sustainability

Article

Optimal Waste-to-Energy Strategy Assisted by Fuzzy MCDM Model for Sustainable Solid Waste Management

Nguyen Van Thanh

Faculty of Commerce, Van Lang University, Ho Chi Minh City 70000, Vietnam; thanh.nguyenvan@vlu.edu.vn

Abstract: In Vietnam, rapid population and economic growth are responsible for the recent increase in solid waste. Energy production from waste is now becoming an effective solution around the world, especially in Vietnam, to solve environmental challenges while contributing to the country's sustainable energy production. Waste-to-energy production has become a solution to the municipal solid waste problem, which is projected to increase by 10–16%. In this study, the author proposed a fuzzy MCDM model to assess and select a solid-waste-to-energy plant location in Vietnam. In the first stage, the fuzzy analytic hierarchy process (FAHP) technique is utilized to analyze the relative weight of the primary and secondary evaluation elements, and a combined compromise solution (CoCoSo) model is used to rank the candidates in the final stage. This is the first solid-waste-to-energy plant location evaluation and selection model used in a renewable energy project in Vietnam based on expert interviews and a literature review. This study's contribution can be a significant guide in analyzing and selecting appropriate locations for solid-waste-to-energy projects, as well as for decision makers and investors in other renewable energy projects in Vietnam and throughout the world.

Keywords: fuzzy theory; MCDM model; decision making; solid waste to energy; sustainable development; operation research

Citation: Van Thanh, N. Optimal Waste-to-Energy Strategy Assisted by Fuzzy MCDM Model for Sustainable Solid Waste Management. *Sustainability* **2022**, *14*, 6565. https://doi.org/10.3390/su14116565

Academic Editors: Eulalia Jadraque Gago and Saioa Etxebarria Berrizbeitia

Received: 12 April 2022
Accepted: 25 May 2022
Published: 27 May 2022

1. Introduction

Currently, on a daily basis, an average of almost 35,000 tons of solid trash is generated in cities, and 34,000 tons of residential solid garbage is generated in rural areas in Vietnam. About 85% of this solid waste is currently being treated mainly by the use of landfill technology that requires a lot of land, 80% of which is an unhygienic landfill with potential for environmental pollution. Vietnam is currently setting goals to increase power production in order to ensure energy security and economic development toward a "green" and sustainable direction. Therefore, energy production from waste is currently becoming an effective solution to address environmental challenges and land use needs in urban areas. However, this resource is being wasted and not fully utilized for energy production [1]. Turning solid waste into energy can help provide a clean and cheaper source of energy, reduce solid waste pollution, and protect the environment. Therefore, according to experts, Vietnam should prioritize large-scale waste power development projects using modern and advanced technology to convert waste into energy. As a result, the building of a solid-waste-to-energy facility in Vietnam is required. Solid waste statistics from 2002 to 2020 as shown in Figure 1.

Solid waste is waste in solid form, including all waste generated by humans in the process of daily life, production, and business. The composition of solid waste varies depending on the climate, locality, economic conditions, and other factors. However, it can be divided into the following three basic types [2]:

✓ Combustible substances (plastics, leather, rubber, paper, food, straw, wood, and grass).
✓ Non-combustible substances (stone, crockery, porcelain, ferrous metals, non-ferrous metals, and glass).
✓ Mixed substances (sand, soil, hair, and pebbles).

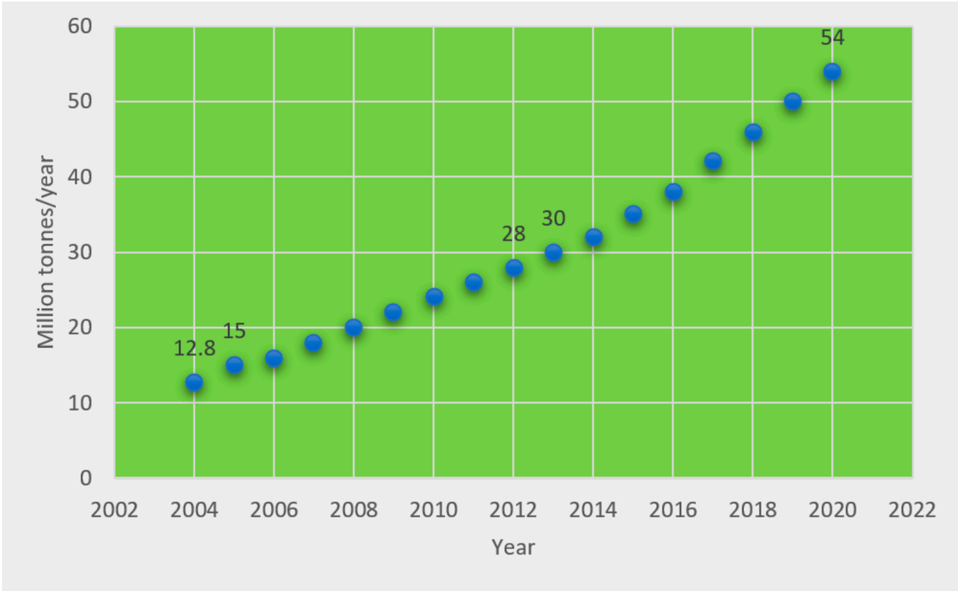

Figure 1. Solid waste in Vietnam.

Currently, the technology of waste incineration for electricity generation is gaining interest in various countries because it shows outstanding advantages compared to traditional landfill methods and incinerators, such as reducing over 90% of the volume and waste volume; potentially using heat; reducing greenhouse gas emissions compared to the disposal approach; and reducing water pollution and smells. There are three waste incinerator technologies most commonly used in power generation waste incineration plants today, namely, stocker incinerators, rotary kiln incinerators, and fluidized bed incinerators [3].

Many studies have used multi-criteria decision-making (MCDM) methodologies in many sectors of science and engineering, and this tendency has been growing for many years. The placement selection problem is one of the domains in which the MCDM model has been used [4]. The MCDM's progression is shown in Figure 2 [5].

