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Solar Energy Implementation in Manufacturing Industry Using Multi-Criteria Decision-Making Fuzzy TOPSIS and S4 Framework

Pedro Ponce [1,*], Citlaly Pérez [1], Aminah Robinson Fayek [2] and Arturo Molina [1,*]

[1] Institute of Advanced Materials for Sustainable Manufacturing, Tecnologico de Monterrey, Monterrey 64849, NL, Mexico
[2] Hole School of Construction Engineering, Department of Civil and Environmental Engineering, University of Alberta, 7-203 Donadeo Innovation Centre for Engineering, 9211 116 St NW, Edmonton, AB T6G 1H9, Canada
* Correspondence: pedro.ponce@tec.mx (P.P.); armolina@tec.mx (A.M.)

Abstract: The demand for electrical energy has increased since the population of and automation in factories have grown. The manufacturing industry has been growing dramatically due to the fast-changing market, so electrical energy for manufacturing processes has increased. As a result, solar energy has been installed to supply electrical energy. Thus, assessing a solar panel company could be a complex task for manufacturing companies that need to assess, install, and operate solar panels when several criteria with different hierarchies from decision-makers are involved. In addition, the stages of a solar panel system could be divided into analysis, installation, operation, and disposal, and all of them must be considered. Thus, the solar panel company must provide a holistic solution for each stage of the solar panel lifespan. This paper provides a fuzzy decision-making approach (Fuzzy TOPSIS) to deal with the assessment of solar companies using the S4 framework in which the sensing, smart, sustainable, and social features are labeled with linguistic values that allow the evaluation of companies using fuzzy values and linguistic labels, instead of using crisp values that are difficult to define when decision-makers are evaluating a solar company for installation of the solar panels. The S4 features are considered the benefits of the evaluation. In the case study presented, three solar panel companies with different alternatives are evaluated on the basis of three decision-makers from manufacturing companies using the S4 framework. This paper considers the benefits of solar companies in the context of decision-makers participating in a multi-decision selection of such a company to install solar panels, so that the selection process is more effective. Thus, the proposed Fuzzy TOPSIS method proved efficient when selecting a solar panel company from among many options that best meets the needs of manufacturing companies.

Keywords: multi-criteria decision-making; fuzzy decision-making; Fuzzy TOPSIS; solar energy; solar panel; S4 framework

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1. Introduction

Global energy demand has been growing exponentially and is expected to increase by 48% in the next 20 years mainly due to the projected growth in the world population and developing countries' economic and industrial growth [1,2]. The role of electrical energy in social and economic development is crucial since it is considered one of the most critical inputs of industrial production and its development [3]. In 2019, industry consumed more than 40% of the electricity produced worldwide, which generated approximately 18% of the global greenhouse gas (GHG) emissions [4,5]. The industry's most common applications for electricity are operating motors and machinery, lighting, computers and office equipment, and heating, cooling, and ventilation [6]. Most industries purchase electricity directly from electric utilities or independent power producers. Nevertheless, due to the recent growth in conventional fuel prices and environmental impacts, companies are starting to produce electricity on-site by installing renewable energy.

Solar energy is abundant, accessible, clean, and does not make any noise or generate any pollution; that is why it is considered to be an excellent promising option to be applied in industries, primarily through the use of photovoltaic (PV) panels to capture solar energy and convert it into electricity [7].

The installation of large-scale and solar distributed generation PV plants has been growing in recent years mainly due to the recent decrease in solar equipment prices, the quick payback, and the long-term savings. However, a lack of information exists regarding the technical and social aspects that a company must consider when making effective decisions on the basis of their needs regarding PV solar energy systems and how to select a solar energy company for installing the solar panels. In addition, assessing a company regarding these decisions could be complex since several criteria with different hierarchies among decision-makers are involved. The solar panel company must provide holistic solutions considering all the stages of the solar panel lifespan.

1.1. Literature Review MCDM/MADM

Multi-criteria decision-making (MCDM) is a decision-making tool that analyzes various available choices to determine the most favorable option, and it is utilized in various areas, such as social sciences, engineering, and medicine, among others [8].

This tool evaluates different alternatives against a set of quantitative/qualitative criteria to formulate a comparison among them by obtaining a ranking result. For improvement of the results obtained, decision-makers can assign weights to the set of criteria, as the level of importance of each criterion varies from one decision-maker to another [9].

MCDM follows the next steps [9]: (1) formulate the problem; (2) identify the requirements; (3) set the goals; (4) identify the alternatives; (5) develop the criteria; and (6) identify and apply the decision-making techniques. The selection of the MCDM technique depends on the problem and the level of complexity of the decision-making process.

MCDM methods can be broadly classified into discrete MADM (multi-attribute decision-making) and continuous MODM (multi-objective decision-making). The first one considers the problems under inherent discrete decision space (the number of alternatives is finite), while the second one is based on mathematical theory and handles the problems under continuous decision space (the number of alternatives is infinite) [9,10].

According to ref. [11], MADM methods are the ones used more often in the renewable energy literature because they are highly effective in obtaining efficient solutions that involve different factors, such as environmental, social, and financial. MADM methods are employed in renewable energy to evaluate energy policies, determine the most suitable energy source, assess energy sources' performances, identify the optimal location of an energy facility, evaluate several energy alternatives under multiple criteria, and select the best energy technology. Table 1 compares the most-used MADM methods in renewable energy.

Table 1. MADM methods used in the renewable energy literature.

Method	Description	Advantages	Disadvantages
Analytic Hierarchy Process (AHP)	It decomposes the decision-making problem into objectives, attributes (or criteria) hierarchies, and alternatives. Decision alternatives are located at the bottom of the hierarchy, whereas the goal is at the top [11,12].	• Easy to use. • Facilitates understanding of the problem. • The human capacity for information processing significantly restrains it. • It can easily adjust to fit many sized problems [13,14].	• Problems due to the interdependence between criteria and alternatives. • It can lead to inconsistencies between judgment and ranking criteria. • Rank reversal problem [13].

