



Research Article

## Sustainability-financial assessment indicators for renewable energy systems using fuzzy SWARA/WASPAS approach

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### ABSTRACT

Renewable energy has a significant share in the world's energy supply today. The need for energy due to growth and development, along with issues such as greenhouse gas emissions, declining fossil reserves and the growing need for energy, have led countries to turn to use renewable energy. As uncertainty is an inseparable part of decision-making process, we assess and prioritize renewable energy technologies using fuzzy multi-criteria decision-making techniques. In this study, sustainability, technical and financial indices are evaluated then four types of renewable systems are ranked, using hybrid Fuzzy Step-wise Weight Assessment Ratio Analysis/ Fuzzy Weighted Aggregated Sum Product Assessment (F-SWARA/F-WASPAS) method. The results show that among the main criteria, the technology criterion with a weight of 0.402 has gained the first rank, the resources criterion with a weight of 0.253 has gained the second rank and the social criterion with a weight of 0.161 has gained the third rank. Among the sub-criteria, system efficiency, capacity factor and material intensity are ranked first to third, respectively. Among the options, solid oxide fuel cells have won first place.

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### INTRODUCTION

Greenhouse gas emissions from the combustion of fossil fuels have many negative effects on the weather, leading to floods, hurricanes, and other natural disasters. This environmental pressure caused by the continuous production of greenhouse gas emissions, affects future energy production. The main sources of these greenhouse gas emissions are non-renewable energies. They are energies whose consumption causes their reserves to decrease, and meanwhile the formation of this type of resources requires

a long time (several hundred thousand years); such as crude oil, gas, coal and all fossil energies [1]. Another option for energy production is renewable energy technologies that use natural energy that can be obtained from the sun, wind, water, ocean (waves, tides, current sea flow and ocean energy thermal system) and geothermal. Renewable energy is any type of energy that can be used without decreasing the reservoirs that supply it. Up to 80% of the energy demand by 2050 could be produced from renewable source [2]. Renewable energies are clean,

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plentiful and reliable, and if they are developed correctly, they can play an important role as sustainable energy sources in achieving the sustainable development goals of countries [3]. It should be known that if the goal is to replace 100% of fossil energy with sustainable energy, it will not be possible in the near future. But if the goal is to save fossil fuel, the existing resources should be used more appropriately. This is completely practical and possible in the current conditions, both in terms of technology and economic [4]. Among of all types of sustainable energies (wind, solar, fuel cells, etc.) sun is not only a great source of energy, but also the beginning of life and the source of all other energies. According to scientific estimates, about 6000 million years of sun's life have passed and every second about 2.4 million tons of the sun's mass is converted into energy. Considering the sun's weight, which is about 333 thousand times the earth's weight, this luminous sphere can be considered as a huge source of energy for the next 5 billion years. The sun is one of the important sources of energy that should be turned to, because it does not require advanced and expensive technologies and can be used as a useful source and supplier of energy in most parts of the world [5]. In this era, solar energy is used and utilized by different systems and for different purposes, which include: 1. Photobiological systems 2. Photochemical systems 3. Photovoltaic systems 4. Thermal and refrigeration systems [6]. Wind is another renewable source of energy that is obtained from the heat of the sun. Approximately 2.5% of the solar energy reaching the earth is converted into wind energy. Wind on the earth is an important factor for the heat exchange, humidity and the transfer of particulate and non-particulate particles from one point to another, which climatically provides human comfort or disturbs it, both in terms of heat and in terms of behavioral comfort [7]. In America, Germany, Holland and Denmark, a significant part of electricity is provided by using large wind power plants. Wind energy has always grown rapidly in energy sources and has a lot of potential. The wind energy cost is very low and the location of wind energy is a pollution-free solution to the energy crisis [8]. Many researches have been working on approaches to prioritize or rank different types of sustainable energy systems based on specific criteria. For instance, [9] developed a sustainability index approach based on technical, economic and environmental criteria to select three energy storage systems (lithium polymer batteries, fuel cells and lead acid batteries) for intermittent and renewable energy sources (solar and wind). They used a new weighting method to determine the sustainability index of energy storage systems. Fuel cell was chosen as the best energy storage option based on the sustainability index presented in this study. Hacetoglu et al. [10] presented an integrated sustainability index for energy systems using multidimensional sustainability criteria. The stability index was determined using normalization, weighting and aggregation of stability indices. This system was applied to autonomous

and hybrid power systems in southern Ontario, Canada. The solar-hydrogen energy system was the best hybrid system compared to the other tested systems according to the sustainability index. Also, the results show that climate change and ozone depletion indicators, reasonable price, commercial viability and land area have the greatest impact on the integrated sustainability index. The results obtained during this study show that the integrated sustainability index has been a useful tool for decision analysis to predict single or combined sustainable energy systems. Papilo et al. [11] developed sustainability indicators for palm oil-based bioenergy. In their study, they used ten indicators for environmental, social and economic factors. The results obtained for the development of bioenergy show that there is a need to balance three aspects and each sustainability index. Dimodke et al. [12] addressed the optimal mapping of hybrid renewable energy systems for locations, using a multi-criteria decision-making algorithm. They carried out an optimal mapping of combined energy systems, based on wind and PV, for households in six locations in the southern geopolitical zone of Nigeria. Optima combined energy systems are capable of providing 7.23 kilowatt hours per day of household energy needs. The combined energy system for each location is optimized based on the calculation of HOMER software and the Technique for Order of Preferences by Similarity to Ideal Solution (TOPSIS) algorithm, which takes into account technical, economic, environmental and socio-cultural criteria. Bauman et al. [13] reviewed Multi Criteria Decision Making (MCDM) methods for evaluating energy storage systems for renewable energy systems. The main objective of this study was to select a suitable and stable EES using the MCDM method for grid-connected renewable power systems. Technical, economic, social and environmental aspects are included in this analysis. Mayer et al. [14] addressed the environmental and economic multi-objective optimization of the combined renewable energy system at the household level by genetic algorithm. This paper aims to fill this gap by presenting a multi-objective design framework for household-scale systems based on technical modeling of several typical components. Solar photovoltaic, wind turbine, solar heat collector, heat pump, heat storage, battery and as a new topic, thermal insulation thickness are considered. They proved that solar photovoltaic is the most competitive technology to reduce the environmental impact of grid-connected systems. However, off-grid systems benefit the most from a balanced mix of different renewable energy sources. Nguyen et al. [15] addressed multi-objective decision making and optimal sizing of a hybrid renewable energy system to meet dynamic energy needs in a wastewater treatment plant. Considering the contemporary economy, system reliability and environmental policies to meet dynamic energy needs in a wastewater treatment plant, this study presents an intelligent management method for optimal measurement and power