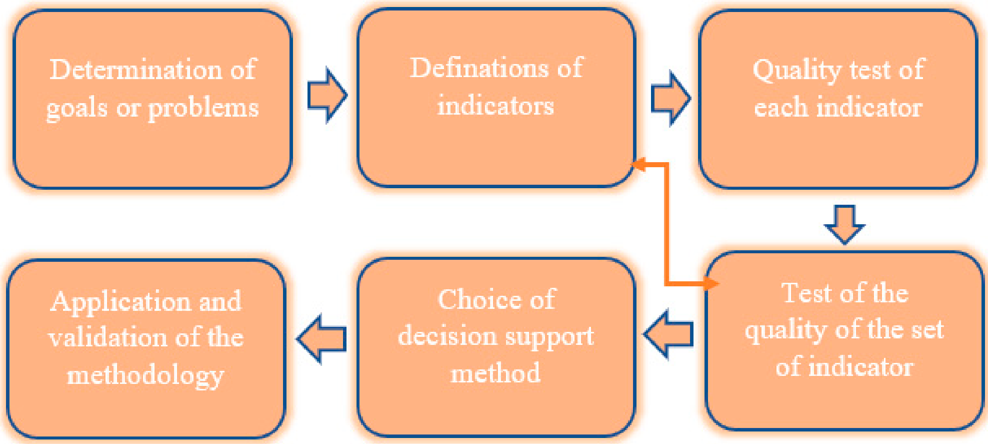

Figure 2. General process of MCDM model.

The major purpose of this research is to present a fuzzy MCDM model, which incorporates the fuzzy analytic hierarchy process (FAHP) and combined compromise solution (CoCoSo) methodologies, for solid-waste-to-energy plant location selection. The FAHP technique is utilized to analyze the relative weight of the primary and secondary evaluation elements, and the CoCoSo model is used to rank the candidates in the final stage. To show the usefulness of the suggested methodology, a case study on five different locations is carried out. Finally, sensitivity analysis is used to evaluate the proposed model's robustness.

2. Literature Review

The fast population growth and changes caused by the improvement in living standards have shown solid waste disposal to be an environmental hazard [6–8]. A random and non-scientific selection of landfill sites may have a negative impact on the climate; people; and surrounding aquatic resources, including groundwater [9–11]. Frequently, it is a challenge to decision making in a multi-criteria environment. Therefore, the use of tools, such as FAHP and fuzzy TOPSIS, should be preferred to emphasize the pros and cons of each of the studied options [12]. Yildirim et al. [13] used an MCDM model and geographical information system (GIS) to solve the problem of solid waste landfill selection. In another study, Dolui et al. [14] stated that an inappropriate selection of landfill sites may have many disadvantageous impacts on the local environment and public health, and face resistance from the political opposition and local community; thus, they used a combination of MCDM and GIS models to solve the above problems. Al-Anbari et al. [15] used AHP and fuzzy TOPSIS to rank landfill sites. Villacreses et al. [16] proposed MCDM and GIS for Wind farms suitability location. Ekmekçioğlu et al. [17] suggested fuzzy TOPSIS and FAHP for the selection of an appropriate disposal method and site for municipal solid waste, and they adopted an integrated system of GIS-based MCDM to provide an effective tool for solving the problem of landfill selection. Mallick's paper [18] provided an integrated framework with a focus on structuring the decision-making process for landfill suitability site maps. Wichapa et al. [19] discussed using a combined method of FAHP and goal programming (GP) to maximize the satisfaction level regarding relevant impacts, such as social and environmental impacts, which is as important as minimization of the total cost. Hanine et al. [20] applied a combination of the fuzzy TODIM and FAHP methods for landfill location selection. Wang et al. [21] proposed fuzzy MCDM to optimize the site selection process for biomass power plants.

WASPAS is a well-known and efficient solution for solving problems, and it was proposed by Zavadskas [22]. Currently, there are many studies using the WASPAS method to solve multi-criteria problems. The following are some examples: Mishra et al. [23] introduced the WASPAS method with Fermatean fuzzy sets (FFSs) for the healthcare waste disposal location selection problem. Nie et al. [24] suggested a newly extended WASPAS technique, which involves three novel procedures and is utilized to handle MCDM issues in the interval number environment; Chakraborty et al. [25] applied the WASPAS method as a multi-criteria decision-making tool. Turskis et al. [26] used a hybrid model based on fuzzy AHP and fuzzy WASPAS for construction site selection. By combining AHP and WASPAS methods, Baušys et al. [27] solved the problem of choosing appropriate garage locations for residential houses. Bagočius et al. [28] proposed a hybrid MCDM model and WASPAS method to select and rank feasible locations for wind farms and to assess the types of wind turbines in the Baltic Sea offshore area. Mardani et al. [29] presented a study that presented a new fuzzy approach under the Hesitant Fuzzy Set (HFS) approach using Stepwise Weight Assessment Ratio Analysis (SWA-RA) and the WASPAS method to evaluate and rank the critical challenges of DT intervention in order to control the COVID-19 outbreak. Mihajlović et al. [30] implemented WASPAS and AHP methods when choosing a logistics distribution center location in Serbia. Table 1 provides an overview of studies on site selection and application of MCDM models.

Table 1. Overview of some work on site selection and application of MCDM model.

No.	Authors	MCDM Models	Main Findings
1	Yildirim et al.	Geographical information system (GIS); TOPSIS	Combined GIS and TOPSIS models for municipal solid waste landfill site selection
2	Dolui et al.	AHP, fuzzy AHP, SRS and RSW weightage methods	Identified potential landfill sites

Table 1. *Cont.*

No.	Authors	MCDM Models	Main Findings
3	Al-Anbari et al.	AHP, fuzzy TOPSIS	Site capacity criterion was found to be more important than land price and land elevation
4	Tavares et al.	Geographical information system (GIS); AHP	System effectiveness was provided in ranking potential locations
5	Ekmekçioğlu et al.	AHP, TOPSIS	Illustrated the importance of weights on various criteria when choosing the optimized location
6	Mallick's et al.	GIS-based fuzzy-AHP-MCDA method	Findings can provide an appropriate guideline to assist decision makers in selecting an optimal landfill site
7	Wichapa et al.	FAHP; goal programming (GP)	The proposed model can lead to selection of optimal locations for infectious waste disposals
8	Hanine et al.	Fuzzy AHP; fuzzy TODIM	Comparisons of two MCDM methods were made
9	Wang et al.	FAHP, TOPSIS	The proposed MCDM model can address the complex problems in location selection
10	Zavadskas	Weighted sum model (WSM); weighted product model (WPM)	The proposed MCDM method increased the ranking accuracy of alternatives
11	Mishra et al.	WASPAS with Fermatean fuzzy sets	The proposed MCDM model can handle the ambiguity and inaccuracy in decision-making processes
12	Nie et al.	WASPAS	Solved location selection problem in wind power projects
13	Chakraborty et al.	WASPAS	Applied WASPAS method as a multi-criteria decision-making tool
14	Turskis et al.	Fuzzy AHP; fuzzy WASPAS	Applied MCDM model for construction site selection

3. Methodology

Multi-criteria decision making (MCDM) is emerging as a discipline in operations research. While the fuzzy theory has been included in MCDM research, both approaches have essentially been developed along the same lines. This has made the fuzzy MCDM model become an effective tool to assist decision makers in choosing the optimal solution. In this study, the author proposed a fuzzy MCDM model to assess and select a solid-waste-to-energy plant location in Vietnam. This study's recommended approach consists of the following three key steps, and a research graph is shown in Figure 3:

Step 1. The criteria affecting the evaluation and selection of the optimal location are determined.