Table 1. *Cont.*

Method	Description	Advantages	Disadvantages
Analytic Network Process (ANP)	It is a generic form of AHP that allows for more complex, interdependent relationships, and feedback among elements in the hierarchy. AHP does not consider mutual dependencies among attributes. Therefore, ANP copes with this difficulty [11,15].	• Allows for measurement of the judgments' consistency. • Assists in specifying weights by breaking up the problem into smaller parts [14].	• The network structure among attributes is complex and difficult to understand [14].
Elimination and Choice-Translating Reality (ELECTRE)	It eliminates inferior solutions by constructing a series of weak dominance relations, thereby gradually reducing the number of options so that decision-makers can choose the most suitable alternative [16].	• Considers uncertainty and vagueness. • It can handle quantitative and qualitative data for outranking alternatives [13,17].	• Process and outcome can be difficult to explain. • Outranking may result in not directly identifying the strengths and weaknesses of the alternatives [13].
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	Its basic principle is to choose the alternative that has the shortest Euclidean distance from the positive-ideal solution (PIS) and the farthest distance from the negative-ideal solution (NIS). The positive-ideal solution combines the best attribute values achievable, whereas the negative one combines the worst attribute values [11,18].	• Simple process. • Easy to use and program. • Usable for situations with many alternatives and attributes. • One of the most effective approaches for solving real-world problems. • Appropriate when quantitative or objective data are offered [13,14].	• The Euclidean Distance does not consider the correlation between attributes. • It may be difficult to assign weights and keep the consistency of judgment [13].
Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)	It uses the preference function, criteria, and weights that decision-makers give, and thus, it determines the classification of the scheme through the superior order relationship [16].	• Easy to use. • It offers simplicity, clearness, and stability. • There is no need for the normalization of scores [13,17].	• It is unclear how to assign weights to criteria, as they must be defined separately because weighting techniques are not part of this method [13,17].
Multicriteria Optimization and Compromise Solution (VIKOR)	It determines the compromise ranking list, the compromise solution, and the weight stability intervals for the preference stability of the compromise solution obtained with the initial weights [18]. As the TOPSIS method, VIKOR determines the best alternative according to the PIS and FIS [19].	• One of the most significant approaches to solving real-world problems. • Usable for situations with many alternatives and attributes. • Appropriate when quantitative or objective data are offered [14].	• Lack of provision to weight elicitation and check the consistency judgment [14].

After the analysis made by Ilbahar [11] regarding the MADM methods used in renewable energy, it was concluded that the use of TOPSIS is quite advantageous in renewable energy problems involving various attributes since it has a simple process, and its procedure complexity remain the same regardless of the increase in the number of attributes.

1.1.1. Fuzzy Sets

At times, data evaluation can present ambiguity and uncertainty due to the insufficiency of crisp numbers; thus, some MADM methods can operate with fuzzy sets and work with linguistic labels to evaluate the performance of each alternative [19]. A fuzzy MADM problem consists of two phases. The first phase is to find the fuzzy utility function (fuzzy ratings) for each alternative; the second phase consists of applying the fuzzy ranking method [20].

Using Fuzzy TOPSIS, linguistic variables can easily be converted to fuzzy numbers and used in calculations to choose the best alternative possible. As it has simple and fast calculations, tolerates uncertainty, and handles incomplete and uncertain information, Fuzzy TOPSIS has been widely employed to address energy problems [21].

1.1.2. MCDM Methods in Renewable Energy

Table 2 presents a comparison of this research and others that use MCDM methods in projects related to solar energy.

Table 2. Comparison among this proposal and others related to MCDM methods used in solar energy.

Research Work	Year	Location/Country	MCDM Method Used	Proposal
This proposal	2022	Mexico	Fuzzy TOPSIS	Fuzzy TOPSIS decision-making approach to deal with the assessment of Mexican manufacturing companies selecting a provider for solar photovoltaic systems considering the S4 Framework.
Sarkodie et al. [22]	2022	Ghana	CRITIC, COPRAS, MOORA, TOPSIS	Four MCDM techniques are employed to evaluate five renewable energy sources and to analyze Ghana's most promising renewable energy source.
Aljaghoub et al. [23]	2022	Not specified	TOPSIS	A methodology that compares photovoltaic panel-cleaning techniques and finds the optimal method concerning sustainable development goals.
Villacreses et al. [24]	2022	Ecuador	AHP, ARAS, OCRA, PSI, SMART, Weighted Superposition, TOPSIS, VIKOR	Method to locate appropriate sites for installing photovoltaic solar farms based on the Ecuadorian energy regulation and combining geographic information systems with MCDM techniques.
Bączkiewicz et al. [25]	2021	Not specified	COMET, TOPSIS, SPOTIS	Application of MCDM methods on the example of a multi-criteria solar panel selection problem.
Wang et al. [26]	2018	Vietnam	FAHP, DEA, TOPSIS	MCDM model combines three methodologies to find the best location for building a solar power plant on the basis of both quantitative and qualitative criteria.

As observed in Table 2, TOPSIS is one of the most widely used MCDM methods in solar energy projects. On the other hand, in the available literature, there are no proposals focused on the provider of solar PV systems; some just address the panel selection problem, for example, Bączkiewicz et al. [25], but they do consider neither other elements of the system nor the social and technical aspects.

1.2. Electricity in Mexico

In 2019, in Mexico, the industry sector consumed more than 60% of the electricity produced in the country; from this amount, less than 0.2% came from solar energy [27,28]. In Table 3 (elaboration with information from ref [28]), the electrical energy consumption by industry type can be observed.

Table 3. Electrical energy consumption in the Industrial Sector, Mexico, 2019.

Type of Industry	Consumption (%)
Mining	7.52%
Cement	6.07%
Iron and steel	3.16%
Chemistry	2.41%
Cellulose and paper	2.00%
Cars and trucks	1.66%
PEMEX petrochemical	0.96%
Beer and malt	0.77%
Glass	0.74%
Sugar	0.64%
Non-alcoholic beverages	0.64%
Construction	0.33%
Rubber	0.27%
Fertilizers	0.13%
Tobacco	0.05%
Others	72.65%

On the other hand, the manufacturing and process industry accounted for almost 14% of the country's net CO_2 emissions [29]. CO_2, along with other greenhouse gas (GHG) produced by human activities, such as industrial processes and electricity generation, is considered the main driver of climate change and global warming, which cause severe negative impacts on the environment and, thus, on human health and wellbeing [30].

Over the last several decades, countries around the world have debated how to combat climate change and its negative impacts; this has given rise to commitments to reduce the amount of GHG released into the atmosphere, such as the Kyoto Protocol and the Paris Agreement [31], with the change from fossil fuels to alternative sources of energy as one of the most important commitments made by governments.

Mexico has committed to producing 35% of its electricity from renewable sources by 2025; the possibility of the country reaching this goal is enormous since it has a currently available potential of 11.6 GW for solar energy. Nevertheless, the current installed capacity of this type of energy is only 0.006 GW [32,33].

Ref. [34] proposed an S4 framework whose objective was to guide small- and medium-sized manufacturing companies with regard to the sensing, smart, sustainable, and social features they must consider in all the stages of PV solar systems: diagnosis or analysis, installation, operation, and disposal.