management of photovoltaic-wind turbines with hydrogen and battery storage. They presented a multi-objective approach based on fuzzy decision-making method to solve the optimization problem. Osturgard et al. [16] investigated sustainable development using renewable energy systems. This research was conducted with the aim of sustainable development using renewable energy systems with special attention to technology evaluation, pricing and regulation and systems analysis. Also case studies and model development from Austria, Cape Verde, Colombia and Iran are presented with different focal points. Ghenai et al. [17] investigated sustainability indicators for renewable energy systems using multicriteria decision-making model and extended SWARA/ARAS<sup>1</sup> hybrid method. Hashemkhani Zolfani et al. [18] proposed a modified and extended version of the traditional Fuzzy SWARA (F-SWARA) to identify the criteria weights called Improved Fuzzy SWARA (IMF-SWARA), and suggested applying the Fuzzy Multi-Attributive Border Approximation area Comparison (F-MABAC) technique to determine the preference ratings of the alternatives. Alghassab [19] evaluated sustainable renewable energy using Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy TOPSIS (FTOPSIS). Cutore et al. [20] presented an optimization model to orient energy experts and urban planners in the capacity sizing and flow management of Renewable Energy Communities (RECs) under the Italian regulatory framework. Thirumalaivasan et al. [21] employed a life cycle assessment method to assess the system's sustainability, encompassing energy, economic, environmental, and social dimensions. They explored how varying meteorological conditions and geographical locations impact on the system's sustainability. Liu et al. [22] evaluated the sustainability and environmental features of renewable energies. They focused on biogas and biohydrogen (Biofuels) production. Mardani et al. [23] analyzed SWARA and WASPAS methods with recent fuzzy developments. Zheng et al. [24] investigated spherical fuzzy soft rough average aggregation operators and applied it to multi-criteria decision making. Mahmood et al. [25] developed Bonferroni mean operators using bipolar complex fuzzy setting and presented a decision making method. Garg et al. [26] applied an MADM method based on Aczel-Alsina power aggregation operators under bipolar fuzzy information to the quantum computing subject. Mahmood and Rehman [27] investigated the role and impact of AI in the field of healthcare, based on bipolar complex fuzzy Schweizer-Sklar power aggregation operators. Naeem et al. [28] evaluated the sources of renewable energy considering the artificial data in the structure of bipolar complex fuzzy set. Mahmood et al. [29] presented a framework of bipolar complex intuitionistic fuzzy N-Soft sets Using TOPSIS. Adan and Filik [30] proposed a techno-economic assessment of a

standalone and on grid hybrid power system. Yolcu [31] investigated the applications of intuitionistic fuzzy hyper-soft topology to multi-criteria decision-making. Güven and Yörükeren [32] designed an off-grid renewable energy system, consisting solar, wind, battery and diesel components and proposed a model to optimize the designed energy system.

The above literature study shows that renewable energy systems are prioritized by many researches, in many various ways. Actually, there are different types of renewable energies that can be evaluated using any of MCDM methods. To the best of our knowledge, no research has been done to use SWARA/WASPAS approach in the field of evaluating renewable energy system considering five kinds of indicators. The nearest study to this article is written by Ghenai et al. [17]. They ranked four systems consisting solar energy, wind energy, phosphoric acid fuel cells and solid oxide fuel cells in terms of five main criteria using SWARA/ARAS method. We ranked those four alternatives adding three financial subcriteria as financial indicator. Also, we found the fuzzy hybrid SWARA/WASPAS more accurate and used that approach with all decisions made by Iranian experts in terms of existing conditions in Iran. In this article, the sustainability and technical indicators for choosing renewable systems taken from the article [17] as well as financial criteria are evaluated and prioritized by using the decision-making method with multiple criteria considering uncertainty. For this purpose, we use hybrid Fuzzy Step-wise Weight Assessment Ratio Analysis/Weighted Aggregated Sum Product Assessment (F-SWARA/WASPAS) method. The reminder of this paper is as follows: In section 2 problem description is presented. Section 3 consists of hybrid SWARA/WASPAS methodology. In section 4 results and discussion are discussed and finally in section 5 conclusion and future researches are presented.

## PROBLRM DESCRIPTION

In the recent decades, energy planning techniques have changed. Reducing cost has been the main goal of choosing type of energy for using in a regional but recently multiple and even contradictory goals are incorporated. This complex environment highlights the multi-criteria nature of the problem. Therefore, adopting the policy of replacing renewable energies instead of fossil fuels should be done in a multi-criteria environment. Multi-Criteria Decision Making (MCDM) is a suitable approach to deal with complex problems with high uncertainty. Many methods have been developed and proposed to solve these problems. However, there is still the problem of choosing an appropriate method in different decision-making situations. In none of the proposed methods as the best and most appropriate method, all decision situations are considered. In simpler terms, although the use of multi-criteria decision-making

methods depends on the purpose of the research and especially on the accuracy and reliability of the data, the correct selection of each of these methods requires a set of evaluation criteria that must be carefully studied. Therefore, in this research, new results will be presented in the evaluation of sustainability-financial-technical indicators for renewable energy systems. In this study, MCDM will be used under uncertainty to evaluate renewable energy systems against sustainability-financial-technical indicators and their sub-indices. In the first stage, the indicators and sub-indices of sustainability will be weighted using the SWARA method, and then the ranking of renewable energy systems will be done using the WASPAS technique.

