. Babatunde, O.M.; Munda, J.L.; Hamam, Y. A comprehensive state-of-the-art survey on hybrid renewable energy system operations and planning. *IEEE Access* **2020**, *8*, 75313–75346. [CrossRef]
4. Kousksou, T.; Bruel, P.; Jamil, A.; El Rhafiki, T.; Zeraouli, Y. Energy storage: Applications and challenges. *Sol. Energy Mater. Sol. Cells* **2014**, *120*, 59–80. [CrossRef]
5. Haynes, M.W.; Gunawan, A.; Yee, S.K. Techno-Economic Comparison Between Conventional and Innovative Combined Solar Thermal Power and Desalination Methods for Cogeneration. In Proceedings of the ASME 2018 Power Conference Collocated with the ASME 2018 12th International Conference on Energy Sustainability and the ASME 2018 Nuclear Forum, Lake Buena Vista, FL, USA, 24–28 June 2018; p. V002T12A013. Available online: https://asmedigitalcollection.asme.org/POWER/proceedings-abstract/POWER2018/51401/V002T12A013/277508 (accessed on 4 October 2018).
6. Khawaja, M.K.; Alkhalidi, A.; Mansour, S. Environmental impacts of energy storage waste and regional legislation to curtail their effects—Highlighting the status in Jordan. *J. Energy Storage* **2019**, *26*, 100919. [CrossRef]
7. Dehghani-Sanij, A.R.; Tharumalingam, E.; Dusseault, M.B.; Fraser, R. Study of energy storage systems and environmental challenges of batteries. *Renew. Sustain. Energy Rev.* **2019**, *104*, 192–208. [CrossRef]
8. Krivik, P.; Baca, P. Electrochemical energy storage. In *Energy Storage—Technologies and Applications*; IntechOpen: London, UK, 2013.
9. Dutt, D. Life cycle analysis and recycling techniques of batteries used in renewable energy applications. In Proceedings of the 2013 International Conference on New Concepts in Smart Cities: Fostering Public and Private Alliances (SmartMILE), Gijon, Spain, 11–13 December 2013; pp. 1–7.
10. Laajimi, M.; Go, Y.I. Energy storage system design for large-scale solar PV in Malaysia: Technical and environmental assessments. *J. Energy Storage* **2019**, *26*, 100984. [CrossRef]
11. Aikhuele, D.O. Development of a fixable model for the reliability and safety evaluation of the components of a commercial lithium-ion battery. *J. Energy Storage* **2020**, *32*, 101819. [CrossRef]
12. Melchor-Martínez, E.M.; Macias-Garbett, R.; Malacara-Becerra, A.; Iqbal, H.M.; Sosa-Hernández, J.E.; Parra-Saldívar, R. Environmental impact of emerging contaminants from battery waste: A mini review. *Case Stud. Chem. Environ. Eng.* **2021**, *3*, 100104. [CrossRef]
13. Gaines, L.; Richa, K.; Spangenberger, J. Key issues for Li-ion battery recycling. *MRS Energy Sustain.* **2018**, *5*, E14. [CrossRef]
14. Lombardo, G.; Ebin, B.; Foreman, M.R.S.J.; Steenari, B.-M.; Petranikova, M. Incineration of EV Lithium-ion batteries as a pretreatment for recycling—Determination of the potential formation of hazardous by-products and effects on metal compounds. *J. Hazard. Mater.* **2020**, *393*, 122372. [CrossRef]
15. Bernardes, A.M.; Espinosa, D.C.R.; Tenório, J.A.S. Recycling of batteries: A review of current processes and technologies. *J. Power Sources* **2004**, *130*, 291–298. [CrossRef]
16. Li, M.; Liu, J.; Han, W. Recycling and management of waste lead-acid batteries: A mini-review. *Waste Manag. Res.* **2016**, *34*, 298–306. [CrossRef] [PubMed]
17. Prengaman, R.D.; Mirza, A.H. Recycling concepts for lead—Acid batteries. In *Lead-Acid Batteries for Future Automobiles*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 575–598.