Step 2. The weights of the criteria are identified using the fuzzy analytic hierarchy process (FAHP) model.

Step 3: In the last stage, the CoCoSo approach is used to evaluate all potential locations based on the criteria.

3.1. Definition of a Fuzzy Number

Zadeh [31] showed that fuzzy sets are an extension of the traditional concept of sets. Fuzzy sets were thought to be a collection of components with varying degrees of membership. According to the traditional set theory [32,33], the membership of items in a set is evaluated in binary terms using a bivalent condition, which means that an element either belongs to or does not belong to the set. Hsieh, Lu, and Tzeng [34] are credited with the mathematical notion. The membership function of a fuzzy number, Triangular Fuzzy Number (TFN) $\widetilde{H}$, is defined as $\mu_{\widetilde{H}}(x)$: $\mathbb{R} \to [0, 1]$.

$$\mu_H \sim (x) = \begin{cases} (x-z)/(q-z), & l \le x \le q \\ (k-x)/(k-q), & q \le x \le k \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

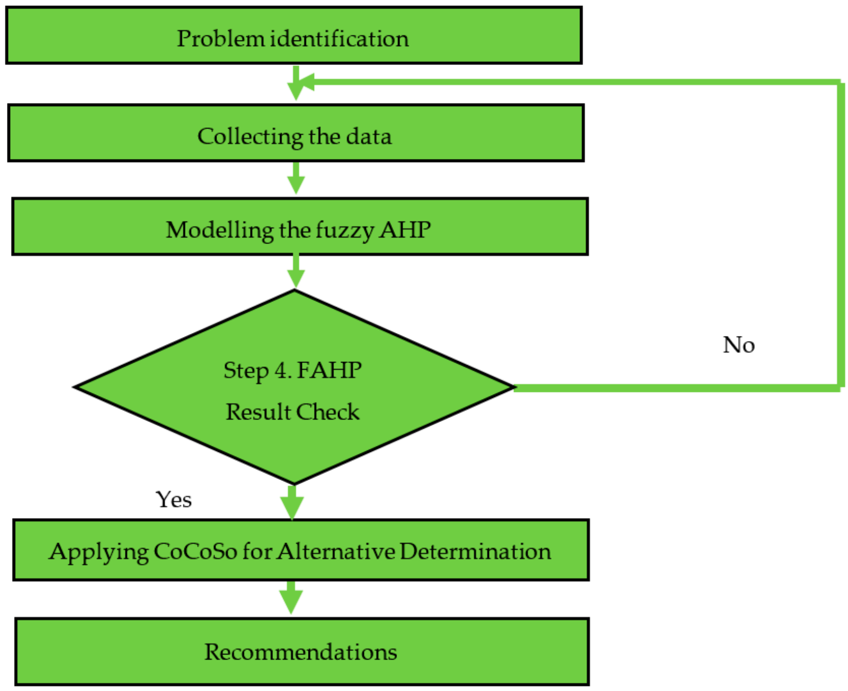

Figure 3. Research graph.

According to Equation (1), z and k represent the lower and upper limits of the fuzzy number $\widetilde{H}$, respectively, and q represents the modal value for e $\widetilde{H}$ (as Figure 4). The TFN is indicated by $\widetilde{H} = (z,\ q,\ k)$. The operational rules of $\widetilde{H}_1 = (z_1,\ q_1,\ k_1)$ and $\widetilde{H}_2 = (z_2,\ q_2,\ k_2)$ are shown in Equations (2)–(6).

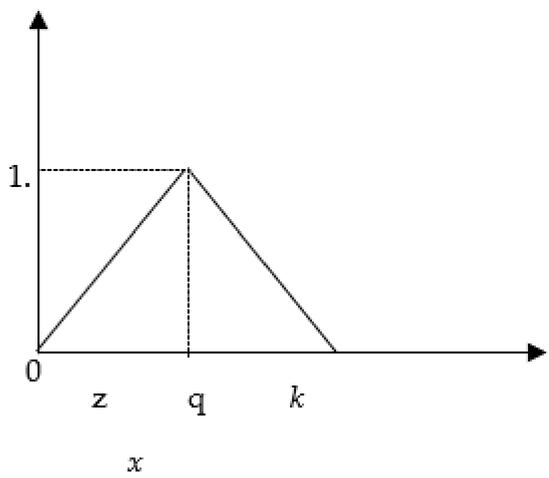

Figure 4. A fuzzy integer with a triangular shape.

Fuzzy number addition $\oplus$

$$\widetilde{H}_1 \oplus \widetilde{H}_2 = (z_1,\ q_1,\ k_1)\ \oplus\ (z_2,\ q_2,\ k_2) = (z_1 + z_2,\ q_1,\ +q_2,\ k_1 + k_2) \tag{2}$$

Fuzzy number multiplication $\times$

$$\begin{gathered}\widetilde{H}_1 \times \widetilde{H}_2 = (z_1,\ q_1,\ k_1) \times (z_2,\ q_2,\ k_2) = (z_1 z_2,\ q_1,\ q_2,\ k_1 k_2) \\ \text{for } z_1, z_2 > 0; q_1, q_2 > 0;\ k_1, k_2 > 0\end{gathered} \tag{3}$$

The fuzzy number is subtracted Θ

$$\widetilde{H}_1 \Theta\ \widetilde{H}_2 = (z_1,\ q_1,\ k_1) \Theta (z_2,\ q_2,\ k_2) = (z_1 -\ k_2,\ q_1\ \ - q_2,\ k_1 - z_2\ ) \tag{4}$$

The division of a fuzzy number $\varnothing$

$$\widetilde{H}_1 \varnothing \widetilde{H}_2 = (z_1,\ q_1, k_1) \varnothing (z_2,\ q_2, k_2) = (z_1/k_2,\ q_1,/q_2, k_1/z_2) \\ \text{for } z_1, z_2 > 0; q_1, q_2 > 0;\ k_1, k_2 > 0 \tag{5}$$

The fuzzy number's reciprocal

$$\widetilde{H}^{-1} = \ (z_1,\ q_1,\ k_1)^{-1} = (1/z_1, 1/q_1,\ 1/\ k_1\ ) \\ \text{for } z_1 > 0;\ \ q_1 > 0;\ k_1 > 0 \tag{6}$$

In this study, the authors compare the assessment dimension for biomass furnace providers using nine core language concepts with the fuzzy nine-level scale proposed by Gumus [35]. These linguistic variables are represented by positive triangular fuzzy integers.