This paper provides a fuzzy decision-making approach to assess solar companies using the S4 framework, labeling each "S" with linguistic values that allow evaluation of the companies using fuzzy values. Using the Fuzzy TOPSIS methodology, this paper considers the S4 features as benefits; it can aid decision-makers from manufacturing companies in evaluating solar panel companies considering the S4 framework to choose the best alternative that meets the manufacturing companies' needs.

This paper is structured as follows: Section 2 presents a short description of the S4 framework for the integration of solar energy systems in manufacturing companies in Mexico; Section 3 explains the Fuzzy TOPSIS method; Section 4 describes the proposed method applying the Fuzzy TOPSIS method in the S4 framework; Section 5 presents the results of a case study of three manufacturing companies using the proposed method to choose a solar panel company; the discussion of results are in Section 6; and finally, Section 7 exposes the conclusions.

2. S4 Framework for the Integration of Solar Energy Systems in Manufacturing Companies in Mexico

The S4 framework considers the stages of evaluation/diagnosis, installation, operation, and disposal of a PV system to choose the sensing, smart, sustainable, and social features needed in each stage, depending on the company's needs.

Figure 1 shows the features that make up each of the S4. As observed, sensors used to measure meteorological, power, or technical variables are found in the sensing category, while the smart category contains features that process relevant data and information for decision-making. The sustainable section includes an environmental impact analysis of the PV system components, from manufacturing to disposal. Finally, the social part is divided into three sections: the first one is the legal and regulatory framework for installing, operating, and disposing of a PV system in Mexico; the second one is the economic pillar, which includes an analysis of the investment and its return, the savings generated by producing the electricity in site, and the available government incentives.

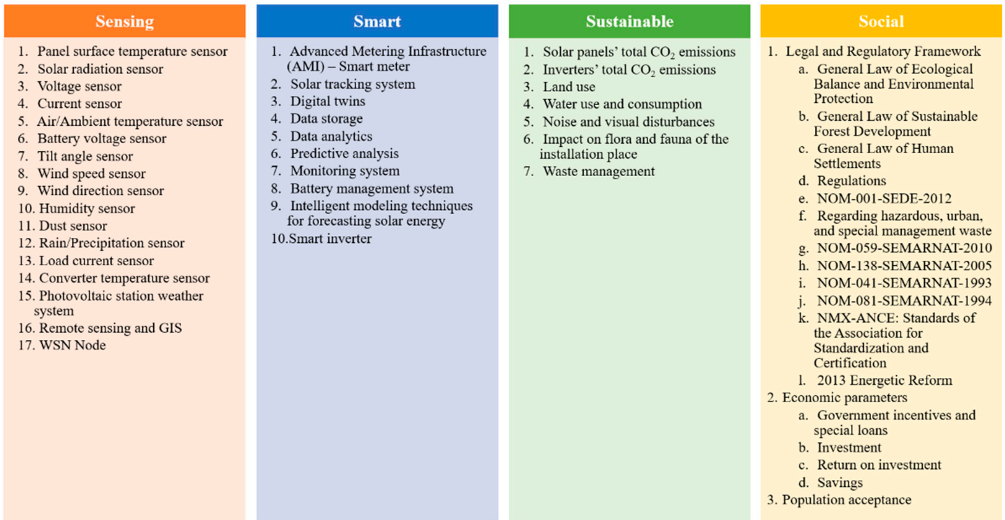

Figure 1. S4 Framework features.

3. Fuzzy TOPSIS Method

Mahdavi et al. (ref. [35]) extended the approach of TOPSIS to develop a methodology for solving MADM problems in fuzzy environments; this paper uses the theory provided by ref. [35] to implement the Fuzzy TOPSIS methodology. In the methodology presented by ref. [35], the linguistic variables are used to assess the weight of each criterion and the rating of each alternative considering each criterion. The decision matrix is converted into a fuzzy decision matrix, and a weighted normalized fuzzy decision matrix is constructed once the decision makers' fuzzy ratings are pooled. The lower bound value of alternatives is designed for detecting the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS). Then, the fuzzy similarity degree of each alternative from FPIS and FNIS is calculated, and a closeness coefficient is defined for each alternative to determine their rankings. The higher value of the closeness coefficient indicates that the alternative is closer to FPIS and farther from FNIS.

Some concepts of fuzzy sets, fuzzy numbers, and linguistic variables are as follows [35]:

Definition 1. *A fuzzy set $\tilde{a}$ in a universe of discourse X is characterized by a membership function $\mu_{\tilde{a}}(x)$ which associates a real number in the interval [0, 1] with each element x in X. The function value $\mu_{\tilde{a}}(x)$ is the grade of membership of x in $\tilde{a}$.*

Definition 2. *A fuzzy number is a fuzzy subset of the universe of discourse X that is both convex and normal. Figure 2 shows a fuzzy number ã in the universe of discourse X that conforms to this definition.*

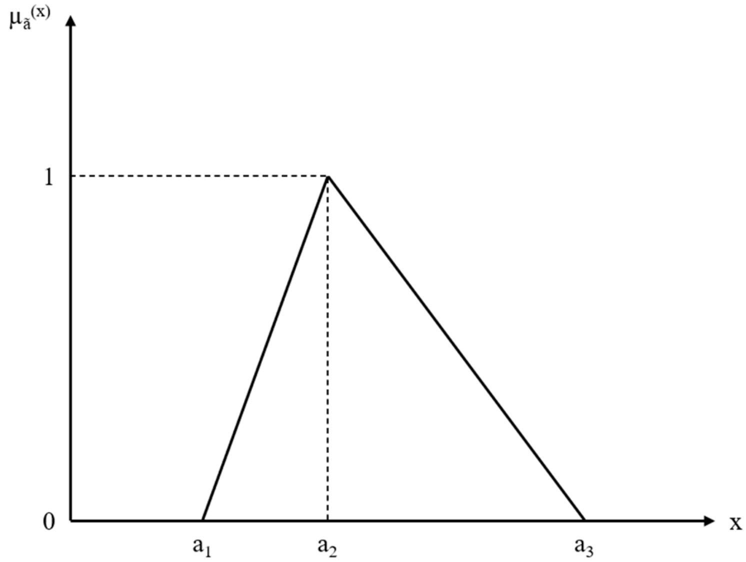

Figure 2. A triangular fuzzy number *ã*.