## RENEWABLE POWER SYSTEMS

In this section, the evaluated alternatives are introduced which are four types of renewable energy technologies. We consider four common renewable energies as follow [17]:

1. Solar energy systems (S1)
2. Wind energy systems (S2)
3. Phosphoric acid fuel cells (S3)
4. Solid oxide fuel cells (S4)

## SUSTAINABILITY INDICATORS

In this section we use five common sustainability criteria by investigating the literature review mostly from [17]. These indicators include Resource, Environmental, Economic-Financial, Social and Technological. A complete description of fourteen subcriteria can be found in [17]. In this study three financial criteria are added as financial subcriteria of economic-financial indicator. These subcriteria are: Net present value, Internal return rate and Payback period. As a result, mentioned criteria and their seventeen subcriteria are as follow:

- A. Resource Indicator
  - A1. Area Intensity [ $\text{m}^2/\text{kW}$ ]
  - A2. Material Intensity [ $\text{kg}/\text{kW}$ ]
  - A3. Energy Intensity (construction) [ $\text{MJ}/\text{kW}$ ]
  - A4. Energy Intensity (fuel) [ $\text{MJ}/\text{kWh}$ ]
- B. Environmental Indicator
  - B1.  $\text{CO}_2$  Intensity (construction) [ $\text{kg}/\text{kW}$ ]
  - B2.  $\text{CO}_2$  Intensity (fuel) [ $\text{kg}/\text{kWh}$ ]
- C. Economic-Financial Indicator
  - C1. Capital Intensity (construction) [ $\text{US}\$/\text{kW}$ ]
  - C2. Capital Intensity (fuel) [ $\text{US}\$/\text{kWh}$ ]
  - C3. Delivered cost [ $\text{US}\$/\text{kWh}$ ]
  - C4. Net present value
  - C5. Internal return rate
  - C6. Payback period
- D. Social Indicator
  - D1. Current installed capacity [GW]
  - D2. Growth rate [% fraction/year]
- E. Technology Indicator
  - E1. Capacity factor [%]

- E2. System efficiency [%]
- E3. Lifetime [years]

## METHODOLOGY- HYBRID FUZZY SWARA/ WASPAS

After determining the criteria and sub-criteria used in this research, at first, these indicators are weighted using the fuzzy SWARA technique, and the most important indicators are introduced. Then, using the fuzzy WASPAS technique, the mentioned renewable energy systems are ranked.

## SWARA METHOD

The SWARA method is one of the multi-criteria decision-making methods aiming to calculate the weight of criteria and sub-criteria. The SWARA method was introduced by Keršulienė et al. [33]. In this method, criteria are ranked based on their value. The most important criterion is given the first rank and the least important criterion is given the last rank. Finally, the criteria are prioritized based on average values of relative importance. This technique is based on the opinions of experts and is a completely judgemental method. In this method, experts play an important role in determining the weight of criteria [34].

## FUZZY SWARA METHOD

The algorithm of this technique is same as the SWARA method, but it is used in a fuzzy environment. As mentioned earlier, the purpose of the SWARA method is to calculate the weight of the factors, so it is of particular importance. Therefore, by implementing this method in a fuzzy environment, the ambiguities in the experts' responses will be decreased and the results will be more accurate. The steps of the fuzzy SWARA method are given below [35]:

Step 1- Each of the criteria is given a score based on five fuzzy linguistic expressions from the point of view of each decision maker as in Table 1.

Step 2- We sort the research factors according to their importance in descending order based on the average of the previous stage. In fact, the output of this stage is the fuzzy average of the previous stage, which is called  $S_j$  and is calculated based on the following equation:

**Table 1.** Linguistic expressions and fuzzy numbers

Language expressions	Triangular fuzzy numbers
Very low	(0,0,0.25)
Low	(0,0.25,0.5)
Moderate	(0.25,0.5,0.75)
High	(0.5,0.75,1)
Very high	(0.75,1,1)

$$S_j = \left( \sum_i \frac{a_{ij}}{n}, \sum_i \frac{b_{ij}}{n}, \sum_i \frac{c_{ij}}{n} \right) \quad (1)$$

The fuzzy number  $(a_{ij}, b_{ij}, c_{ij})$  is the triangular fuzzy number for language expression of  $i$ th decision maker for  $j$ th criterion.

Step 3- Calculating the coefficient  $K_j$ , assuming  $\tilde{1} = (1,1,1)$ . This coefficient is calculated using equation (2):

$$\tilde{K}_j = \begin{cases} \tilde{1} & j = 1 \\ \tilde{S}_j & j > 1 \end{cases} \quad (2)$$

Step 4- Calculating fuzzy weights ( $q_j$ ). Fuzzy weights are obtained from equation (3):

$$\tilde{q}_j = \begin{cases} \tilde{1} & j = 1 \\ \frac{\tilde{q}_{j-1}}{\tilde{k}_j} & j > 1 \end{cases} \quad (3)$$

Step 5- Calculating relative weights.

$$\tilde{W}_j = \frac{\tilde{q}_j}{\sum_{k=1}^n \tilde{q}_k} \quad (4)$$

The output of this step is relative fuzzy weights ( $w_{jb}, w_{jm}, w_{ju}$ ). To convert these weights into crisp numbers, equation (5) is used.

$$W_{crisp} = \frac{(w_j^m - w_j^l) + (w_j^u - w_j^l)}{3} + w_j^l \quad (5)$$

**WASPAS METHOD**

WASPAS method is one of the new multi-criteria decision-making methods which was introduced by [36]. This method is a combination of two models (weighted sum model) and (weighted multiplication model) and has more accuracy compared to independent methods.

**FUZZY WASPAS METHOD**

Fuzzy WASPAS technique was presented in [37]. The algorithm of this method is almost similar to the WASPAS

method, but it is implemented in a fuzzy environment. Also in this research, verbal expressions and fuzzy numbers listed in Table 2 have been used [38].

