Fuzzy multi-criteria decision making for carbon dioxide geological storage in Turkey

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ABSTRACT

The problem of choosing the best location for CO_2 storage is a crucial and challenging multi-criteria decision problem for some companies. This study compares the performance of three fuzzy-based multi-criteria decision making (MCDM) methods, including Fuzzy TOPSIS, Fuzzy ELECTRE I and Fuzzy VIKOR for solving the carbon dioxide geological storage location selection problem in Turkey. The results show that MCDM approach is a useful tool for decision makers in the selection of potential sites for CO_2 geological storage.

1. Introduction

According to the IEA World Energy Outlook (WEO) Reference Scenario, CO_2 emission will increase 63% by 2030 from today's level, which is 90% higher than the 1990 CO_2 emission level. This is a global issue. Thus, stronger actions/policies are required and expected from the governments, including generation and utilization of certain technology options (IEA, 2004) to avoid massive CO_2 emission increases. CO_2 capture and storage (CCS) is a successful emission reduction option, which is used for capturing CO_2 generated from fuel use and preventing pollution by storing it. Besides energy supply security benefits, this option has also numerous environmental, economic and social benefits (Blunt, 2010; Liao et al., 2014; Kissinger et al., 2014; IEA, 2004). CCS can make large reductions in greenhouse gas emissions, which involves capturing CO_2 in deep geological formations (Davison, 2007). It is increasingly being considered as a significant greenhouse gas (GHG) mitigation option that allows continuity of the use of fossil fuels and provides time needed for deployment of the renewable energy sources at large scale (Ramirez et al., 2009).

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CO2 can be stored underground in geological formations. Underground depleted reservoirs (depleted oil and gas reservoirs, aquifer reservoirs, salt cavern reservoirs, coal mine and mined cavern) are important types of underground CO_2 storage (Sunjay and Singh, 2010). In some cases, underground storage has a commercial value. For example, the oil and gas companies have used CO_2 extensively for three decades to improve oil recovery. Apart from this, CO_2 can also be used for coal-bed methane recovery (Adams and Davison, 2007). Natural gas reservoirs, due to their proven record of gas production and integrity against gas escape, are obvious candidate sites for carbon sequestration by direct carbon dioxide (CO_2) injection (Sunjay and Singh, 2010). CCS is a method for distilling carbon dioxide and transporting it through pipelines and injecting it into available rock formations to prevent its emission to the atmosphere (Feron and Paterson, 2011; Stasa et al., 2013).

Even with energy efficiency and use of renewable energy resources it is predicted that the dependence on fossil fuels will continue. Despite the fact that in all combustion processes carbon dioxide is an output, it is not possible to get rid of carbon dioxide entirely.

This paper focuses on the CO_2 storage issues in Turkey. Similar to many other countries in the world, the annual increase of CO_2 emission in Turkey is quite high. The biggest CO_2 site in this country is in the West Raman area. CO_2 has been transferred through pipelines from the Dodan Area and injected into this site starting from 1985 (Sahin et al., 2012). Most of the real-world strategic decisions require consideration of many conflicting factors. Multi-criteria Decision Making (MCDM) techniques provide the means to solve such problems supporting decision makers with the best option from a set of alternatives with respect to those factors (Alpay, 2010). There are some previous studies proposing a variety of solution methods for finding the optimum location for CO_2 storage (Kissinger et al., 2014; Ramirez et al., 2009; Stasa et al., 2013; Grataloup et al., 2009) and only a few of them are based on MCDM (Hsu et al., 2012; Llamas and Cienfuegos, 2012; Llamas and Camara, 2014).

In this study, we have designed and applied fuzzy-based MCDM approaches, including Fuzzy TOPSIS, Fuzzy ELECTRE I and Fuzzy VIKOR, comparing their performance to decide the best CO_2 storage reservoir in Turkey, which has not been studied before. In fact, this problem can be solved by using any of these three methods, but given the importance of selection of storage location problem, the best alternative is searched by testing many techniques. Furthermore, the elasticity of these methods is also compared to each other.

The rest of the paper is organized as the following. Section 2, provides an overview of the relevant work. Section 3 discusses the location selection criteria for the CO_2 storage and describes the Fuzzy TOPSIS, Fuzzy ELECTRE I and Fuzzy VIKOR methods. Section 4, presents a case study from Turkey and compares the performance of different fuzzy methods applied to this case study. Finally, Section 5 concludes this study.