3.2. Fuzzy AHP (FAHP)

The suggested fuzzy AHP implementation approach consists of the following two stages:

Stage 1: For each criterion, a pairwise comparison matrix is built. The linguistic words are then assigned to the pairwise comparisons, as seen in matrix $\widetilde{H}$ below:

$$\widetilde{H} = \begin{bmatrix} 1 & \widetilde{\mathrm{h}}_{12} & \cdots & \widetilde{\mathrm{h}}_{1n} \\ \widetilde{\mathrm{h}}_{21} & 1 & \cdots & \widetilde{\mathrm{h}}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{\mathrm{h}}_{n1} & \widetilde{\mathrm{h}}_{n2} & \vdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \widetilde{\mathrm{h}}_{12} & \cdots & \widetilde{\mathrm{h}}_{1n} \\ 1/\widetilde{\mathrm{h}}_{21} & 1 & \cdots & \widetilde{\mathrm{h}}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\widetilde{\mathrm{h}}_{2n} & \widetilde{\mathrm{h}}_{n2} & \cdots & 1 \end{bmatrix} \tag{7}$$

Stage 2: Using the geometric mean approach, the fuzzy geometric mean and the fuzzy weights of each criterion are computed [36]:

$$\widetilde{t}_c = \left(\widetilde{\mathrm{h}}_{c1} \times \ldots . \times \ldots \widetilde{\mathrm{h}}_{cd} \times \ldots \times \widetilde{\mathrm{h}}_{cd}\right)^{1/n} \\ \widetilde{p}_c = \widetilde{t}_c \times \left(\widetilde{t}_1 \oplus \ldots \widetilde{t}_c \oplus \ldots \oplus \widetilde{t}_n\right)^{-1} \tag{8}$$

where $\widetilde{\mathrm{h}}_{cd}$ represents the fuzzy comparison value of dimension c to criteria d.

$\widetilde{t}_c$ is the geometric mean of the fuzzy comparison value of criterion c to each criteria.

$\widetilde{s}_c$ is the cth criterion's fuzziness weight.

3.3. Combined Compromise Solution (CoCoSo)

CoCoSo is an MCDM technique that uses an integrated simple additive weighting and an exponentially weighted product model [37]:

Stage 1: Create the basic decision-making matrix:

$$x_{cd} = \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{1n} \\ x_{21} & x_{22} & \ldots & x_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ x_{m1} & x_{m2} & & x_{mn} \end{bmatrix} \\ \text{With } c = 1, 2, \ldots,\ m;\quad d = 1, 2, \ldots, n \tag{9}$$

Stage 2: Normalize the criteria values:

For the advantageous criterion:

$$t_{cd} = \frac{x_{cd} - \min\limits_{c} x_{cd}}{\max\limits_{c} x_{cd} - \min\limits_{c} x_{cd}} \tag{10}$$

Regarding the cost criterion:

$$t_{cd} = \frac{\max_{c} x_{cd} - x_{cd}}{\max_{c} x_{cd} - \min_{c} x_{cd}} \tag{11}$$

Stage 3: Calculate the total of the weighted comparability sequence (S_c) and the total of the power weight of comparability sequences for each alternative, as well as the sum of the weighted comparability sequence (P_c) for each choice:

$$S_c = \sum_{d=1}^{n} (s_d t_{cd}) \tag{12}$$

Compute the S_c value using the grey relational generation method:

$$P_c = \sum_{d=1}^{n} \left(t_{cd}{}^{s_d}\right) \tag{13}$$

Calculate the P_c value using the WASPAS multiplicative attitude.
Stage 4: Determine the relative weights of each alternative.
Determine the arithmetic mean of the sums of the WSM and WPM scores:

$$k_{ca} = \frac{P_c + S_c}{\sum_{c=1}^{m} (P_c + S_c)}, \tag{14}$$

Calculate the total of the relative scores of WSM and WPM in comparison to the best alternative:

$$k_{cb} = \frac{S_c}{\min_{c} S_c} + \frac{P_c}{\min_{c} P_c} \tag{15}$$

Calculate the balanced compromise of the WSM and WPM model scores as follows:

$$k_{cc} = \frac{\lambda(S_c) + (1 - \lambda)P_c}{\lambda \max_{c} S_c + (1 - \lambda)\max_{c} P_c} \tag{16}$$

Stage 5: Define the final ranking of the alternative k_c:

$$k_c = (k_{ca} k_{cb} k_{cc})^{\frac{1}{3}} + \frac{1}{3}(k_{ca} + k_{cb} + k_{cc}) \tag{17}$$

4. Case Study

The incineration of waste to generate electricity is one of the current advanced methods that can take advantage of available raw materials, limit the use of fossil fuels, and, at the same time, reduce the area of land used for landfilling. According to the latest report from the Vietnam Ministry of Industry and Trade, domestic waste from urban and rural areas is discharged into the environment at about 70,000 tons per day; Hanoi and Ho Chi Minh City alone generate between 7000 and 8000 tons of garbage every day. With the large amount of waste in Vietnam, burning waste to generate electricity can generate hundreds and thousands of MW to supply the power system. However, this type of power generation has not really reached its potential [38]. Trash is piled atop each other on Tran Huu Duc Street in Hanoi is shown in Figure 5.

Figure 5. Trash is piled atop each other on Tran Huu Duc Street in Hanoi.

Typical studies on the site assessment selection process focus nearly entirely on how to determine the ideal choice with a single model, ignoring the management concept. That is, previous studies cannot be immediately integrated into project management due to a lack of actual operability. In this work, the author suggests a fuzzy MCDM model to analyze and select the location of a solid-waste-to-electricity facility in Vietnam. The FAHP technique is utilized to analyze the relative weights of the primary and secondary evaluation elements, and the WASPAS model is then used to rank the candidates in the final stage. All of the criteria in the first stage affecting the waste-to-energy plant site selection is presented in Table 2.