The steps of the fuzzy WASPAS method are as follows: First, we form the current situation matrix based on the designed indicators. Then, the de-scaling of the decision matrix is discussed based on the following two equations:

$$\tilde{x}_{ij} = \frac{\tilde{x}_{ij}}{\max_i \tilde{x}_{ij}} \quad \text{for beneficial criteria} \quad (6)$$

$$\tilde{x}_{ij} = \frac{\min_i \tilde{x}_{ij}}{\tilde{x}_{ij}} \quad \text{for non – beneficial criteria} \quad (7)$$

In the WASPAS method, a common criterion from optimization, follows two optimal criteria. The first optimization criterion, that is the weighted average success criterion, is similar to the Weighted Sum Method (WSM) method. It is a popular and acceptable multi-criteria decision-making approach that is used to evaluate considered alternatives regarding to a set of decision-making criteria. Based on the WSM method, the total relative importance of the  $i$ -th alternative is calculated as below:

$$Q_i = \sum_{j=1}^n \tilde{x}_{ij} \tilde{W}_j \quad (8)$$

In this equation,  $W_j$  is the  $j$ -th criterion weight.

On the other hand, according to the Weighted Product Method (WPM) method, the relative value of all alternatives is calculated using the following equation:

$$P_i = \prod_{j=1}^n (\tilde{x}_{ij})^{\tilde{W}_j} \quad (9)$$

In the next step, we defuzzy the value of  $P_i$  and  $Q_i$  using the following equation:

$$Q_i = \frac{1}{3} (Q_{i\alpha}, Q_{i\beta}, Q_{i\gamma}) \quad (10)$$

**Table 2.** Verbal expressions and corresponding fuzzy numbers to rank alternatives [38] [created by author]

no	Priorities	Fuzzy equivalent of priorities		
		Lower limit (L)	Moderate (M)	Upper limit (U)
1	Very low	1	1	3
2	Low	1	3	5
3	Moderate	3	5	7
4	High	5	7	9
5	Very high	7	9	11

$$P_i = \frac{1}{3}(P_{i\alpha}, P_{i\beta}, P_{i\gamma}) \tag{11}$$

Then a general criterion for integrating WSM and WPM would be as follows:

$$K_i = \lambda Q_i + (1 - \lambda)P_i = \lambda \sum_{j=1}^n \bar{x}_{ij}w_j + (1 - \lambda) \prod_{j=1}^n (\bar{x}_{ij})^{w_j} \tag{12}$$

If  $\lambda=0$ , the WASPAS model will become the WPM model; If  $\lambda=1$ , the WASPAS model becomes the WSM model. For deciding the optimal value,  $\lambda$  is calculated from the following equation [36]:

$$\lambda = \frac{\sum_{i=1}^m P_i}{\sum_{i=1}^m P_i + \sum_{i=1}^m Q_i} \tag{13}$$

### RESULTS AND DISCUSSION

In this part, the research data is analyzed. The aim of this research is to rank renewable systems based on sustainability, technical and financial indicators. To achieve this goal, first the factors are extracted from the literature review, then using the fuzzy SWARA weighting method all criteria and subcriteria are weighted and finally the alternatives of the research are ranked using the fuzzy WASPAS method. Based on the review of the literature and research

background, 17 indicators of sustainability-financial-technical, affecting renewable systems are identified and extracted in five main dimensions. Using five Likert scale (1 = very little importance, 2 = little importance, 3 = moderate importance, 4 = high importance, 5 = very high importance), we asked 20 experts in this area to give appropriate score to each index, considering the geographical, environmental and financial conditions in Iran. Preliminary results from the experts' comments are given in Table 3.

Table 3 shows the number of experts' opinions on research indicators. To fuzzify the numbers, we first convert them into a fuzzy number based on the spectrum in Table 1, then based on the the fuzzy average is obtained from the scores, and then the fuzzy average is converted into a crisp number by equation (5). The results of all fuzzification calculations are given in Table 4. For example, the criterion of row 1 of fuzzy score calculations are as follows:

0 people gave very low points, 1 person gave low points, 10 people gave average points, 0 people gave high points and 9 people gave very high points. Therefore, the fuzzy and non-fuzzy score is as follows:

$$Score_{Fuzzy} = \frac{0*(0,0,0,25)+1*(0,0,25,0,5)+10*(0,25,0,5,0,75)+0*(0,5,0,75,1)+9*(0,75,1,1)}{20} = (0.273,0.505,0.738)$$

$$Score_{Crisp} = \frac{0.463+0.713+0.85}{3} = 0.675$$

**Table 3.** The results of experts' opinions

Criteria	Sub-criteria code	Sub-criteria	Importance level				
			Very Low	Low	Moderate	High	Very high
<b>Resource</b>	A1	Area intensity	0	1	10	0	9
	A2	Material intensity	0	2	4	7	7
	A3	Energy intensity (construction)	3	1	11	0	5
	A4	Energy intensity (fuel)	4	5	0	2	9
<b>Environmental</b>	B1	CO <sub>2</sub> intensity (construction)	7	1	4	0	8
	B2	CO <sub>2</sub> intensity (fuel)	3	5	4	0	8
<b>Economic-Financial</b>	C1	Capital intensity (construction)	6	3	6	0	5
	C2	Capital intensity (fuel)	2	2	4	3	9
	C3	Delivered cost	7	2	2	3	6
	C4	Net present value	9	5	0	0	6
	C5	Internal return rate	4	1	1	7	7
	C6	Payback period	7	2	0	0	11
<b>Social</b>	D1	Current installed capacity	3	2	1	0	14
	D2	Growth rate	6	3	1	4	6
<b>Technology</b>	E1	Capacity factor	4	0	0	8	8
	E2	System efficiency	0	2	0	4	14
	E3	Lifetime	0	6	6	1	7

**Table 4.** Fuzzy score results

Criteria	Sub-criteria code	Sub-criteria	Fuzzy average	Non-fuzzy average
<b>Resource</b>	A1	Area intensity	(0.463,0.713,0.85)	0.675
	A2	Material intensity	(0.488,0.738,0.9)	0.708
	A3	Energy intensity(construction)	(0.325,0.538,0.725)	0.529
	A4	Energy intensity(fuel)	(0.388,0.588,0.725)	0.567
<b>Environmental</b>	B1	CO <sub>2</sub> intensity (construction)	(0.35,0.513,0.663)	0.508
	B2	CO <sub>2</sub> intensity (fuel)	(0.35,0.563,0.713)	0.542
<b>Economic-Financial</b>	C1	Capital intensity(construction)	(0.263,0.438,0.625)	0.442
	C2	Capital intensity(fuel)	(0.463,0.688,0.825)	0.658
	C3	Delivered cost	(0.325,0.488,0.663)	0.492
	C4	Net present value	(0.225,0.363,0.538)	0.375
	C5	Internal return rate	(0.45,0.65,0.813)	0.638
	C6	Payback period	(0.413,0.575,0.688)	0.558
<b>Social</b>	D1	Current installed capacity	(0.538,0.75,0.825)	0.704
	D2	Growth rate	(0.338,0.513,0.688)	0.513
<b>Technology</b>	E1	Capacity factor	(0.5,0.7,0.85)	0.683
	E2	System efficiency	(0.625,0.875,0.95)	0.817
	E3	Lifetime	(0.363,0.613,0.775)	0.583