A triangular fuzzy number $\tilde{a}$ can be defined by a triplet (a_1, a_2, a_3). Its conceptual schema and mathematical form are shown in Equation (1).

$$\mu(x) = \begin{cases} 0, & x \leq a_1, \\ \frac{x-a_1}{a_2-a_1}, & a_1 < x \leq a_2 \\ \frac{a_3-x}{a_3-a_2}, & a_2 < x \leq a_3 \\ 0, & x > a_3 \end{cases}, \tag{1}$$

Definition 3. *If both* $\tilde{a} = (a_1, a_2, a_3)$ *and* $\widetilde{b} = (b_1, b_2, b_3)$ *are real numbers, then the basic operations on fuzzy triangular numbers are as follows:*

$\tilde{a} \times \widetilde{b} = (a_1 \times b_1, a_2 \times b_2, a_3 \times b_3)$ *for multiplication,*

$\tilde{a} + \widetilde{b} = (a_1 + b_1, a_2 + b_2, a_3 + b_3)$ *for addition.*

Definition 4. *A matrix*$\widetilde{D}$ *is called a fuzzy matrix if at least one element in* $\widetilde{D}$ *is a fuzzy number.*

Definition 5. *A linguistic variable is a variable whose values are expressed in linguistic terms, and the concept is handy for describing situations that are too complex or cannot be defined in conventional quantitative expressions. For example, "weight" is a linguistic variable whose values could be very low, low, medium, high, very high, etc.*

Definition 6. *The fuzzy MADM can be expressed in matrix format as follows:*

$$C_1 \quad C_2 \quad C_3 \quad \cdots \quad C_n \widetilde{D} = \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ \vdots \\ A_m \end{array} \begin{bmatrix} \widetilde{x}_{11} & \widetilde{x}_{12} & \widetilde{x}_{13} & \cdots & \widetilde{x}_{1n} \\ \widetilde{x}_{21} & \widetilde{x}_{22} & \widetilde{x}_{23} & \cdots & \widetilde{x}_{2n} \\ \widetilde{x}_{31} & \widetilde{x}_{32} & \widetilde{x}_{33} & \cdots & \widetilde{x}_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \widetilde{x}_{m1} & \widetilde{x}_{m1} & \widetilde{x}_{m3} & \cdots & \widetilde{x}_{mn} \end{bmatrix}, \tag{2}$$

$$\widetilde{W} = [\widetilde{w}_1, \widetilde{w}_2, \cdots, \widetilde{w}_n], \tag{3}$$

where $\widetilde{x}_{ij}$, i = 1, 2, . . . , m, j = 1, 2, . . . , n, and $\widetilde{w}_j$, j = 1, 2, . . . , n are linguistic triangular fuzzy numbers such that $\widetilde{x}_{ij} = (a_{ij},\ b_{ij},\ c_{ij})$ and $\widetilde{w}_j = (w_{j1},\ w_{j2},\ w_{j3})$ Note that $\widetilde{w}_j$ represents the weight of the jth criteria, C_j, and $\widetilde{x}_{ij}$ is the performance rating of the ith alternative, A_i, concerning the jth criteria, C_j, evaluated by k evaluators. In their study, ref. [35] apply the method of average value to integrate the fuzzy performance score $\widetilde{x}_{ij}$ for k evaluators concerning the same evaluation criteria:

$$\widetilde{x}_{ij} = \frac{1}{k}\left(\widetilde{x}_{ij}^1 + \widetilde{x}_{ij}^2 + \cdots + \widetilde{x}_{ij}^k\right), \tag{4}$$

where $\widetilde{x}_{ij}^k$ is the rating of alternative A_i concerning criterion C_j evaluated by k evaluators and $\widetilde{x}_{ij}^k = \left(\widetilde{a}_{ij}^k, \widetilde{b}_{ij}^k, \widetilde{c}_{ij}^k\right)$.

Definition 7. *The normalized fuzzy decision matrix denoted by $\widetilde{R}$ is shown as:*

$$\widetilde{R} = [\widetilde{r}_{ij}]_{m\ \times\ n}, \tag{5}$$

If ($\widetilde{x}_{ij}$, i = 1, 2, . . . , m, j = 1, 2, . . . , n) are triangular fuzzy numbers, then the normalization process can be performed by:

$$\widetilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \qquad i = 1,2,\ldots m,\ j \in B, \tag{6}$$

$$\widetilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \qquad i = 1,2,\ldots m,\ j \in C, \tag{7}$$

where B and C are the set of benefit criteria and cost criteria, respectively, and

$$c_j^* = max\ c_{ij}\ j \in B,$$

$$a_j^- = min\ a_{ij}\ j \in C.$$

The normalized $\widetilde{r}_{ij}$ are still triangular fuzzy numbers. For trapezoidal fuzzy numbers, the normalization process can be conducted similarly. The weighted fuzzy normalized decision matrix is shown as follows:

$$\widetilde{V} = \begin{bmatrix} \widetilde{v}_{11} & \widetilde{v}_{12} & \widetilde{v}_{13} & \cdots & \widetilde{v}_{1n} \\ \widetilde{v}_{21} & \widetilde{v}_{22} & \widetilde{v}_{23} & \cdots & \widetilde{v}_{2n} \\ \widetilde{v}_{31} & \widetilde{v}_{32} & \widetilde{v}_{33} & \cdots & \widetilde{v}_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \widetilde{v}_{m1} & \widetilde{v}_{m1} & \widetilde{v}_{m3} & \cdots & \widetilde{v}_{mn} \end{bmatrix} = \begin{bmatrix} \widetilde{w}_1\widetilde{r}_{11} & \widetilde{w}_2\widetilde{r}_{12} & \cdots & \widetilde{w}_j\widetilde{r}_{1j} & \cdots & \widetilde{w}_n\widetilde{r}_{1n} \\ \widetilde{w}_1\widetilde{r}_{21} & \widetilde{w}_2\widetilde{r}_{22} & \cdots & \widetilde{w}_j\widetilde{r}_{2j} & \cdots & \widetilde{w}_n\widetilde{r}_{2j} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \widetilde{w}_1\widetilde{r}_{i1} & \widetilde{w}_2\widetilde{r}_{i2} & \cdots & \widetilde{w}_j\widetilde{r}_{ij} & \cdots & \widetilde{w}_n\widetilde{r}_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \widetilde{w}_1\widetilde{r}_{m1} & \widetilde{w}_2\widetilde{r}_{m2} & \cdots & \widetilde{w}_j\widetilde{r}_{mj} & \cdots & \widetilde{w}_n\widetilde{r}_{mn} \end{bmatrix} \tag{8}$$

4. Proposed Fuzzy TOPSIS Method for Solar Energy

After the manufacturing company chooses the S4 features that best meet its needs, it is time to analyze the features provided by different solar panel companies and select the most suitable option. In this case, three solar panel companies, C_1, C_2, and C_3, offer different solutions for PV solar systems, and a committee of three decision-makers from the manufacturing companies D_1, D_2, and D_3 will oversee the analysis and selection of the best alternative. The benefit criteria considered are:

(1) Sensing (S_1)
(2) Smart (S_2)

(3) Sustainable (S_3)
(4) Social (S_4)

Following the approach of the Fuzzy TOPSIS method constructed by [35], Figure 3 shows the flow diagram for the proposed method with the S4 features as input and the solar panel company that best meets the manufacturing company's needs as output. The process starts by assigning linguistic variables and fuzzy numbers to weighting the criteria, then the decision-makers evaluate each alternative according to their needs, the calculations are performed, and finally, the alternative that best meets those needs is returned. Below is a detailed description of the process:

STEP 1. Rank each criterion in linguistic variables and assign a triangular fuzzy number from 0–1 ($\widetilde{x}_{ij}$, $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$) (Table 4). For this instance, the $\widetilde{D}$ defined by Equation (2) is equivalent to the $\widetilde{R}$ defined by Equation (5).