Table 2. List of main and sub-criteria.

No.	Main Criteria	Sub-Criteria	Source	
			Literature Review	Experts
1	Economic factor	Construction cost (WE1)	Sadaf Feyzi et al. [36] Yunna Wu et al. [39]	X
		Operation and maintenance cost (WE2)	Jianwei Gao et al. [40] Yunna Wu et al. [39]	X
		Potential demand (WE3)	Jianwei Gao et al. [40]	X
2	Technical factor	Land use (WE4)	Sadaf Feyzi et al. [36] Tavares et al. [41] Yunna Wu et al. [39]	X
		Solid waste quantity (WE5)	Jianwei Gao et al. [40]	X
		Distance to the city (WE6)	World bank (2005) [42]	X
		Distance to landfills (WE7)	Jianwei Gao et al. [40] Yunna Wu et al. [39]	X
		Distance from electric grid (WE8)	Sadaf Feyzi et al. [36] Yunna Wu et al. [39]	X
3	Environment factor	Impact on life quality of resident (WE9)	Sadaf Feyzi et al. [36]	X
		Elevation (WE10)	Jianwei Gao et al. [40]	X
		Solid texture (WE11)	World bank (2005) [42]	X
4	Social factor	Growth of GDP (WE12)	Jianwei Gao et al. [40]	X
		Government policy (WE13)	Jianwei Gao et al. [40] Yunna Wu et al. [39]	X
		Public support (WE14)	Jianwei Gao et al. [40] Yunna Wu et al. [39]	X
		Available employee (WE15)	Yunna Wu et al. [39]	X

According to the statistics on the amount of solid waste and the opinions of experts, there are five places to consider for investment in a solid-waste-to-energy plant, namely, Ha

Noi (DMUWE 1), Ho Chi Minh (DMUWE 2), Hue (DMUWE 3), Da Nang (DMUWE 4), and Hai Phong (DMUWE 5). The FAHP methodology is combined with the CoCoSo method in this work to create a unique algorithm–fuzzy multi-criteria decision-making model to evaluate the placement of solid-waste-to-energy plants. To accomplish this objective, the fuzzy AHP technique is used to examine fuzzy information from expert evaluations in order to determine priority weights. Table 3 displays the FAHP findings.

Table 3. Result of FAHP.

Criteria	Fuzzy Sum of Each Row			Fuzzy Synthetic Extent			Degree of Possibility	Normalization
WE 1	12.65408	17.73456	24.11035	0.03583	0.06835	0.12965	0.67081	0.06695
WE 2	12.13408	17.32285	24.01852	0.03436	0.06676	0.12916	0.66183	0.06605
WE 3	15.52096	21.60082	28.49693	0.04395	0.08325	0.15324	0.86275	0.08610
WE 4	14.17687	20.14792	26.85583	0.04014	0.07765	0.14442	0.80928	0.08077
WE 5	18.70575	25.73977	33.40429	0.05297	0.09920	0.17963	1.00000	0.09980
WE 6	11.38350	15.40831	20.48769	0.03223	0.05938	0.11017	0.57144	0.05703
WE 7	9.49865	13.23950	18.79210	0.02690	0.05103	0.10105	0.49953	0.04985
WE 8	13.66866	19.27269	25.62867	0.03870	0.07428	0.13782	0.77295	0.07714
WE 9	14.15539	20.51264	28.07008	0.04008	0.07906	0.15095	0.82945	0.08278
WE 10	10.03724	13.95303	19.88857	0.02842	0.05378	0.10695	0.54303	0.05420
WE 11	9.06600	12.49746	17.77592	0.02567	0.04817	0.09559	0.45508	0.04542
WE 12	16.26079	23.13051	31.12386	0.04604	0.08915	0.16737	0.91920	0.09174
WE 13	9.59264	13.03898	18.30196	0.02716	0.05025	0.09842	0.48147	0.04805
WE 14	8.89311	11.98044	16.85137	0.02518	0.04617	0.09062	0.41520	0.04144
WE 15	10.21197	13.88541	19.34778	0.02892	0.05352	0.10404	0.52784	0.05268

During this step, a decision-making matrix for the evaluation of solid-waste-to-energy plant locations is constructed. In this respect, five potential locations in Vietnam are selected as a case study. The problem is addressed using the CoCoSo method, as described in Section 3, and the results are shown in Tables 4–6.

According to Table 6 and Figure 6, the potential locations' ranks are as follows: DMUWE 5 $\succ$ DMUWE 1 $\succ$ DMUW3 $\succ$ DMUW4 $\succ$ DMUWE 2. Thus, Hai Phong (DMUWE 5) is the optimal location. It is demonstrated that, in addition to Equation (16), which is a typical technique used for coefficient λ results, a fixed value in the range of 0.1, 0.2, 0.3,..., 1.0 may be employed. As a result, in the first stage of the sensitivity analysis, a change was made to the coefficient λ. Table 6 shows the ranking performance of the CoCoSo model for various λ values.

Table 4. Weighted comparability sequence and Si.

	DMUWE 1	DMUWE 2	DMUWE 3	DMUWE 4	DMUWE 5
WE 1	0.00000	0.03347	0.03347	0.06695	0.03347
WE 2	0.00000	0.06605	0.06605	0.00000	0.06605
WE 3	0.00000	0.04305	0.08610	0.04305	0.08610
WE 4	0.04038	0.00000	0.04038	0.08077	0.04038
WE 5	0.09980	0.04990	0.09980	0.00000	0.04990
WE 6	0.05703	0.01901	0.00000	0.05703	0.03802
WE 7	0.04985	0.00000	0.02493	0.04985	0.00000
WE 8	0.03857	0.00000	0.03857	0.07714	0.03857
WE 9	0.08278	0.04139	0.04139	0.00000	0.04139
WE 10	0.05420	0.05420	0.00000	0.05420	0.05420
WE 11	0.02271	0.00000	0.02271	0.04542	0.02271
WE 12	0.09174	0.09174	0.04587	0.00000	0.04587
WE 13	0.04805	0.02403	0.02403	0.00000	0.04805
WE 14	0.02072	0.00000	0.02072	0.04144	0.02072
WE 15	0.02634	0.05268	0.00000	0.02634	0.02634

Table 5. Exponentially weighted comparability sequence and Pi.