2. Related Work

Although underground CO_2 storage location selection problem is a crucial strategic decision this problem has not been addressed fully by others. On the other hand, there are plenty studies on a variety of facility location problems. Here we provide an overview of previous work. Grataloupa et al. (2009) studied on-site selection for CO_2 underground storage in deep saline aquifers. As a case study, the proposed approach was applied to PICOREF, located in Paris Basin, where potential site(s) in deep saline aquifers were investigated. Kissinger et al. (2014) addressed different aspects while considering potential CO_2 storage reservoirs, including safety and economical feasibility of each location. This work is based on the Gravitational Number applied to the North German Basin. Ramirez et al. (2010) presented a methodology to screen and rank Dutch reservoirs suitable for long-term large scale CO_2 storage. The screening was focused on gas, oil and aquifers fields. In total 177 storage reservoirs were taken into consideration (139 gas fields, 4 oil fields and 34 aquifers) from over five hundred suitable locations. The total number of storage reservoirs were reduced by applying preconditions with associated threshold values. Then, linear aggregation was used for deciding on the location. Stasa et al. (2013) investigated into the potential of using principles of Darcy´s law and numerical computing for CO_2 capture and storage in Czech Republic.

In recent years, many papers on facility location problems have been published. Many of those previous studies propose multi-criteria decision making (MCDM) techniques as a solution method. Considering that multiple criteria with imperfect and uncertain factors are involved, fuzzy based methods, such as, TOPSIS, VIKOR and ELECTRE I, (Zadeh, 1965) are commonly utilised as approaches to such MCDM problems. An overview of previous work on relevant MCDM studies is provided in Table 1, which covers the MCDM solution methods, particularly focusing on analytic hierarchy/network process, fuzzy ELCTRE I, Fuzzy TOPSIS and Fuzzy VIKOR, applied to given location selection problems. Hsu et al. (2012) presented an analytic network process (ANP) approach for the selection of potential sites for CO_2 geological storage. The results obtained in this study have proven that ANP-based approach is a useful tool in pre-screening potential sites for CO_2 geological storage. Llamas and Cienfuegos (2012) described a methodology for the selection of site areas or structures for CO_2 geological storage based on an analytic hierarchy process (AHP). Ertugrul and Karakasoglu (2008) compared the fuzzy TOPSIS and fuzzy AHP methods for facility location selection. The proposed methods were applied to a facility location selection problem of a textile company in Turkey. The authors illustrated the similarities and differences of two methods. Demirel et al. (2010) proposed Choquet integral for multi-criteria warehouse location selection. This study provides a successful application of multi-criteria Choquet integral to a real warehouse location selection problem for a large Turkish logistics firm. Kahraman et al. (2003) studied four different fuzzy multi-attribute group decision-making approaches, including fuzzy modelling of group decisions and fuzzy analytic hierarchy process. Although four approaches have the same objective of selecting the best facility location, each has a different theoretic basis and relate differently to the discipline of multi-attribute group decision-making. Opricovic (2011) presented a fuzzy VIKOR approach for a dam (water resources) location selection, providing a conceptual and operational validation of the approach on a real-world problem. Ozdagoglu (2011) proposed a fuzzy ANP approach to overcome the problem of facility location selection. Chou et al. (2008) integrated fuzzy set theory, factor rating system and simple additive weighting into fuzzy simple additive weighting system to select the facility locations. Zandi and Roghanian (2013) extended Fuzzy ELECTRE based on VIKOR method. The purpose of this paper is to extend ELECTRE I method based on VIKOR to rank a set of alternatives versus a set of criteria to show the decision maker's preferences. Chu (2002) presented a fuzzy TOPSIS model was developed in which ratings and weights of each alternative location can be aggregated by interval arithmetic and α-cuts of fuzzy numbers. Ulukan and Kop (2009) used fuzzy TOPSIS method in a two step procedure. Firstly, candidate locations were defined by a trapezoidal membership function. Then, this trapezoidal numbers embedded into criteria and alternatives in TOPSIS. Finally, suitable facility location selected for the medical waste disposal company, able to handle the fuzziness of the real world. Tre et al. (2011) considered elementary Logic Scoring of Preference (LSP) suitability map criteria for evaluating a distribution of points of interests (POIs) in a geographical region.

Table 1

An overview of some previous studies on multi-criteria location selection problems.

Author (Year)	**Subject**	**AHP/ ANP**	**Fuzzy ELECTRE**	**Fuzzy TOPSIS**	**Fuzzy VIKOR**	**Fuzzy Choquet**
Ashrafzadeh et al. (2012)	Warehouse location selection			x		
Choudhary and Shankar (2012)	Thermal power plant location selection	x		x		
Devi and Yadav (2013)	Plant location selection		x			
Fetanat and Khorasaninejad (2015)	Wind farm site selection	x	x			
Hsu et al. (2012)	CO_2 storage location selection	x				
Hu et al. (2009)	Distribution center location selection problem			x		
Ka (2011)	Dry port location selection	x	x			

Kabir and Sumi (2014)	Power substation location selection	x				
Kaboli et al. (2007)	Plant location selection	x				
Llamas and Cienfuegos (2012)	CO_2 storage location selection	x				
Llamas and Camara (2014)	CO_2 storage location selection	x				
Momeni et al. (2011)	Plant location selection				x	
Nazari et al. (2012)	Landfill site selection	x				
Panigrahi (2014)	Thermal power plant site selection			x		
Rezaei et al. (2013)	Underground dam selection	x				
Sanchez-Lozano et al. (2015)	Solar thermoelectric power plants location selection	x	x	x		
Verma et al. (2010	Facility location selection			x		
Wu et al. (2014)	Thermal power plant location selection					x
Yong (2006)	Plant location selection			x		