STEP 2. Assign linguistic variables ($\widetilde{w}_j,\ j = 1, 2, \ldots, n$) to rank the results of each alternative (Table 5).

STEP 3. Decision-makers assign a weight to each criterion using the linguistic variables from Table 4.

STEP 4. Decision-makers evaluate each alternative according to the criteria and linguistic variables from Table 5.

STEP 5. Convert the evaluations to fuzzy triangular numbers, as defined in Step 1.

STEP 6. Obtain the fuzzy decision matrix by calculating the average score for each criterion for each participant and evaluating each criterion's average weight.

STEP 7. Normalize the fuzzy decision matrix by finding the fuzzy number with which each criterion is maximized (the maximum number) and dividing all the fuzzy numbers of that criterion by that number.

STEP 8. The normalized values are joined with the average of the weight of each criterion by multiplying the normalized values with the weight averages obtained in Step 6.

STEP 9. Determine the FPIS and the FNIS. In this case, the FPIS and the FNIS are the same for all the criteria:

$$A^* = (1.00; 1.00; 1.00)$$

$$A^- = (0.00; 0.00; 0.00)$$

STEP 10. Calculate the Euclidean distance for each candidate concerning the FPIS and FNIS using Equations (9) and (10).

$$D = \sqrt{\frac{1}{3}\left[\sum_{i=1}^{3}(b_i - a_i)^2\right]}, \tag{9}$$

$$D_{A_m} = \sum_{i=1}^{4} D_i, \tag{10}$$

where for triangular fuzzy numbers $\tilde{a}$ = (a_1, a_2, a_3) and $\widetilde{b} = (b_1, b_2, b_3)$, in this case, $\widetilde{b}$ represents values for FPIS and FNIS.

STEP 11. Calculate each alternative's closeness coefficient (CC_i) using Equation (11).

$$CC_i = \frac{D^-_{A_m}}{D^*_{A_m} + D^-_{A_m}}, \tag{11}$$

STEP 12. Rank the three alternatives according to CC_i and choose the best option closer to 1.

STEP 13. Analyze whether the selected option meets the manufacturing company's needs; if it does not, start the process again; if it does, end the process.

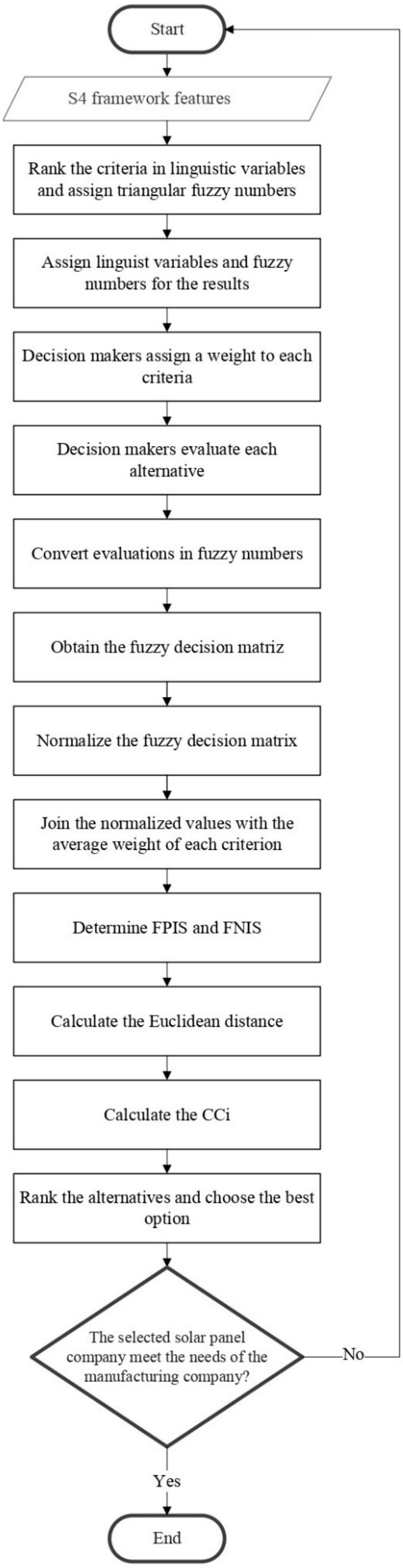

Figure 3. Flowchart for solar energy implementation in the manufacturing industry using the Fuzzy TOPSIS method and the S4 Framework.

Table 4. Linguistic variables for the importance weight of each criterion.

Linguistic Variable	Fuzzy Numbers
Very low (VL)	(0; 0; 0.1)
Low (L)	(0; 0.1; 0.3)
Medium-low (ML)	(0.1; 0.3; 0.5)
Medium (M)	(0.3; 0.5; 0.7)
Medium-high (MH)	(0.5; 0.7; 0.9)
High (H)	(0.7; 0.9; 1.0)
Very high (VH)	(0.9; 1.0; 1.0)

Table 5. Linguistic variables for the ratings.

Category/Benefit Criteria	Linguistic Variable	Fuzzy Numbers
S_1, S_2, S_3, S_4	Very poor (VP)	(0; 0; 1)
	Poor (P)	(0; 1; 3)
	Medium-poor (MP)	(1; 3; 5)
	Fair (F)	(3; 5; 7)
	Medium-good (MG)	(5; 7; 9)
	Good (G)	(7; 9; 10)
	Very good (VG)	(9; 10; 10)

5. Case Study: Mexican Companies

Three Mexican solar panel companies have been analyzed according to the S4 Framework. Table A1 (Appendix A) shows each solar panel company's sensing, smart, sustainable, and social information. Furthermore, three different manufacturing companies participated in the study. The first one is a company that has installed solar panels and does not want to add more solar energy in the short term. The second one has not installed solar panels and wants to install them, and the third one has solar panels installed and wants to install more to increase its solar energy production. They have decided to connect the PV systems to the main electric grid.