	DMUWE 1	DMUWE 2	DMUWE 3	DMUWE 4	DMUWE 5
WE 1	0.0000	0.9547	0.9547	1.0000	0.9547
WE 2	0.0000	1.0000	1.0000	0.0000	1.0000
WE 3	0.0000	0.9421	1.0000	0.9421	1.0000
WE 4	0.9456	0.0000	0.9456	1.0000	0.9456
WE 5	1.0000	0.9332	1.0000	0.0000	0.9332
WE 6	1.0000	0.9393	0.0000	1.0000	0.9771
WE 7	1.0000	0.0000	0.9660	1.0000	0.0000
WE 8	0.9479	0.0000	0.9479	1.0000	0.9479
WE 9	1.0000	0.9442	0.9442	0.0000	0.9442
WE 10	1.0000	1.0000	0.0000	1.0000	1.0000
WE 11	0.9690	0.0000	0.9690	1.0000	0.9690
WE 12	1.0000	1.0000	0.9384	0.0000	0.9384
WE 13	1.0000	0.9672	0.9672	0.0000	1.0000
WE 14	0.9717	0.0000	0.9717	1.0000	0.9717
WE 15	0.9641	1.0000	0.0000	0.9641	0.9641

Table 6. Final ranking from CoCoSo.

Alternatives	Ka	Ranking	Kb	Ranking	Kc	Ranking	K
DMUWE 1	0.2095	2	2.5482	2	0.8767	2	1.9879
DMUWE 2	0.1711	5	2.0000	5	0.7163	5	1.5884
DMUWE 3	0.2047	3	2.3428	3	0.8569	3	1.8783
DMUWE 4	0.1761	4	2.1635	4	0.7369	4	1.6803
DMUWE 5	0.2386	1	2.6858	1	0.9986	1	2.1694

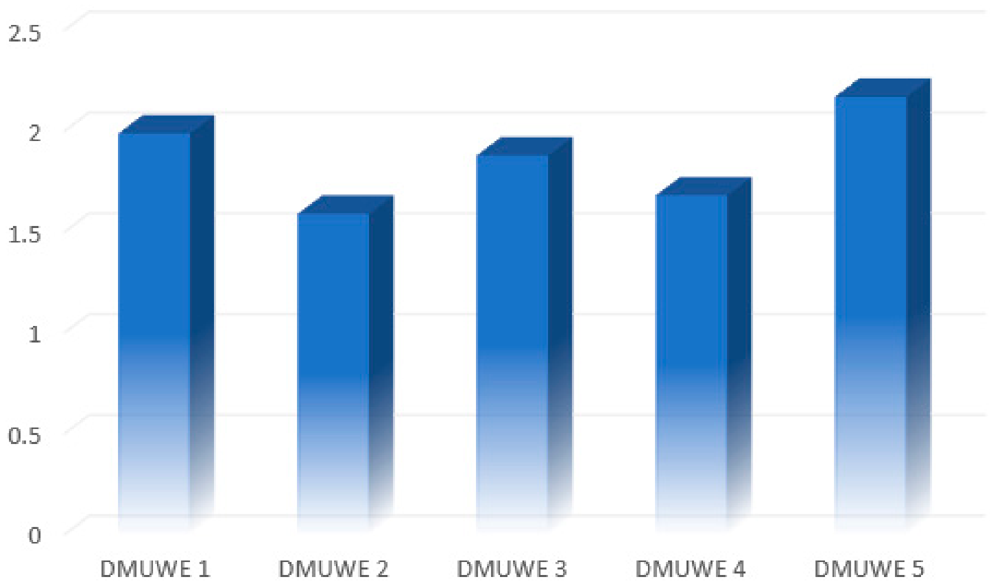

Figure 6. Ranking list.

Table 7 and Figure 7 display the relative computed values of the alternatives based on the value of the coefficient λ. It should be noted that the coefficient λ values have no effect on the change in the rank of the alternatives. This study resulted in the effective development of a hybrid MCDM model that uses FAHP and CoCoSo to determine the supplier assessment and selection method in renewable energy projects.

Table 7. Rankings of robots for various λ values.

Alternatives	λ Values									
	λ = 0.1	**λ = 0.2**	**λ = 0.3**	**λ = 0.4**	**λ = 0.5**	**λ = 0.6**	**λ = 0.7**	**λ = 0.8**	**λ = 0.9**	**λ = 1**
DMUWE 1	1.9847	1.9852	1.9858	1.9867	1.9879	1.9895	1.9922	1.9970	2.0081	2.0637
DMUWE 2	1.5875	1.5876	1.5878	1.5881	1.5884	1.5889	1.5896	1.5910	1.5943	1.6106
DMUWE 3	1.8782	1.8782	1.8782	1.8783	1.8783	1.8784	1.8784	1.8786	1.8789	1.8806
DMUWE 4	1.6771	1.6777	1.6783	1.6791	1.6803	1.6819	1.6845	1.6892	1.7001	1.7545
DMUWE 5	2.1702	2.1700	2.1699	2.1697	2.1694	2.1690	2.1683	2.1671	2.1643	2.1501

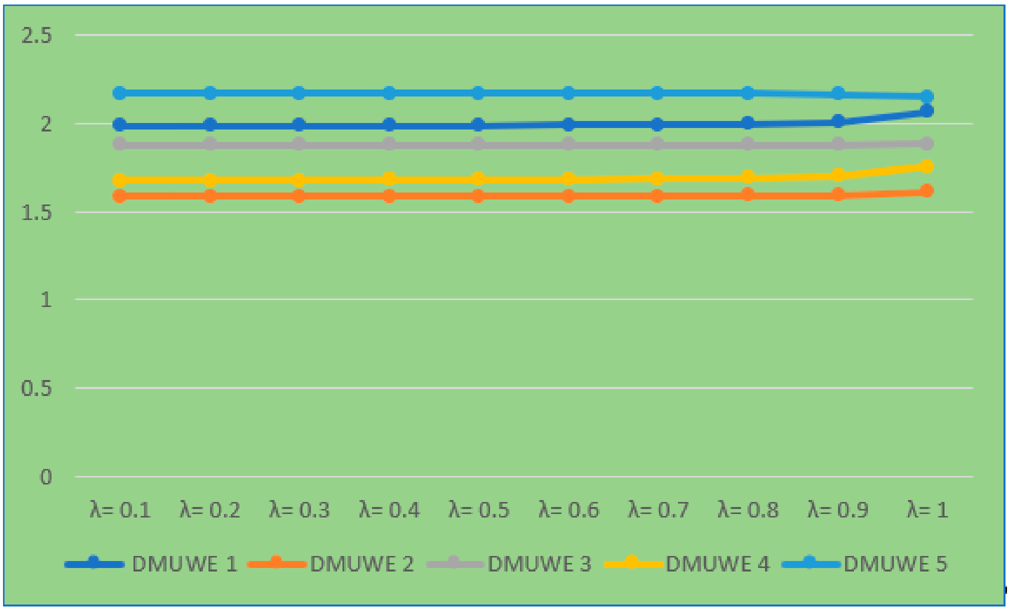

Figure 7. Sensitivity analysis.