3. Methodology

The proposed methodology consists of three basic stages: (1) Identification of the criteria, alternatives and linguistic variables to be used in the model (2) Analysis of methods using these selected criteria, alternatives and linguistic variables (3) Ranking the alternatives using fuzzy TOPSIS, fuzzy VIKOR, and fuzzy ELECTRE I. The schematic diagram of the proposed methodology for the selection of CO_2 storage location is shown in Fig. 1. The stages are as follows:

Stage 1: Form the fuzzy model using selected criteria, location alternatives and a team of decision makers. Also fuzzy weights of each criterion and alternative are computed.

Stage 2: Analyze different alternatives based on the relevant algorithmic framework.

Stage 3: Rank each alternative based on the outcome from Stage 2.

The steps of this methodology are constructed with inspiration by other studies in the literature. The primary logic of Fuzzy TOPSIS is the determination of positive ideal and negative ideal distances of the alternatives and according to that making a ranking between the alternatives. In Fuzzy ELECTRE I, concordance and discordance indices are used. In Fuzzy VIKOR method, maximum group benefit and minimum individual regret are taken into account for ranking the alternatives. Hence, the effect of each method's calculation technique on the problem can be seen. As a result, finding the best alternative is aimed with these MDCM techniques.

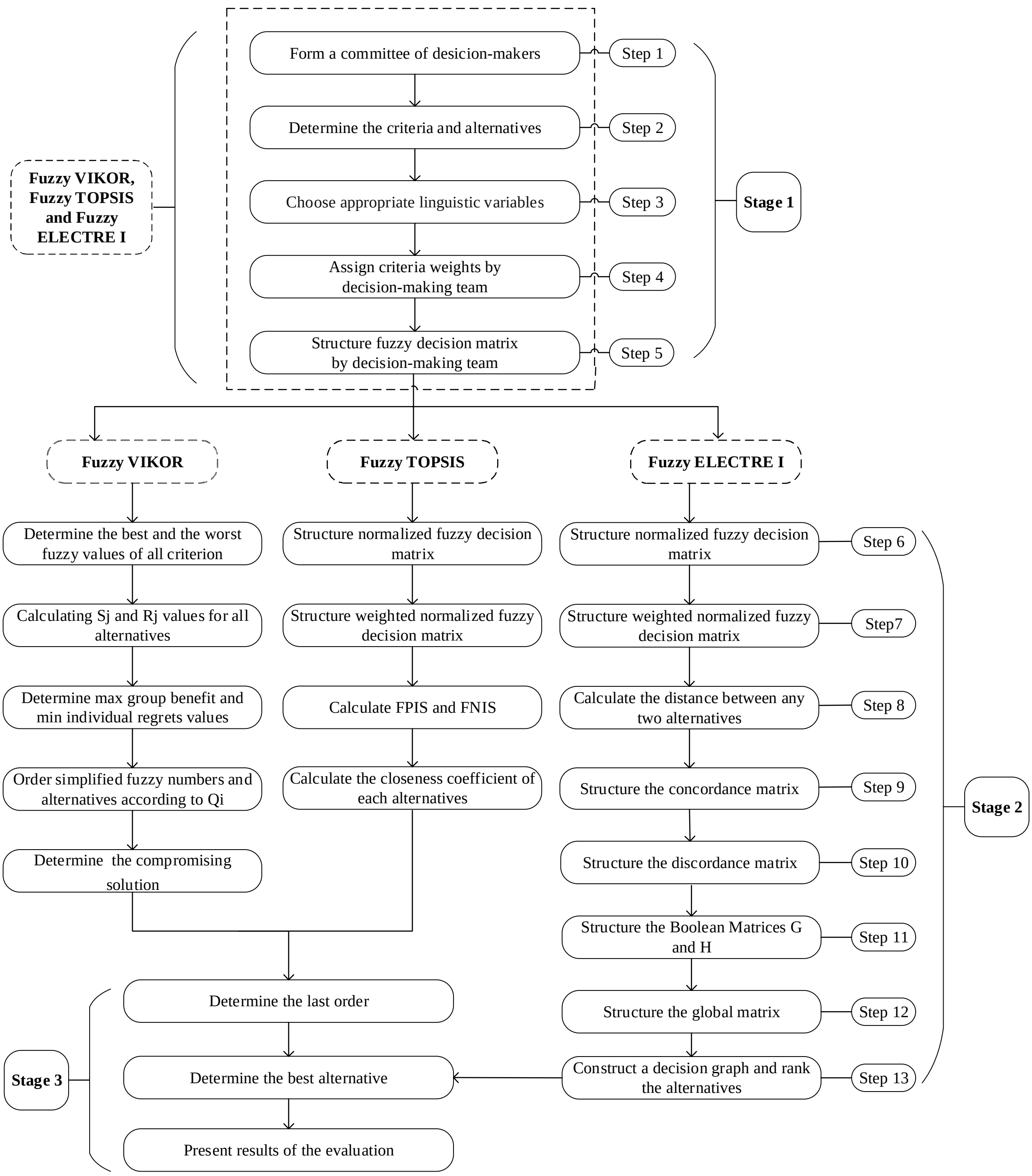

Fig. 1. Steps of Fuzzy VIKOR, Fuzzy TOPSIS and Fuzzy ELECTRE I for location selection.

Criteria

There is no consensus on the main criteria for the selection of CO_2 storage location in the scientific literature. For example, Badri (1999) suggested that cost and legal restrictions determine the final decision on choosing the best storage location, while Ersoy (2011) confirmed that legal restrictions are relevant and additionally, proximity to suppliers/resources and infrastructure availability are extremely crucial criteria. In this study, we employ 12 different criteria identified and synthesized from the scientific literature. Each criterion is presented and explained in Table 2.

Table 2
Criteria and definitions.

Criteria		Definition	Criteria Type
C_1:	Cost	There are different types of cost. Initial cost for the investment, transportation costs, maintenance costs, labor costs, etc.	Cost
C_2:	Storage capacity	The capacity of the underground geological formations	Benefit
C_3:	Regional Risks	Risks in the region (like earthquake risk, natural risk, etc.)	Cost
C_4:	Legal Restrictions	Government regulations, environmental legislation and work and health safety, bureaucracy.	Benefit
C_5:	Environment and public	Social acceptability, community attitudes, environmental regulations.	Benefit