**FUZZY SWARA METHOD RESULTS**

In this section, the weight and importance of indicators are determined using the SWARA method. The Fuzzy SWARA method is implemented separately on the sub-criteria of each main criterion, which is given below.

$$K_{A1} = (1,1,1) + S_{A1} = (1.463,1.713,1.85)$$

$$q_{Q3} = \frac{q_{j-1}}{K_j} = \frac{q_{A2}}{K_{A1}} = \frac{(1,1,1)}{(1.463,1.713,1.85)} = (0.541,0.584,0.684)$$

$$W_{Q3} = \frac{q_j}{\sum q_j} = \frac{q_{A1}}{\sum q_j} = \frac{(0.541,0.584,0.684)}{(2.036,2.191,2.548)} = (0.212,0.267,0.336)$$

**FUZZY SWARA RESULTS OF “RESOURCES” SUB-CRITERIA**

The first step in this method is to sort the indicators according to their importance in descending order (from high to low), using the average scores given in table 4. This process is carried out as shown in table 5. In this section the fuzzy average is the same as  $S_j$ .

In the next step, using equations (2) to (4), we calculate the weight of the criteria based on the opinions of each expert. The results are shown in Table 6 and Fig. 1. The  $W_j$  column shows the weight of the criteria. For example, for the “area intensity” criterion, it is calculated as follows:

Also, to defuzzify  $W$  based on equation (5), we have:

$$W_{crisp} = \frac{(w_j^m - w_j^l) + (w_j^u - w_j^l)}{3} + W_j^l = \frac{(0.267 - 0.212) + (0.336 - 0.212)}{3} + 0.212 = 0.272$$

According to Table 6, the material intensity with a weight of 0.439 has won the first rank. The area intensity with a weight of 0.267 has obtained the second place and the energy intensity (fuel) with a weight of 0.175 has achieved the third place. Figure 1 shows the priority of other sub-criteria.

**Table 5.** Descending order of resource indices

Sub-criteria code	Sub-criteria	Fuzzy average
A2	Material intensity	(0.488, 0.738, 0.9)
A1	Area intensity	(0.463, 0.713, 0.85)
A4	Energy intensity(fuel)	(0.388, 0.588, 0.725)
A3	Energy intensity(Construction)	(0.325, 0.538, 0.725)

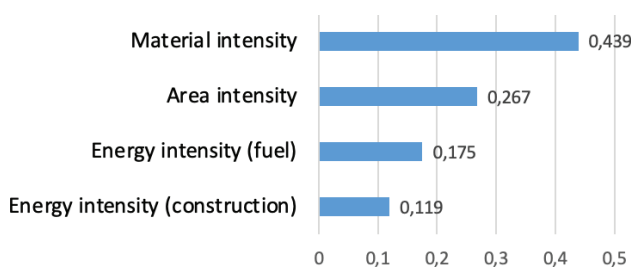
**Table 6.** The weights of resource sub-criteria

Sub-criteria code	Sub-criteria	$S_j$	$K_j$	$Q_j$	Fuzzy $W_j$	Non-fuzzy weight	Normal non-fuzzy weight
A2	Material intensity	-	(1,1,1)	(1,1,1)	(0.392, 0.456, 0.491)	0.447	0.439
A1	Area intensity	(0.463, 0.713, 0.85)	(1.463, 1.713, 1.85)	(0.541, 0.584, 0.684)	(0.212, 0.267, 0.336)	0.272	0.267
A4	Energy intensity(fuel)	(0.388,0.588,0.725)	(1.388,1.588,1.725)	(0.313,0.368,0.493)	(0.123,0.168,0.242)	0.178	0.175
A3	Energy intensity (construction)	(0.325,0.538,0.725)	(1.325,1.538,1.725)	(0.182,0.239,0.372)	(0.071,0.109,0.183)	0.121	0.119

**FUZZY SWARA RESULTS OF “ENVIRONMENTAL” SUB-CRITERIA**

In a similar way, calculations were made for the environmental sub-criteria which are given in Table 7 and Fig. 2.

According to Table 7, among the environmental sub-criteria, CO<sub>2</sub> intensity (fuel) with a weight of 0.599 is ranked first and CO<sub>2</sub> intensity (construction) with a weight of 0.401 is ranked second.

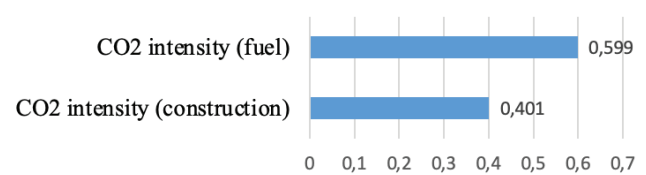


**Figure 1.** Weights of resource sub-criteria.

**FUZZY SWARA RESULTS OF “ECONOMIC-FINANCIAL” SUB-CRITERIA**

In a similar way, calculations were made for the economic sub-criteria which are given in Table 8 and Fig. 3.

According to Table 8, among the economic-financial sub-criteria, the capital intensity (fuel) with a weight of 0.374 has gained the first rank. The Internal return rate with a weight of 0.233 has been second and the Payback period with a weight of 0.152 has got the third place.