The site selection of energy conversion plants requires a complex decision-making process, in which the decision maker must consider all quantitative and qualitative factors. In this case study, the author proposed and applied a fuzzy MCDM model, which included FAHP and CoCoSo. FAHP was used to determine the weight of all criteria, and the CoCoSo model was applied to rank five alternatives. Finally, a sensitivity analysis was conducted to evaluate the proposed model's robustness.

5. Conclusions

In this study, the author proposed a fuzzy MCDM model to assess and select a solid-waste-to-energy plant location in Vietnam. The FAHP technique was utilized to analyze the relative weight of the primary and secondary evaluation elements, and the WASPAS model was then used to rank the candidates in the final stage. A real problem of solid-waste-to-energy site selection in Vietnam was employed to examine the performance of the proposed algorithm. As a result, Hai Phong (DMUWE 5) was found to be the optimal location to build a solid-waste-to-energy plant.

The following are some of the most noteworthy contributions and achievements in this research:

✓ The suggested model is the first fuzzy MCDM model used to evaluate and select solid-waste-to-energy plant locations in Vietnam, and it is based on expert interviews and literature research.

✓ This is the first research to present a case study on the assessment of locations for the renewable energy industry, using a mix of fuzzy theory, the AHP model, and the CoCoSo model.

✓ The findings of this study may be used as a beneficial reference to analyze and select the best sites for solid-waste-to-energy projects, as well as for decision makers and investors in other renewable energy initiatives.

For further research on this topic, the work may be expanded to other MCDM models, such as TOPSIS, data envelopment analysis (DEA), and the WASPAS model.

Funding: This research was funded by Van Lang University and the APC was funded by Van Lang University.

Acknowledgments: The authors wish to express their gratitude to Van Lang University, Vietnam, for financial support for this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tăng Cường Sản Xuất điện Năng Từ Chất Thải, Góp Phần Phát Triển Năng Lượng Và Bảo Vệ Môi Trường. Available online: http://daidoanket.vn/tang-cuong-san-xuat-dien-nang-tu-rac-thai-5667575.html (accessed on 10 December 2021).
2. CHẤT THẢI RẮN, THÀNH PHẦN PHÂN LOẠI VÀ CÁC QUY TRÌNH XỬ LÝ. Available online: https://moitruonghse.com/chat-thai-ran-thanh-phan-phan-loai-va-cac-quy-trinh-xu-ly (accessed on 13 December 2021).
3. Một Số Công Nghệ Lò đốt Chất Thải Phát điện. Available online: https://www.most.gov.vn/vn/tin-tuc/20523/mot-so-cong-nghe-lo-dot-chat-thai-phat-dien.aspx (accessed on 10 December 2021).
4. Wang, C.N.; Nguyen, V.T.; Duong, D.H.; Thai, H.T.N. A hybrid fuzzy analysis network process (FANP) and the technique for order of preference by similarity to ideal solution (TOPSIS) approaches for solid waste to energy plant location selection in Vietnam. *Appl. Sci.* **2018**, *8*, 1100. [CrossRef]
5. Benmoussa, N.; Elyamami, A.; Mansouri, K.; Qbadou, M.; Illoussamen, E. A multi-criteria decision making approach for enhancing university accreditation process. *Eng. Technol. Appl. Sci. Res.* **2019**, *9*, 3726–3733. [CrossRef]
6. Al-Ansari, A.; Al-Hanbali, A.; Knutsson, S. Locating solid waste landfills in Mafraq city, Jordan. *J. Adv. Sci. Eng. Res.* **2012**, *2*, 40–51.
7. Cheng, S.; Chan, C.W.; Huang, G.H. Using multiple criteria decision analysis for supporting decisions of solid waste management. *J. Environ. Sci. Health* **2002**, *37*, 975–990. [CrossRef]
8. Pandey, P.C.; Sharma, L.K.; Nathawat, M.S. Geospatial strategy for sustainable management of municipal solid waste for growing urban environment. *Environ. Monit. Assess.* **2011**, *184*, 2419–2431. [CrossRef]
9. Vaverková, M.D. Landfill Impacts on the environment-review. *Geosciences* **2019**, *9*, 431. [CrossRef]
10. Zamorano, M.; Molero, E.; Hurtado, A.; Grindlay, A.; Ramos, A. Evaluation of a municipal landfill site in Southern Spain with GIS-aided methodology. *J. Hazard. Mater.* **2008**, *160*, 473–481. [CrossRef]
11. Singh, C.K.; Kumar, A.; Roy, S.S. Estimating Potential Methane Emission from Municipal Solid Waste and a Site Suitability Analysis of Existing Landfills in Delhi, India. *Technologies* **2017**, *5*, 62. [CrossRef]
12. Beskese, A.; Demir, H. Landfill site selection using fuzzy AHP and fuzzy TOPSIS: A case study for Istanbul. *Environ. Earth Sci.* **2015**, *73*, 3513–3521. [CrossRef]
13. Yildirim, V.; Memisoglu, T.; Bediroglu, S.; Colak, H.E. Municipal solid waste landfill site selection using multi-criteria decision making and GIS: Case study of Bursa province. *J. Environ. Eng. Landsc. Manag.* **2018**, *26*, 107–119. [CrossRef]
14. Dolui, S.; Sarkar, S. Identifying potential landfill sites using multicriteria evaluation modeling and GIS techniques for Kharagpur city of West Bengal, India. *Environ. Chall.* **2021**, *5*, 100243. [CrossRef]
15. Al-Anbari, A.; Thameer, Y.; Al-Ansari, N.; Knutsson, S. Ranking landfill sites in Najaf Governorate, Iraq ssing AHP and fuzzy TOPSIS methods. *J. Civ. Eng. Archit.* **2016**, *10*, 815–821.
16. Villacreses, G.; Gaona, G.; Martínez-Gómez, J.; Jijón, D.J. Wind farms suitability location using geographical information system (GIS), based on multi-criteria decision making (MCDM) methods: The case of continental Ecuador. *Renew. Energy* **2017**, *109*, 275–286. [CrossRef]
17. Ekmekçioğlu, M.; Kaya, T.; Kahraman, C. Fuzzy multicriteria disposal method and site selection for municipal solid waste. *Waste Manag.* **2010**, *30*, 1729–1736. [CrossRef]
18. Mallick, J. Municipal solid waste landfill site selection based on fuzzy-AHP and geoinformation techniques in Asir region Saudi Arabia. *Sustainability* **2021**, *13*, 1538. [CrossRef]
19. Wichapa, N.; Khokhajaikiat, P. Solving multi-objective facility location problem using the fuzzy analytical hierarchy process and goal programming: A case study on infectious waste disposal centers. *Oper. Res. Perspect.* **2017**, *4*, 39–48. [CrossRef]
20. Hanine, M.; Boutkhoum, O.; Tikniouine, A.; Agouti, T. Comparison of fuzzy AHP and fuzzy TODIM methods for landfill location selection. *SpringerPlus* **2016**, *5*, 1–30. [CrossRef]
21. Wang, C.N.; Tsai, T.T.; Huang, Y.F. A model for optimizing location selection for biomass energy power plants. *Processes* **2019**, *7*, 353. [CrossRef]