C_6:	Proximity to suppliers & resources	Distance to roads, distance to powerline, accessibility of raw materials	Benefit
C_7:	Infrastructure availability	Technological quality and availability of basic infrastructure, pressure and flow systems.	Benefit
C_8:	Reservoir area and net thickness	The storage capacity potential in the geological field given that the reservoir has a high net thickness. Because the net thickness of reservoir formation provides opportunities for CO_2, it should be at a certain thickness (Hsu et al., 2012).	Benefit
C_9:	Cap rock permeability and thickness	CO_2 storage in the long term must necessitate cap rocks with sufficient thickness for safe storage. The seal capacity of a cap rock enabling successful sealing of the original hydrocarbon in the reservoirs for a geological period (Ramirez et al., 2010).	Benefit
C_{10}:	Transportation availability	Quality of transportation and distribution infrastructure.	Benefit
C_{11}:	Porosity	Required to estimate the potential volume available for CO2 sequestration in depleted oil and gas reservoirs (Hsu et al., 2012).	Benefit
C_{12}:	Sustainability	Sustainability in the long term denotes the economic, social and environmental viability of the storage.	Benefit

3.1. Fuzzy TOPSIS Method

The TOPSIS (**T**echnique for **O**rder **P**reference by **S**imilarity To An **I**deal **S**olution) method was proposed for the first time for multi-criteria decision-making problems in 1981 (Hwang and Yoon, 1981). This method determines the alternative closest to the positive ideal solution and the most distant to the negative ideal solution and makes a ranking accordingly (Chen, 2000). The logic behind this method is to make fuzzy assessments which are expressed linguistically and using the linguistic variables in the analysis. In this paper, the fuzzy TOPSIS method proposed by Chen (2000) and Chen et al. (2006), is used. The pseudo-code of this method is as follows:

Step 1. Form a committee of decision-makers (k = 1, 2, . . . , K).

Step 2. Determine criteria (j=1, 2, …, n) and alternatives (i=1, 2, …, m).

Step 3. Choose linguistic variables for evaluating criteria and alternatives. The proposed linguistic variables used for determining the criteria weights, significance degrees of the alternatives and the corresponding fuzzy numbers are provided in Table 3. In fuzzy set theory, scales are applied to convert the linguistic terms to fuzzy numbers. In multi-criteria decision making problems, fuzzy sets are used as a method to include the assessment of the decision makers under an uncertain environment. In this study, triangular fuzzy numbers are used. The triangular fuzzy number is represented as a triplet $\widetilde{X} = (l, m, u)$.

Table 3
Linguistic variables and fuzzy numbers (Chen, 2000).