The manufacturing companies are located in the central region of Mexico and have an average energy consumption per month of 17,484,982 kWh minimum and 19,425,376 kWh maximum.

With the S4 features chosen and being familiar with the products and services offered by the three solar panel companies, C_1, C_2, and C_3, three decision-makers, D_1, D_2, and D_3, from the manufacturing companies, M_1, M_2, and M_3, respectively, evaluate each of the solar panel companies considering four benefit criteria: sensing (S_1), smart (S_2), sustainable (S_3), and social (S_4).

Table 6 shows the weight assignation to each of the benefit criteria made by the decision-makers from the manufacturing companies using the linguistic variables from Table 4. In Table 7, decision-makers evaluate each alternative according to Table A1 and the criteria and linguistic variables from Table 5.

Table 6. Weight of each criterion by the decision-makers from M_1, M_2, and M_3.

	M_1			M_2			M_3		
Benefit Criterion	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
S_1	MH	L	L	L	H	L	L	L	L
S_2	VH	ML	H	H	ML	VH	H	VH	H
S_3	VH	VH	VH	H	MH	VH	VH	VH	VH
S_4	MH	VH	H	VH	VH	H	VH	VH	VH

Table 7. Evaluation of each alternative by the decision-makers from M_1, M_2, and M_3.

Benefit Criterion	Solar Panel Company	M_1			M_2			M_3		
		D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
S_1	C_1	VG	G	G	F	MG	MG	G	G	G
	C_2	G	F	F	MG	MP	F	F	MG	G
	C_3	G	MG	F	F	F	VP	P	VG	MG
S_2	C_1	MG	MP	MG	MG	G	G	P	G	G
	C_2	F	G	F	MP	MG	MP	MP	G	P
	C_3	G	F	G	MP	P	MG	P	F	VG
S_3	C_1	F	P	P	G	MP	F	F	MG	F
	C_2	MP	F	MP	MP	MP	VP	F	G	MP
	C_3	MG	MG	G	G	MG	MG	MG	F	MP
S_4	C_1	F	F	P	G	G	F	MG	MP	G
	C_2	MG	MG	MP	F	G	MG	MP	MP	VG
	C_3	G	VP	G	F	P	MG	MP	P	VG

6. Results and Discussion

This section presents the implementation results of the proposed method to investigate the case study and, thus, select the best solar panel company for each manufacturing company.

It can be observed in Table 6 that the sustainable and social features are the most important for the decision-makers of the three manufacturing companies, and even though the smart features are considered essential, some decision-makers do not consider it that way. Finally, the sensing features are not considered necessary for most decision-makers.

Table 8 shows the transformation of decision-makers' evaluations (Table 7) to triangular fuzzy numbers according to Table 5.

Table 8. Triangular fuzzy numbers of the evaluations for each manufacturing company.

Benefit Criterion	Solar Panel Company	M_1			M_2			M_3		
		D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
S_1	C_1	(9; 10; 10)	(7; 9; 10)	(7; 9; 10)	(3; 5; 7)	(5; 7; 9)	(5; 7; 9)	(7; 9; 10)	(7; 9; 10)	(7; 9; 10)
	C_2	(7; 9; 10)	(3; 5; 7)	(3; 5; 7)	(5; 7; 9)	(1; 3; 5)	(3; 5; 7)	(3; 5; 7)	(5; 7; 9)	(7; 9; 10)
	C_3	(7; 9; 10)	(5; 7; 9)	(3; 5; 7)	(3; 5; 7)	(3; 5; 7)	(0; 0; 1)	(0; 1; 3)	(9; 10; 10)	(5; 7; 9)
S_2	C_1	(5; 7; 9)	(1; 3; 5)	(5; 7; 9)	(5; 7; 9)	(7; 9; 10)	(7; 9; 10)	(0; 1; 3)	(7; 9; 10)	(7; 9; 10)
	C_2	(3; 5; 7)	(7; 9; 10)	(3; 5; 7)	(1; 3; 5)	(5; 7; 9)	(1; 3; 5)	(1; 3; 5)	(7; 9; 10)	(0; 1; 3)
	C_3	(7; 9; 10)	(3; 5; 7)	(7; 9; 10)	(1; 3; 5)	(0; 1; 3)	(5; 7; 9)	(0; 1; 3)	(3; 5; 7)	(9; 10; 10)
S_3	C_1	(3; 5; 7)	(0; 1; 3)	(0; 1; 3)	(7; 9; 10)	(1; 3; 5)	(3; 5; 7)	(3; 5; 7)	(5; 7; 9)	(3; 5; 7)
	C_2	(1; 3; 5)	(3; 5; 7)	(1; 3; 5)	(1; 3; 5)	(1; 3; 5)	(0; 0; 1)	(3; 5; 7)	(7; 9; 10)	(1; 3; 5)
	C_3	(5; 7; 9)	(5; 7; 9)	(7; 9; 10)	(7; 9; 10)	(5; 7; 9)	(5; 7; 9)	(5; 7; 9)	(3; 5; 7)	(1; 3; 5)
S_4	C_1	(3; 5; 7)	(3; 5; 7)	(0; 1; 3)	(7; 9; 10)	(7; 9; 10)	(3; 5; 7)	(5; 7; 9)	(1; 3; 5)	(7; 9; 10)
	C_2	(5; 7; 9)	(5; 7; 9)	(1; 3; 5)	(3; 5; 7)	(7; 9; 10)	(5; 7; 9)	(1; 3; 5)	(1; 3; 5)	(9; 10; 10)
	C_3	(7; 9; 10)	(0; 0; 1)	(7; 9; 10)	(3; 5; 7)	(0; 1; 3)	(5; 7; 9)	(1; 3; 5)	(0; 1; 3)	(9; 10; 10)

Tables 9–11 illustrate the fuzzy decision matrices and the average weight of each criterion for each manufacturing company.

Table 9. Fuzzy decision matrix for M_1.

Solar Panel Company	S_1	S_2	S_3	S_4
C_1	(7.67; 9.33; 10.00)	(3.67; 5.67; 7.67)	(1.00; 2.33; 4.33)	(2.00; 3.67; 5.67)
C_2	(4.33; 6.33; 8.00)	(4.33; 6.33; 8.00)	(1.67; 3.67; 5.67)	(3.67; 5.67; 7.67)
C_3	(5.00; 7.00; 8.67)	(5.67; 7.67; 9.00)	(5.67; 7.67; 9.33)	(4.67; 6.00; 7.00)
Weight	(0.17; 0.30; 0.50)	(0.57; 0.73; 0.83)	(0.90; 1.00; 1.00)	(0.70; 0.87; 0.97)

Table 10. Fuzzy decision matrix for M_2.