22. Zavadskas, E.K.; Turskis, Z.; Antucheviciene, J.; Zakarevicius, A. Optimization of weighted aggregated sum product assessment. *Elektron. Elektrotechnika* **2012**, *122*, 3–6. [CrossRef]
23. Mishra, A.R.; Rani, P. Multi-criteria healthcare waste disposal location selection based on Fermatean fuzzy WASPAS method. *Complex Intell. Syst.* **2021**, *7*, 2469–2484. [CrossRef]
24. Nie, R.X.; Wang, J.Q.; Zhang, H.Y. Solving solar-wind power station location problem using an extended weighted aggregated sum product assessment (WASPAS) technique with interval neutrosophic sets. *Symmetry* **2017**, *9*, 106. [CrossRef]
25. Chakraborty, S.; Zavadskas, E.K.; Antucheviciene, J. Applications of WASPAS method as a multi-criteria decision-making tool. *Econ. Comput. Econ. Cybern. Stud. Res.* **2015**, *49*, 5–22.
26. Turskis, Z.; Zavadskas, E.K.; Antucheviciene, J.; Kosareva, N. A hybrid model based on fuzzy AHP and fuzzy WASPAS for construction site selection. *Int. J. Comput. Commun. Control.* **2015**, *10*, 113. [CrossRef]
27. Baušys, R.; Juodagalvienė, B. Garage location selection for residential house by WASPAS-SVNS method. *J. Civ. Eng. Manag.* **2017**, *23*, 421–429. [CrossRef]
28. Bagočius, V.; Zavadskas, E.K.; Turskis, Z. Multi-person selection of the best wind turbine based on the multi-criteria integrated additive-multiplicative utility function. *J. Civ. Eng. Manag.* **2014**, *20*, 590–599. [CrossRef]
29. Mardani, A.; Saraji, M.K.; Mishra, A.R.; Rani, P. A novel extended approach under hesitant fuzzy sets to design a framework for assessing the key challenges of digital health interventions adoption during the COVID-19 outbreak. *Appl. Soft Comput.* **2020**, *96*, 106613. [CrossRef] [PubMed]
30. Mihajlović, J.; Rajković, P.; Petrović, G.; Ćirić, D. The selection of the logistics distribution center location based on MCDM methodology in southern and eastern region in Serbia. *Oper. Res. Eng. Sci. Theory Appl.* **2019**, *2*, 72–85. [CrossRef]
31. Zadeh, L.A. Fuzzy sets. *Inf. Control* **1965**, *8*, 338–353. [CrossRef]
32. Liou, J.J.H.; Yen, L.; Tzeng, G.H. Building an effective safety management system for airlines. *J. Air Transp. Manag.* **2008**, *14*, 20–26. [CrossRef]
33. Wu, W.W.; Lee, Y.T. Developing global managers' competencies using the fuzzy DEMATEL method. *Expert Syst. Appl.* **2007**, *32*, 499–507. [CrossRef]
34. Hsieh, T.Y.; Lu, S.T.; Tzeng, G.H. Fuzzy MCDM approach for planning and design tenders selection in public office buildings. *Int. J. Proj. Manag.* **2004**, *22*, 573–584. [CrossRef]
35. Gumus, A.T. Evaluation of hazardous waste transportation firms by using a two-step Fuzzy-AHP and TOPSIS methodology. *Expert Syst. Appl.* **2009**, *36*, 4067–4074. [CrossRef]
36. Feyzi, S.; Khanmohammadi, M.; Abedinzadeh, N.; Aalipour, M. Multi-criteria decision analysis FANP based on GIS for siting municipal solid waste incineration power plant in the north of Iran. *Sustain. Cities Soc.* **2019**, *47*, 101513. [CrossRef]
37. Yazdani, M.; Zarate, P.; Zavadskas, E.K.; Turskis, Z. A combined compromise solution (CoCoSo) method for multi-criteria decision-making problems. *Manag. Decis.* **2019**, *57*, 2501–2519. [CrossRef]
38. Biến Rác Thải Thành điện: Cần Có Cơ Chế Thúc đẩy đầu Tư. Available online: https://www.vietnamplus.vn/bien-rac-thai-thanh-dien-can-co-co-che-thuc-day-dau-tu/632126.vnp (accessed on 13 December 2021).
39. Wu, Y.; Chen, K.; Zeng, B.; Yang, M.; Geng, S. Cloud-based decision framework for waste-to-energy plant site selection–A case study from China. *Waste Manag.* **2016**, *48*, 593–603. [CrossRef]
40. Gao, J.; Li, X.; Guo, F.; Huang, X.; Men, H.; Li, M. Site selection decision of waste-To-Energy projects based on an extended cloud-TODIM method from the perspective of low-carbon. *J. Clean. Prod.* **2011**, *303*, 127036. [CrossRef]
41. Tavares, G.; Zsigraiová, Z.; Semiao, V. Multi-criteria GIS-based siting of an incineration plant for municipal solid waste. *Waste Manag.* **2011**, *31*, 1960–1972. [CrossRef]
42. World Bank. *Waste Management in China: Issues and Recommendation. Urban Development Working Papers East Asia Infrastructure Department World Bank*; World Bank: Washington, DC, USA, 2005.