**Figure 2.** Final weights of environmental sub-criteria.

**Table 7.** Weights of environmental sub-criteria

Sub-criteria code	Sub-criteria	$S_j$	$K_j$	$Q_j$	Fuzzy $W_j$	Non-fuzzy weight	Normal non-fuzzy weight
B2	CO <sub>2</sub> intensity (fuel)	-	(1,1,1)	(1,1,1)	(0.574,0.602,0.624)	0.600	0.599
B1	CO <sub>2</sub> intensity (construction)	(0.35,0.513,0.663)	(1.35,1.513,1.663)	(0.602,0.661,0.741)	(0.346,0.398,0.463)	0.402	0.401

**Table 8.** Economic-financial sub-criteria weights

Sub- criteria code	Sub- criteria	$S_j$	$K_j$	$Q_j$	$W_j$ Fuzzy	Non-fuzzy weight	Normal non-fuzzy weight
C2	Capital intensity (fuel)	-	(1,1,1)	(1,1,1)	(0.325,0.39,0.44)	0.385	0.374
C5	Internal return rate	(0.45,0.65,0.813)	(1.45,1.65,1.813)	(0.552,0.606,0.69)	(0.179,0.237,0.303)	0.240	0.233
C6	Payback period	(0.413,0.575,0.688)	(1.413,1.575,1.688)	(0.327,0.385,0.488)	(0.106,0.15,0.215)	0.157	0.152
C3	Delivered cost	-	(1.325,1.488,1.663)	(0.197,0.259,0.368)	(0.064,0.101,0.162)	0.109	0.106
C1	Capital intensity (construction)	(0.263,0.438,0.625)	(1.263,1.438,1.625)	(0.121,0.18,0.292)	(0.039,0.07,0.128)	0.079	0.077
C4	Net present value	(0.225,0.363,0.538)	(1.225,1.363,1.538)	(0.079,0.132,0.238)	(0.026,0.052,0.105)	0.061	0.059

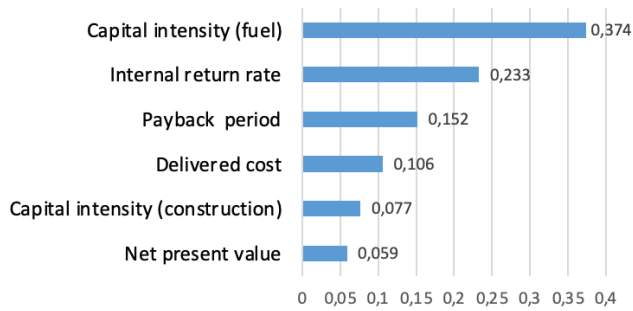


Figure 3. Final weights of economic-financial sub-criteria.

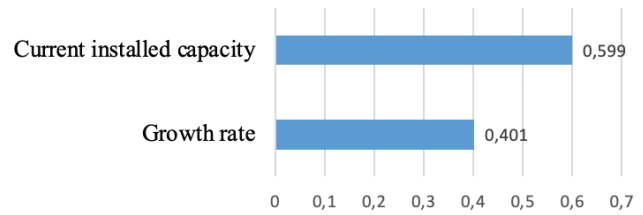


Figure 4. Weights of social sub-criteria.

Table 9. The weights of social sub-criteria

Sub-criteria code	Sub-criteria	$S_j$	$K_j$	$Q_j$	$W_j$ , Fuzzy	Non-fuzzy weight	Normal non-fuzzy weight
D1	Current installed capacity		(1,1,1)	(1,1,1)	(0.572,0.602,0.628)	0.601	0.599
D2	Growth rate	(0.338,0.513,0.688)	(1.338,1.513,1.688)	(0.593,0.661,0.748)	(0.339,0.398,0.469)	0.402	0.401

**FUZZY SWARA RESULTS OF “SOCIAL” SUB-CRITERIA**

In a similar way, calculations were made for the social sub-criteria which are given in Table 9 and Fig. 4.

According to Table 9, among the social sub-criteria, the current installed capacity with a weight of 0.599 is ranked first and the growth rate with a weight of 0.499 has been ranked second.

**FUZZY SWARA RESULTS OF “TECHNOLOGY” SUB-CRITERIA**

In a similar way, calculations were made for technology sub-criteria which are given in Table 10 and Fig. 5.

According to Table 10, among technology sub-criteria, system efficiency with a weight of 0.502 has been ranked first. The capacity factor with a weight of 0.302 has won the second place and the lifetime with a weight of 0.196 has won the third place.

**MAIN CRITERIA WEIGHTS**

To calculate the weight of the main criteria, first, the Likert scores of the sub-criteria of each criterion are averaged to determine the score of the main criterion, then the criteria are sorted in descending order based on the average scores in Table 4, and then in a similar way, with the SWARA algorithm the weight of the criteria is calculated. The results are shown in Table 11 and Fig. 6. Accordingly, the technology criterion with a weight of 0.402 has gained

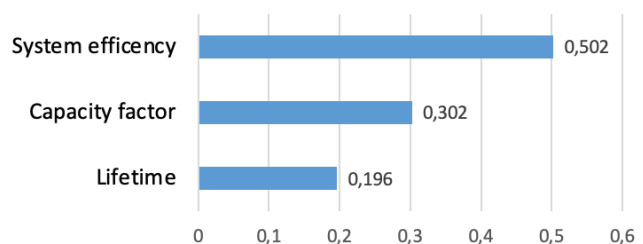


Figure 5. Weights of technology sub-criteria.

**Table 10.** The weights of technology sub-criteria

Sub-criteria code	Sub-criteria	$S_j$	$K_j$	$Q_j$	$W_j$ Fuzzy	Non-fuzzy weight	Normal non-fuzzy weight
E2	System efficiency		(1,1,1)	(1,1,1)	(0.464,0.512,0.542)	0.506	0.502
E1	Capacity factor	(0.5,0.7,0.85)	(1.5,1.7,1.85)	(0.541,0.588,0.667)	(0.251,0.301,0.361)	0.304	0.302
E3	Lifetime	(0.363,0.613,0.775)	(1.363,1.613,1.775)	(0.305,0.365,0.489)	(0.141,0.187,0.265)	0.198	0.196

the first rank, the resource criterion with a weight of 0.253 has earned the second rank, and the social criterion with a weight of 0.161 has earned the third rank.

**FINAL WEIGHTS OF SUB-CRITERIA**

The final weights of the sub-criteria is obtained by multiplying the the main criteria weight by the relative weight of the sub-criteria calculated in the previous step, which is given in Table 12.