Solar Panel Company	S_1	S_2	S_3	S_4
C_1	(4.33; 6.33; 8.33)	(6.33; 8.33; 9.67)	(3.67; 5.67; 7.33)	(5.67; 7.67; 9.00)
C_2	(3.00; 5.00; 7.00)	(2.33; 4.33; 6.33)	(0.67; 2.00; 3.67)	(5.00; 7.00; 8.67)
C_3	(2.00; 3.33; 5.00)	(2.00; 3.67; 5.67)	(5.67; 7.67; 9.33)	(2.67; 4.33; 6.33)
Weight	(0.23; 0.37; 0.53)	(0.57; 0.73; 0.83)	(0.70; 0.87; 0.97)	(0.83; 0.97; 1.00)

Table 11. Fuzzy decision matrix for M_3.

Solar Panel Company	S_1	S_2	S_3	S_4
C_1	(7.00; 9.00; 10.00)	(4.67; 6.33; 7.67)	(3.67; 5.67; 7.67)	(4.33; 6.33; 8.00)
C_2	(5.00; 7.00; 8.67)	(2.67; 4.33; 6.00)	(3.67; 5.67; 7.33)	(3.67; 5.33; 6.67)
C_3	(4.67; 6.00; 7.33)	(4.00; 5.33; 6.67)	(3.00; 5.00; 7.00)	(3.33; 4.67; 6.00)
Weight	(0.00; 0.10; 0.30)	(0.77; 0.93; 1.00)	(0.9; 1.00; 1.00)	(0.9; 1.00; 1.00)

The fuzzy normalized decision matrices for each manufacturing company are shown in Tables 12–14.

Table 12. Fuzzy normalized decision matrix for M_1.

Solar Panel Company	S_1	S_2	S_3	S_4
C_1	(0.77; 0.93; 1.00)	(0.41; 0.63; 0.85)	(0.11; 0.25; 0.46)	(0.26; 0.48; 0.74)
C_2	(0.43; 0.63; 0.80)	(0.48; 0.70; 0.89)	(0.18; 0.39; 0.61)	(0.48; 0.74; 1.00)
C_3	(0.50; 0.70; 0.87)	(0.63; 0.85; 1.00)	(0.61; 0.82; 1.00)	(0.61; 0.78; 0.91)

Table 13. Fuzzy normalized decision matrix for M_2.

Solar Panel Company	S_1	S_2	S_3	S_4
C_1	(0.52; 0.76; 1.00)	(0.66; 0.86; 1.00)	(0.39; 0.61; 0.79)	(0.63; 0.85; 1.00)
C_2	(0.36; 0.60; 0.84)	(0.24; 0.45; 0.66)	(0.07; 0.21; 0.39)	(0.56; 0.78; 0.96)
C_3	(0.24; 0.40; 0.60)	(0.21; 0.38; 0.59)	(0.61; 0.82; 1.00)	(0.30; 0.48; 0.70)

Table 14. Fuzzy normalized decision matrix for M_3.

Solar Panel Company	S_1	S_2	S_3	S_4
C_1	(0.70; 0.90; 1.00)	(0.61; 0.83; 1.00)	(0.48; 0.74; 1.00)	(0.54; 0.79; 1.00)
C_2	(0.50; 0.70; 0.87)	(0.35; 0.57; 0.78)	(0.48; 0.74; 0.96)	(0.46; 0.67; 0.83)
C_3	(0.47; 0.60; 0.73)	(0.52; 0.70; 0.87)	(0.39; 0.65; 0.91)	(0.42; 0.58; 0.75)

Tables 15–17 show the normalized values joined with the average of the weight of each criterion of Tables 9–11 for each manufacturing company.

Table 15. Fuzzy weighted normalized decision matrix for M_1.

Solar Panel Company	S_1	S_2	S_3	S_4
C_1	(0.13; 0.28; 0.50)	(0.23; 0.46; 0.71)	(0.10; 0.25; 0.46)	(0.18; 0.41; 0.71)
C_2	(0.07; 0.19; 0.40)	(0.27; 0.52; 0.74)	(0.16; 0.39; 0.61)	(0.33; 0.64; 0.97)
C_3	(0.08; 0.21; 0.43)	(0.36; 0.62; 0.83)	(0.55; 0.82; 1.00)	(0.43; 0.68; 0.88)

Table 16. Fuzzy weighted normalized decision matrix for M_2.

Solar Panel Company	S_1	S_2	S_3	S_4
C_1	(0.12; 0.28; 0.53)	(0.37; 0.63; 0.83)	(0.28; 0.53; 0.76)	(0.52; 0.82; 1.00)
C_2	(0.08; 0.22; 0.45)	(0.14; 0.33; 0.55)	(0.05; 0.19; 0.38)	(0.46; 0.75; 0.96)
C_3	(0.06; 0.15; 0.32)	(0.12; 0.28; 0.49)	(0.43; 0.71; 0.97)	(0.25; 0.47; 0.7.0)

Table 17. Fuzzy weighted normalized decision matrix for M_3.

Solar Panel Company	S_1	S_2	S_3	S_4
C_1	(0.00; 0.09; 0.30)	(0.47; 0.77; 1.00)	(0.43; 0.74; 1.00)	(0.49; 0.79; 1.00)
C_2	(0.00; 0.07; 0.26)	(0.27; 0.53; 0.78)	(0.43; 0.74; 0.95)	(0.41; 0.67; 0.83)
C_3	(0.00; 0.06; 0.22)	(0.40; 0.65; 0.87)	(0.35; 0.65; 0.91)	(0.38; 0.58; 0.75)

Table 18 shows the Euclidean distance of each solar panel company concerning the FPIS and FNIS of each manufacturing company. Equations (9) and (10) are used for this evaluation.

Table 18. Euclidean distance of each solar panel company for each manufacturing company.

	M_1		M_2		M_3	
Solar Panel Company	A^*	A^-	A^*	A^-	A^*	A^-
C_1	2.63	1.64	1.95	2.36	1.90	2.51
C_2	2.40	1.93	2.60	1.67	2.18	2.12
C_3	1.88	2.42	2.50	1.80	2.20	2.07

Using Equation (11), the CC_i of each solar panel company is calculated and ranked for each manufacturing company. The results can be observed in Table 19.

Table 19. CC_i of each solar panel company for each manufacturing company.