Linguistic variables for the importance weight of each criterion		Linguistic variables for the ratings	
Linguistic variables	Membership function	Linguistic variables	Membership function
Very low (VL)	(0, 0, 0.1)	Very poor (VP)	(0, 0, 1)
Low (L)	(0, 0.1, 0.3)	Poor (P)	(0, 1, 3)
Medium low (ML)	(0.1, 0.3, 0.5)	Medium poor (MP)	(1, 3, 5)
Medium (M)	(0.3, 0.5, 0.7)	Fair (F)	(3, 5, 7)
Medium high (MH)	(0.5, 0.7, 0.9)	Medium good (MG)	(5, 7, 9)
High (H)	(0.7, 0.9, 1)	Good (G)	(7, 9, 10)
Very high (VH)	(0.9, 1, 1)	Very good (VG)	(9, 10, 10)

Step 4. Fuzzy weights for each criterion and alternative are calculated using the equations (1) and (2), where "K" is the number of decision makers.

$$\widetilde{w}_j = \frac{1}{K}\left[\widetilde{w}_j^1 (+)\, \widetilde{w}_j^2 (+) \dots (+) \widetilde{w}_j^K\right], \qquad j = 1,2,\dots,n \tag{1}$$

$$\tilde{x}_{ij} = \frac{1}{K}\left[\tilde{x}_{ij}^1\, (+)\, \tilde{x}_{ij}^1\, (+) \dots (+) \tilde{x}_{ij}^K\right], \qquad i = 1,2,\dots,m \tag{2}$$

$\tilde{x}_{ij}$ is the degree of alternative I according criterion j and $\widetilde{w}_j$ is the significance weight of criterion j (where $\widetilde{w}_j^k$ and $\tilde{x}_{ij}^k$ are the rating and the significance weight of the *k*th decision maker).

Step 5. Structure the fuzzy decision matrix. The fuzzy decision matrix is created using the equations (3) and (4). The fuzzy decision matrix for the alternatives ($\widetilde{D}$) and the criteria ($\widetilde{w}$) are constructed as follows:

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \tag{3}$$

$$\widetilde{w}_j = [\widetilde{w}_1, \widetilde{w}_2, \dots \dots, \widetilde{w}_n] \tag{4}$$

where $\tilde{x}_{ij}$ ∀ i,j and $\tilde{w}_j$; j =1,2,…., n (criteria) are the linguistic variables which can be described by triangular fuzzy numbers, $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ and $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$.

Step 6. Normalize the fuzzy decision matrix.

$$\tilde{R} = [\tilde{r}_{ij}]_{mxn} \qquad i = 1, 2, \dots, m\,;\; j = 1, 2, \dots, n \tag{5}$$

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

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right),\; j \in B \text{ and } \; c_j^* = \max_i c_{ij} \quad if \;\; j \in B \text{ (benefit criteria)} \tag{6}$$

$$\tilde{r}_{ij} = \left(\frac{c_j^-}{c_{ij}}, \frac{c_j^-}{b_{ij}}, \frac{c_j^-}{a_{ij}}\right),\; j \in C \text{ and } \; c_j^- = \min_i a_{ij} \quad if \;\; j \in C \text{ (cost criteria)} \tag{7}$$

$\tilde{R}$: Normalized fuzzy decision matrix

c_j^*: Maximum value of the third component in one column in fuzzy decision matrix

$\tilde{r}_{ij}$: Normalized values obtained by dividing each value in fuzzy decision matrix into c_j^* value. Each of a, b, c are the values in the fuzzy decision matrix.

Step 7. Structure the weighted normalized matrix.

$$\tilde{V} = [\tilde{v}_{ij}]_{mxn}, \qquad i = 1, 2, \dots, m\,;\; j = 1, 2, \dots, n \quad \text{where} \quad \tilde{v}_{ij} = \tilde{r}_{ij}(.)\tilde{w}_j \tag{8}$$

Step 8. Compute the distance of each alternative from fuzzy positive-ideal solution (FPIS) and fuzzy negative-ideal solution (FNIS), respectively as follows:

$$A^* = (\tilde{v}_1{}^*, \tilde{v}_2{}^*, \dots, \tilde{v}_n{}^*) \quad \text{where} \quad \tilde{v}_j{}^* = \max_i v_{ij} \qquad i = 1, 2, \dots, m\,;\; j = 1, 2, \dots, n \tag{9}$$

$$A^- = (\tilde{v}_1{}^-, \tilde{v}_2{}^-, \dots, \tilde{v}_n{}^-) \quad \text{where} \quad \tilde{v}_j{}^- = \min_i v_{ij} \qquad i = 1, 2, \dots, m\,;\; j = 1, 2, \dots, n \tag{10}$$

Compute the distance of each alternative from FPIS and FNIS.

$$d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j{}^*), \quad i = 1, 2, \dots, m \quad (11) \qquad d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j{}^-) \; i = 1, 2, \dots, m \quad (12)$$

Where; d(.,.) refers to the distance between two triangular fuzzy numbers. This distance is found using vertex method and this method is used for finding the distance between “m” and “n” (Chen, 2000). $\tilde{m} = (m_1, m_2, m_3)$ and $\tilde{n} = (n_1, n_2, n_3)$

$$d(\tilde{m}, \tilde{n}) = \sqrt{\frac{1}{3}[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2]} \tag{13}$$

Step 9. Calculate the closeness coefficient of each alternative. Then, rank the alternatives according to their closeness coefficients that are between 0 and 1, and finally choose the alternative whose closeness coefficient is adjacent to 1.