**RESULTS OF FUZZY WASPAS METHOD**

In this section, 4 types of energy are used to rank research alternatives. These 4 types of energy are: Solar energy systems (S1), Wind energy systems (S2), Phosphoric acid fuel cells (S3) and Solid oxide fuel cells (S4).

**First step: establishing the decision matrix**

In this step, we form the decision matrix of opinions. The decision matrix of the WASPAS method is a matrix consisting of criteria (sub-criteria) and research alternatives. This decision matrix is completed by 20 experts and then it is integrated by arithmetic mean method. The fuzzy feedback decision matrix is given in Table 13. In this matrix, there are 17 research sub-criteria in the column and 4 alternatives in the row.

**Second step: normalization of the decision matrix**

In the second step, we normalize the decision matrix based on equations (6) and (7). For example, for cell A11, which is the intersection of criterion A1 and alternative S1, normalization is done as follows. First, the fuzzy numbers of the criterion column S1 should be divided by the maximum of the upper limits of the fuzzy numbers of the criterion column A1. The maximum value is equal to 7.9. For example, for the first level, the calculations are as follows:

$$A_{11}^{Normal} = \frac{(4.1,5.9,7.9)}{7.9} = (0.519,0.747,1)$$

Calculations are done in a similar way for other cells, which are given in Table 14.

**Third step: determining the weighted sum and weighted multiplication values**

In the third step, using equations (8) and (9), we calculate the values of WSM (weighted sum) (Q) and WPS model (weighted product) (P). And then, we defuzzify these values using equations (10) and (11), which is given in table 15.

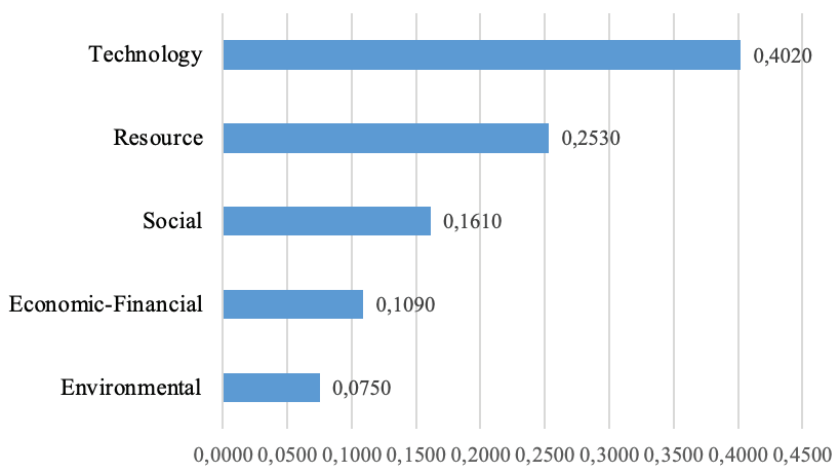
**Fourth step: determining the final score and ranking the options**

In the fourth step, the score of each attribute is calculated using equation (10), but before that, the value of  $\lambda$  is calculated based on equation (2), which is given in table 16 and Fig. 17.

$$\lambda = \frac{\sum_{i=1}^m P_i}{\sum_{i=1}^m P_i + \sum_{i=1}^m Q_i} = \frac{2.61}{2.61 + 2.634} = 0.498$$

**Table 11.** The weights of the main criteria

Code	Main criteria	$S_j$	$K_j$	$Q_j$	$W_j$ , Fuzzy	Normal non-fuzzy weight	Non-fuzzy weight
E	Technology	-	(1,1,1)	(1,1,1)	(0.354,0.42,0.461)	0.402	0.411
A	Resource	(0.416,0.644,0.8)	(1.416,1.644,1.8)	(0.556,0.608,0.706)	(0.196,0.255,0.326)	0.253	0.259
D	Social	(0.438,0.631,0.756)	(1.438,1.631,1.756)	(0.316,0.373,0.491)	(0.112,0.157,0.226)	0.161	0.165
C	Economic-Financial	(0.356,0.533,0.692)	(1.356,1.533,1.692)	(0.187,0.243,0.362)	(0.066,0.102,0.167)	0.109	0.112
B	Environmental	(0.35,0.538,0.688)	(1.35,1.538,1.688)	(0.111,0.158,0.268)	(0.039,0.066,0.124)	0.075	0.076



**Figure 6.** The main criteria weights.

**Table 12.** Weights and final ranking of sub-criteria

Criteria	Criteria weight	Sub-criteria	Relative weight	Final weight	Final rank
<b>Resource</b>	0.253	Area intensity	0.267	0.0676	6
		Material intensity	0.439	0.1112	3
		Energy intensity (construction)	0.119	0.0301	11
		Energy intensity (fuel)	0.175	0.0442	9
<b>Environmental</b>	0.075	CO <sub>2</sub> intensity (construction)	0.401	0.299	12
		CO <sub>2</sub> intensity (fuel)	0.599	0.0447	8
<b>Economic-Financial</b>	0.109	Capital intensity (construction)	0.077	0.0084	16
		Capital intensity (fuel)	0.374	0.0408	10
		Delivered cost	0.106	0.0115	15
		Net present value	0.059	0.0064	17
		Internal return rate	0.233	0.0254	13
		Payback period	0.152	0.0166	14
<b>Social</b>	0.161	Current installed capacity	0.599	0.096	4
		Growth rate	0.401	0.0646	7
<b>Technology</b>	0.402	Capacity factor	0.302	0.1214	2
		System efficiency	0.502	0.2017	1
		Lifetime	0.196	0.0788	5

**Table 13.** Fuzzy WASPAS decision matrice

	A1	A2	A3	...	E1	E2	E3
S1	(4.1,5.9,7.9)	(2.6,4.3,6.3)	(3.4,4.6,4)	...	(3.2,5.1,7.1)	(4.2,6,8)	(3.2,4.7,6.7)
S2	(3.9,5.6,7.6)	(3.3,5,7)	(3.1,4.6,6.6)	...	(3.2,4.9,6.9)	(2.4,3.8,5.8)	(3.4,4.8,6.8)
S3	(3.1,4.5,6.5)	(3.5,5.1,7.1)	(4.5,7,7.7)	...	(3.4,5,6.5)	(2,3.7,5.7)	(3.5,5.2,7.2)
S4	(4,5,6,7.6)	(3.8,5.5,7.5)	(4.7,6.4,8.4)	...	(2.7,4.1,6.1)	(3.2,4.8,6.8)	(3.1,4.4,6.4)