18. Kebede, A.A.; Kalogiannis, T.; Van Mierlo, J.; Berecibar, M. A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. *Renew. Sustain. Energy Rev.* **2022**, *159*, 112213. [CrossRef]
19. Hunt, J.D.; Zakeri, B.; Lopes, R.; Barbosa, P.S.F.; Nascimento, A.; de Castro, N.J.; Brandão, R.; Schneider, P.S.; Wada, Y. Existing and new arrangements of pumped-hydro storage plants. *Renew. Sustain. Energy Rev.* **2020**, *129*, 109914. [CrossRef]
20. Larcher, D.; Tarascon, J.M. Towards greener and more sustainable batteries for electrical energy storage. *Nat. Chem.* **2015**, *7*, 19–29. [CrossRef] [PubMed]

21. Rarotra, S.; Sahu, S.; Kumar, P.; Kim, K.H.; Tsang, Y.F.; Kumar, V.; Kumar, P.; Srinivasan, M.; Veksha, A.; Lisak, G. Progress and challenges on battery waste management: A critical review. *ChemistrySelect* **2020**, *5*, 6182–6193. [CrossRef]
22. Rai, P.K.; Lee, S.S.; Zhang, M.; Tsang, Y.F.; Kim, K.-H. Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environ. Int.* **2019**, *125*, 365–385. [CrossRef]
23. Aral, H.; Vecchio-Sadus, A. Toxicity of lithium to humans and the environment—A literature review. *Ecotoxicol. Environ. Saf.* **2008**, *70*, 349–356. [CrossRef]
24. Buxton, S.; Garman, E.; Heim, K.E.; Lyons-Darden, T.; Schlekat, C.E.; Taylor, M.D.; Oller, A.R. Concise review of nickel human health toxicology and ecotoxicology. *Inorganics* **2019**, *7*, 89. [CrossRef]
25. Biotto, G.; Silvestri, S.; Gobbo, L.; Furlan, E.; Valenti, S.; Rosselli, R. GIS, multi-criteria and multi-factor spatial analysis for the probability assessment of the existence of illegal landfills. *Int. J. Geogr. Inf. Sci.* **2009**, *23*, 1233–1244. [CrossRef]
26. Heelan, J.; Gratz, E.; Zheng, Z.; Wang, Q.; Chen, M.; Apelian, D.; Wang, Y. Current and prospective Li-ion battery recycling and recovery processes. *JOM* **2016**, *68*, 2632–2638. [CrossRef]
27. Aikhuele, D.O.; Odofin, S. A Generalized Triangular Intuitionistic Fuzzy Geometric Averaging Operator for Decision-Making in Engineering and Management. *Information* **2017**, *8*, 78. [CrossRef]
28. Afsordegan, A. *A Contribution to Multi-Criteria Decision Making in Sustainable Energy Management based on Fuzzy and Qualitative Reasoning*; Universitat Politècnica de Catalunya: Barcelona, Spain, 2015.
29. Ighravwe, D.E.; Babatunde, M.O.; Denwigwe, I.H.; Aikhuele, D.O. A STEEP-cum-SWOT approach for maintenance strategy evaluation for an off-grid PV-powered street lighting system. *Afr. J. Sci. Technol. Innov. Dev.* **2020**, *12*, 703–714. [CrossRef]
30. Zhao, H.; Guo, S. Selecting green supplier of thermal power equipment by using a hybrid MCDM method for sustainability. *Sustainability* **2014**, *6*, 217–235. [CrossRef]
31. Turan, F.M.; Aikhuele, D.O.; Johan, K. Reliability information to support decision making for e-government projects. In Proceedings of the 3rd International Conference on Communication and Information Processing, Online, 24 November 2017; ACM: New York, NY, USA, 2017; Volume F1338. [CrossRef]
32. Gul, M.; Celik, E.; Gumus, A.T.; Guneri, A.F. A fuzzy logic based PROMETHEE method for material selection problems. *Beni-Suef Univ. J. Basic Appl. Sci.* **2017**, *7*, 68–79. [CrossRef]