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-} \quad , i = 1, 2, \ldots, m \tag{14}$$

3.2. Fuzzy ELECTRE I Method

ELECTRE I (**EL**imination **E**t **C**hoix **T**raduisant la **RE**alitéwas developed by Benayoun et al. (1966). The method uses concordance and discordance indexes to analyze the outranking relations among different alternatives (Rouyendegh and Erkan, 2013). Although linguistic variables and the evaluation of weightings are the same in both multi criteria decision methods, there are several differences between fuzzy TOPSIS and fuzzy ELECTRE I. The main difference between them is the ranking mechanism. Fuzzy ELECTRE I focuses on the selection of a single action among a small set of available actions, while fuzzy TOPSIS aims to select a complete or partial order of the actions. The fuzzy ELECTRE I method proposed here can be described in 13 steps. The first seven steps in the Fuzzy ELECTRE method are the same as Fuzzy TOPSIS method. Hatami-Marbini and Tavana (2011) and Hatami-Marbini et al. (2013) describe the extensions towards fuzzy ELECTRE I.

Let us assume that decision making committee involves K decision makers (DMs) D_k (k = 1, 2, . . . , K). The DMs are expected to determine the importance weights of n criteria C_j (j = 1,2,. . . ,n) and the performance ratings of m possible alternatives A_i (i = 1,2,. . . ,m) on the attributes by means of linguistic variables.

Step 8: Compute the distance between any two options: The concordance and discordance matrices are structured by using the weighted normalized fuzzy decision matrix ($\tilde{v}$) and paired comparison among the alternatives Hatami-Marbini et al. (2013). In this study, Hamming distance (Hamming, 1950), denoted as $d(\tilde{a}, \tilde{b})$ between given two fuzzy numbers $\tilde{m}$ and $\tilde{n}$ is computed as follows:

$$d(\tilde{a}, \tilde{b}) = \int_R \left| \mu_{\tilde{a}}(x) - \mu_{\tilde{b}}(x) \right| dx \tag{15}$$

where R is the set of real numbers.

For each pair of alternatives A_p and A_r (p, r = 1,2,…,m and p ≠r) the set of criteria is divided into two distinct subsets. Taking two alternatives A_p and A_r, the concordance set is formed as $J^x = \{ j | \tilde{v}_{pj} \geq \tilde{v}_{rj} \}$ where J^x is the concordance coalition of the attributes where A_p S A_r, and the discordance set is defined by $J^y = \{ j | \tilde{v}_{pj} \leq \tilde{v}_{rj} \}$ in which J^y is the discordance coalition, which is against the assertion A_p S A_r. In order to compare any two alternatives A_p and A_r with respect to each attribute, and to define the concordance and discordance sets, the least upper bound of the alternatives are specified, $max(\tilde{v}_{pj}, \tilde{v}_{rj})$. After that the Hamming distance is applied based on the following formulation Hatami-Marbini et al. (2013):

$$\begin{aligned} &\tilde{v}_{pj} \geq \tilde{v}_{rj} \Leftrightarrow d\left(\max(\tilde{v}_{pj}, \tilde{v}_{rj}), \tilde{v}_{rj}\right) \geq d\left(\max(\tilde{v}_{pj}, \tilde{v}_{rj}), \tilde{v}_{pj}\right) \ and \\ &\tilde{v}_{pj} \leq \tilde{v}_{rj} \Leftrightarrow d\left(max(\tilde{v}_{pj}, \tilde{v}_{rj}), \tilde{v}_{rj}\right) \leq d\left(max(\tilde{v}_{pj}, \tilde{v}_{rj}), \tilde{v}_{pj}\right) \end{aligned} \tag{16}$$

Step 9: Compute the concordance matrix: The concordance matrix is constructed based on the Hamming distance. The elements of the concordance matrix are specified as fuzzy summation of the fuzzy weights of all criteria in the concordance set.

$$\tilde{X} = \begin{bmatrix} - & \tilde{x}_{1r} & \dots & \tilde{x}_{1m} \\ \tilde{x}_{p1} & \tilde{x}_{pr} & \dots & \tilde{x}_{pm} \\ \vdots & \vdots & \dots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{mr} & \dots & - \end{bmatrix} \tag{17}$$

Where

$$\tilde{x}_{pr} = \left(x^l_{pr,}\ \ x^m_{pr,}\ \ x^u_{pr}\right) = \sum_{j\epsilon J^x} \widetilde{W}_j = \left(\sum_{j\epsilon J^x} w^l_{j,} \sum_{j\epsilon J^x} w^m_{j,} \sum_{j\epsilon J^x} w^u_{j,} \right) \tag{18}$$