**Table 14.** Fuzzy WASPAS normal matrice

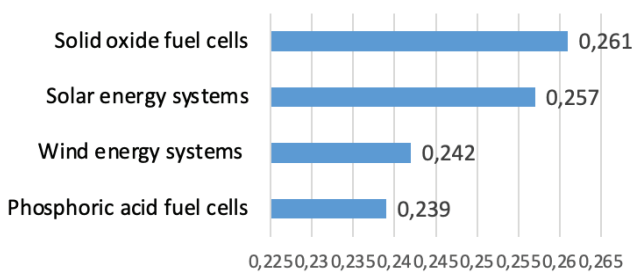
	A1	A2	A3	...	E1	E2	E3
S1	(0.519,0.747,1)	(0.347,0.573,0.84)	(0.357,0.524,0.762)	...	(0.451,0.718,1)	(0.525,0.75,1)	(0.444,0.653,0.931)
S2	(0.494,0.709,0.962)	(0.44,0.667,0.933)	(0.369,0.548,0.786)	...	(0.451,0.69,0.972)	(0.3,0.475,0.725)	(0.472,0.667,0.944)
S3	(0.392,0.57,0.823)	(0.467,0.68,0.947)	(0.476,0.679,0.917)	...	(0.423,0.634,0.915)	(0.25,0.463,0.713)	(0.486,0.722,1)
S4	(0.506,0.709,0.962)	(0.507,0.733,1)	(0.56,0.762,1)	...	(0.38,0.577,0.859)	(0.4,0.6,0.85)	(0.431,0.611,0.889)

**Table 15.** WSM and WPM values

	Q (fuzzy)	P (fuzzy)	Q (crisp)	P (crisp)
A1	(0.443,0.662,0.929)	(0.436,0.655,0.924)	0.678	0.672
A2	(0.416,0.617,0.883)	(0.409,0.61,0.878)	0.639	0.633
A3	(0.403,0.613,0.88)	(0.392,0.606,0.874)	0.632	0.624
A4	(0.457,0.666,0.933)	(0.453,0.663,0.93)	0.685	0.682

**Table 16.** Scores of attributes and their ranking

Code	Alternatives	K	k Normal	Rank
A1	Phosphoric acid fuel cells	0.675	0.257	2
A2	Wind energy systems	0.636	0.242	3
A3	Solar energy systems	0.628	0.239	4
A4	Solid oxide fuel cells	0.684	0.261	1



**Figure 7.** Weights and final ranking of alternatives.

As a result, the solid oxide fuel cells ranked as the first attribute in the sustainability evaluation among the selected green power generation systems. This is followed by solar energy systems, the land-based wind energy systems and phosphoric acid fuel, as follows:

1. Solid oxide fuel cells.
2. Solar energy systems [poly-silicon]
3. Wind energy systems [Land-based].
4. Phosphoric acid fuel cells.

In this study, the hybrid Fuzzy SWARA/WASPAS method is done for sustainability-financial evaluation of renewable energy systems in order to help sustainable energy development. Solid oxides fuel cells (SOFCs) running with natural gas or propane as fuel are the most efficient fuel cells for electricity generation with low emissions [17]. As natural gas is one of natural resources in Iran, it completely makes sense that our experts and decision makers ranked it over other indicators. So, it has gained the first rank, whereas in [17] it ranked as the second attribute, using SWARA/ARAS method without considering three financial subcriteria. Also, solar energy systems have no greenhouse gas emissions during operation and construction, so their contribution to global warming is negligible. Solar energy that is always available in some regions in Iran has gained the second rank in contrast with the last place in [17].

## CONCLUSION

In this study, we have investigated four types of renewable energy systems considering five main sustainability-financial-technical indicators and their seventeen sub-criteria. The evaluated technologies consisting land-based wind energy systems, solid oxide fuel cells, phosphoric acid fuel cells, and poly-silicon solar energy systems are considered as alternatives. The five sustainability indicators were resource, environmental, economic-financial, social and technological. Also, their seventeen subcategories were: area, material, energy-construction, energy-fuel, CO<sub>2</sub> construction, CO<sub>2</sub>-fuel, capital-construction, capital-fuel, delivered cost of energy, current installed capacity, growth rate, capacity factor, net present value, Internal return rate, payback period, system efficiency, and lifetime.

To assess the importance of these criteria and their subcriteria considering vagueness of the data we used the Fuzzy Step-wise Weight Assessment Ratio Analysis (F-SWARA) method consulting twenty energy experts according to the current state of environment, economy and society in Iran. Then after finding all weights, we used Fuzzy Weighted Aggregated Sum Product Assessment (F-WASPAS) to prioritize the alternatives. The final results of the study showed that the most to the least preferable renewable energy system are: system efficiency, capacity factor, material intensity, current installed capacity, lifetime, area intensity, growth rate, CO<sub>2</sub> intensity-fuel, energy intensity-fuel, capital intensity-fuel, energy intensity-construction, CO<sub>2</sub> intensity-construction, internal efficiency rate, payback period, delivered cost of energy, capital intensity-construction and net present value. The ranking of the different renewable energy systems showed that solid oxide fuel cells are ranked first with respect to sustainability indicators and their sub-indicators, followed by solar energy systems, then wind energy systems, and lastly phosphoric acid fuel cells. The limitations of this study can be manifested through the small number of considered renewable energy systems, as there are many other technologies to investigate and prioritize. Also, in real world situations various criteria and subcriteria are involved in making decisions, depending on the region. It is suggested that in the future studies, the uncertainty of the data should be entered into the model in gray form and its effect on the criteria and sub-criteria should be investigated. Also, other multi-indicator decision making models can be used to compare the results with the proposed model. Finally, more criteria and sub-criteria can be used in future researches.

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

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