	M_1		M_2		M_3	
Solar Panel Company	CC_i	Rank	CC_i	Rank	CC_i	Rank
C_1	0.39	3	0.55	1	0.57	1
C_2	0.45	2	0.40	3	0.50	2
C_3	0.56	1	0.42	2	0.48	3

Table 20 shows the main characteristics of the manufacturing companies and the resulting panel company that best meets their needs.

As observed in Table 20, the three manufacturing companies of the case study are located in the central region of Mexico and have an average energy consumption of 17,484,982 kWh minimum and 19,425,376 kWh maximum per month; these technical needs are important for selecting the S4 features and then applying the proposed Fuzzy TOPSIS method. The primary need of each company is essential to better assess that C_1 is the best panel company for M_2 and M_3, while C_3 is the best one for M_1.

C_1 is the solar panel company that best meets the needs of manufacturing companies M_2 and M_3 since they are interested in installing solar panels, and C_1 offers many facilities for installing solar PV systems, as well as technical and economic viability analysis and advice about governmental incentives and financing plans. Furthermore, C_1 offers smart features to facilitate the monitoring of the PV system, as storage and data analysis are available in a cellphone application so that the user can easily access them as well as smart inverters and meters. The information about the CO_2 not released into the atmosphere offered by C_1 is attractive for these two manufacturing companies because, as observed in Table 6, the decision-makers assigned a weight of medium-high to very-high to the benefit criteria of sustainability, which means the companies care about the environmental impact.

Table 20. Main characteristics of the manufacturing companies and their resulting solar panel company.

Manufacturing Company	Location	Energy Consumption	Main Need	Best Solar Panel Company Obtained with the Proposed Method
M_1	The central region of Mexico	Average energy consumption per month of 17,484,982 kWh minimum and 19,425,376 kWh maximum	It has installed solar panels and does not want to add more solar energy.	C_3
M_2			It has not installed solar panels and wants to install them.	C_1
M_3			It has solar panels installed and wants to install more.	C_1

On the other hand, C_3 resulted as the best option for M_1 because, as mentioned before, this company is not interested in installing a PV system since they already have one. However, they are interested in features to improve their system, and C_3 offers features to monitor the system and provides advice about systems interconnected to the network. In addition, the sustainability features are essential for this manufacturing company, and C_3 provides an environmental footprint for the PV system.

These results confirm that decision-making is essential for solar energy deployment and operation. Moreover, selecting the S4 features and implementing this multi-criteria methodology can provide a complete evaluation of the solar energy system according to specific companies' needs. Thus, a correct company selection that can fulfill the needs is achieved.

7. Conclusions and Future Work

In this work, a Fuzzy TOPSIS method is proposed considering the "S4 Framework for the Integration of Solar Energy Systems in Small- and Medium-Sized Manufacturing Companies in Mexico" in order to choose the best solar panel company that suits the technical and social needs of a manufacturing company interested in installing a solar photovoltaic system. Although with the TOPSIS method, it can be difficult to assign weights and keep the consistency of judgment, and the correlation between attributes is not considered, it is one of the most used methods in renewable energy problems, specifically in solar energy problems, since it has a simple process, which makes it easy to use, and can involve various alternatives and attributes at the same time. By adding fuzzy numbers, TOPSIS can tolerate uncertainty and handle incomplete and vague information; additionally, linguistic variables can be added, which facilitates the decision-making process, as they are converted to fuzzy numbers and used in calculations to choose the best alternative possible.

A case study was presented as a result of the proposed method, in which three decision-makers from three manufacturing companies evaluated the products and services offered by three solar panel companies. Thus, the method proposed selected the one that best met the manufacturing companies' needs. After the evaluation, it could be observed that the resulting solar panel company was indeed the best alternative for each manufacturing company. In the case of manufacturing companies M_2 and M_3, C_1 was the panel company as their best option since they are interested in installing solar panels, and C_1 offers many facilities for installing PV systems. Meanwhile, as M_1 already has a PV system and is interested in improving it, C_3 resulted as its best option because it offers features to monitor the system and advice about systems interconnected to the network.

Future work includes the automation of the method by creating a computational program that integrates the S4 Framework and the proposed Fuzzy TOPSIS method, in which the manufacturing companies will add their social and technical needs. Thus, the program could indicate which S4 features are the best and which solar panel company offers those S4 features and could meet their needs.

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Appendix A

Table A1. Solar panel companies' information.

Company	Does the Company Realize Any Type of Diagnosis to Know the Project's Viability, Both Technical and Economical?	Does the Company Use or Offer Some Type of Sensor to Measure Meteorological or Electrical Variables?	Does the Company Use or Offer Solar Tracking Systems?	Does the Company Use or Offer Storage and Data Analysis?	Does the Company Use or Offer a Monitoring System?	Does the Company Use or Offer Smart Inverters?	Does the Company Use or Offer Smart Meters?	Does the Company Use or Offer a Battery Management System?	Does the Company Carry Out Any Type of Environmental Impact Analysis? If So, What Does This Analysis Include?	What Are the Laws and Regulations (Both National and International) That the Company's Products and Services Comply with?	Does the Company Offer Any Kind of Advice So the User Can Obtain Benefits, Incentives, or Government Loans for the Development of the Project?
C_1	Yes, it asks for a picture of the electricity bill and analyzes the last year's consumption. Later, it schedules a visit to review the roof, shades, meter, interconnection point, etc.	No	No	Yes, through a cellphone or computer app.	Yes, through a cellphone or computer app.	Yes, smart micro-inverters.	Yes	No	No, but it can give information about the amount of CO_2 not released into the atmosphere.	The PV, micro-inverters, piping, and wiring comply with all the current regulations.	It offers advice on the tax incentive of the Income Tax Law, as well as financing plans with CIBanco
C_2	Yes, it does a technical survey, which carries out a structural study, a shadow study, projections of the year's four seasons, and determines the best location for the solar panels.	No, but it has a cellphone app with a master monitor in which the requested information appears, and it is monitored 24/7 by the software and technical team.	Yes	Yes	Yes	Yes	Yes	Yes	Only for solar farms in forest regions.	Its products have Tier 1 certifications, and its services are governed by Mexican regulations for installing PV panels and electrical installations.	Yes, it has trained personnel to provide personalized advice, as well as governmental and non-governmental support for the financing of projects.
C_3	Yes, first, it requests the electricity bill, then it sizes the system and coordinates a survey visit to confirm the feasibility.	No	No	No	Yes	No	No	No	Yes, it has sizing software which gives an environmental footprint.	Its solar modules are Tier 1 and comply with standards, such as UL and IEC, and the inverters also comply with UL.	Yes, it advises everything related to a photovoltaic project interconnected to the network.

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