We then specify the concordance level as $\tilde{x} = (x^L{}_, x^M{}_, x^U)$, where

$$x^l = \frac{\sum_{r=1}^m \sum_{p=1}^m x^l_{pr}}{m(n-1)}, \ x^m = \frac{\sum_{r=1}^m \sum_{p=1}^m x^m_{pr}}{m(m-1)} \ and \ x^u = \frac{\sum_{r=1}^m \sum_{p=1}^m x^u_{pr}}{m(m-1)} \tag{19}$$

Step 10: Compute the discordance matrix: The discordance matrix is constructed with respect to the Hamming distance. The discordance matrix can be described as;

$$\tilde{Y} = \begin{bmatrix} - & \tilde{y}_{1r} & \cdots & \tilde{y}_{1m} \\ \tilde{y}_{p1} & \tilde{y}_{pr} & \cdots & \tilde{y}_{pm} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{y}_{m1} & \tilde{y}_{mr} & \cdots & - \end{bmatrix} \tag{20}$$

Where

$$y_{pr} = \frac{max_{j\epsilon J^y}|\tilde{v}_{pj} - \tilde{v}_{rj}|}{\underset{j}{max}|\tilde{v}_{pj} - \tilde{v}_{rj}|} = \frac{max_{j\epsilon J^y}|\mathrm{d}\left(max(\tilde{v}_{pj}, \tilde{v}_{rj}), \tilde{v}_{rj}\right)|}{\underset{j}{max}|\mathrm{d}\left(max(\tilde{v}_{pj}, \tilde{v}_{rj}), \tilde{v}_{rj}\right)|} \tag{21}$$

and the discordance level is described as;

$$\bar{Y} = \frac{\sum_{r=1}^{m} \sum_{p=1}^{m} y_{pr}}{m(m-1)} \tag{22}$$

Step 11: Calculate the Boolean Matrices G and H: Boolean matrix *G* is formed according to the minimum concordance level $\bar{\tilde{X}}$ as

$$G = \begin{bmatrix} - & g_{1r} & \cdots & g_{1m} \\ g_{p1} & g_{pr} & \cdots & g_{pm} \\ \vdots & \vdots & \cdots & \vdots \\ g_{m1} & g_{mr} & \cdots & - \end{bmatrix} \tag{22}$$

$$\begin{cases} \tilde{x}_{pr} \geq \bar{\tilde{X}} \Leftrightarrow g_{pr} = 1 \\ \tilde{x}_{pr} < \bar{\tilde{X}} \Leftrightarrow g_{pr} = 0 \end{cases} \tag{23}$$

and similarly, the Boolean matrix *H* is obtained based on the minimum discordance level, $\bar{Y}$ as follows:

$$H = \begin{bmatrix} - & h_{1r} & \cdots & h_{1m} \\ h_{p1} & h_{pr} & \cdots & h_{pm} \\ \vdots & \vdots & \cdots & \vdots \\ h_{m1} & h_{mr} & \cdots & - \end{bmatrix} \tag{24}$$

$$\begin{cases} \tilde{y}_{pr} < \bar{Y} \Leftrightarrow h_{pr} = 1 \\ \tilde{y}_{pr} \geq \bar{Y} \Leftrightarrow h_{pr} = 0 \end{cases} \tag{25}$$

The elements in matrices G and H with the value of "1" indicate the relation of dominance between alternatives.

Step 12: Calculate the global matrix: The global matrix *Z* is calculated by multiplication of the elements of the matrices *G* and *H* as follows

$$Z = G \otimes H \tag{26}$$

where each element (z_{pr}) of matrix *Z* is obtained using $z_{pr} = g_{pr} \cdot h_{pr}$

Step 13: Draw a decision graph and rank the alternatives: With regard to the general matrix, a decision graph is drawn in order to determine the ranking order of the alternatives. There is an arc between the two alternatives from A_p to A_r in case that alternative A_p outranks A_r, on the other hand there is no arc between the two alternatives if alternatives A_p and A_r are incomparable, and lastly there are two arcs between the two alternatives in both directions if these alternatives are indifferent Hatami-Marbini and Tavana (2011).

3.3. Fuzzy VIKOR Method

VIKOR method is one of the MCDM methods developed by Opricovic (1998) for the multi-criteria optimization of complex systems. The purpose of the method is to reach a compromise solution which would provide maximum group benefit (majority rule) and minimum individual regret at the stage of listing and selection of the alternatives. The method is used for the cases where multi criteria have to be considered on the final decision in the process of selection among the alternatives (Opricovic and Tzeng, 2004). And Fuzzy VIKOR method, the form in which fuzzy logic is applied to the VIKOR method, is a method appropriate for use in cases where different criteria which are determinant of the final decision and conflicting with one another within an indefinite framework are in question. A compromise solution is obtained by the VIKOR method of compromise ranking, which in turn provides a maximum ''group utility'' for the ''majority'' and a minimum of an individual regret for the ''opponent'' (Opricovic, 2011). The steps used for the solution of multi-criteria decision problems using Fuzzy VIKOR method can be described as the following. The first five steps in the Fuzzy VIKOR method are the same as Fuzzy TOPSIS method as shown in the Fig. 1. To prevent unnecessary repetition of describing steps, only the steps after the 6th step are shown.

Step 6: The best and worst values of all criteria functions are determined (alternatives i=1, 2,..., m). The equation numbered (27) is used for calculating the best value and the equation numbered (28) is used for calculating the worst value (criteria j=1, 2,..., n; x_{ij}= Aggregated fuzzy ratings).

$$\tilde{f}_i^* = \max_j x_{ij} \qquad (27) \qquad\qquad \tilde{f}_i^- = \max_j x_{ij} \qquad (28)$$

Step 7: $\tilde{S}_j$ (29) and $\tilde{R}_j$ (30) values are calculated for j=1, 2,…, n and i=1,2,…,m.

$$\tilde{S}_j = \sum_{j=1}^{n} [\tilde{w}_i(\tilde{f}_i^* - x_{ij})/(\tilde{f}_i^* - \tilde{f}_i^-)], \qquad (29)$$

$$\tilde{R}_j = \max_i [\tilde{w}_i(\tilde{f}_i^* - x_{ij})/(\tilde{f}_i^* - \tilde{f}_i^-)], \qquad (30)$$

While $\tilde{w}_i$ refers to criteria weight and significance, $\tilde{S}_j$ is the distance of "i" alternative to the best fuzzy values and $\tilde{R}_j$ value is the maximum distance of "i" alternative to the worst fuzzy values (Akyuz, 2012).

Step 8: $\tilde{S}_i$ **,** $\tilde{S}^*$ (31) **,** $\tilde{R}_i$ **,** $\tilde{R}^*$(32) and $\tilde{Q}_i$(33) values that refer to maximum group benefit are calculated.

$$\tilde{S}^* = \min_i \tilde{S}_i \quad \text{and} \quad \tilde{S}^- = \max_i \tilde{S}_i \tag{31}$$

$$\tilde{R}^* = \min_i \tilde{R}_i \quad \text{and} \quad \tilde{R}^- = \max_i \tilde{R}_i \tag{32}$$

$$\tilde{Q}_i = v\,(\tilde{S}_i - \tilde{S}^*)/(\tilde{S}^- - \tilde{S}^*) + (1-v)\,(\tilde{R}_i - \tilde{R}^*)/(\tilde{R}^- - \tilde{R}^*) \tag{33}$$

$\tilde{S}^*$ refers to compromising majority rule and $\tilde{R}^*$ refers to minimum individual regrets of those having different alternatives. Following those calculations $\tilde{Q}_i$ index is obtained, this index is calculated through joint assessment of group benefit and individual regret. And while the "v" value underlines the significance of the strategy that provides majority of the criteria or maximum group benefit (v=0.5) "1-v" corresponds to individual regret value (Opricovic, 2011).

Step 9: Triangular fuzzy numbers are simplified and alternatives are listed according to "$\tilde{Q}_i$" index. The minimum value of this index indicates the best alternative. In this study, BNP (Best Nonfuzzy Performance Value) simplification method suggested by Hsieh et.al. (2004) (see Equation (34)) is used.

$$BNP_i = \frac{(u_i - l_i) + (m_i - l_i)}{3} + l_i \qquad i = 1, 2, \ldots, m \tag{34}$$

Step 10: The two following conditions should be met to determine the compromising solution.

1st Condition: Acceptable advantage

$$Q(a'') - Q(a') \geq DQ \text{ and } DQ = \frac{1}{m-1} \quad (\text{if } m \leq 4 \text{ then } DQ = 0.25) \tag{35}$$

2nd Condition: Stability acceptable in decision making

Alternative a' should be the best alternative in the ranking made according to S and/or R values (Opricovic and Tzeng, 2004). If the 1st Condition cannot be provided, $Q(a^{(m)}) - Q(a') \leq DQ$ and if it is made $a^{(m)}$ and a' should be the same compromising solution.

If the 2nd Condition cannot be provided although a' has a relative advantage there is inconsistency in decision making. For this reason $a'$and a'' compromising solutions are the same.

Step 11: The minimum "Q" value among alternatives is selected.

4. Case Study

This study presents a model using the methods described above for selecting candidate sites for underground CO_2 geological storage in Turkey. A committee of four decision makers D_1, D_2, D_3 and D_4 was formed to select the best alternative using 12 criteria as provided in Table 2. Five alternative locations for depleted reservoirs (depleted oil and gas reservoirs, aquifer reservoirs, salt cavern reservoirs, coal mine and mined cavern) are determined by four experts: Adiyaman, Aksaray, Diyarbakir, Afyon and Tekirdag. Hierarchical structure for a location selection problem is shown in Fig. 2.

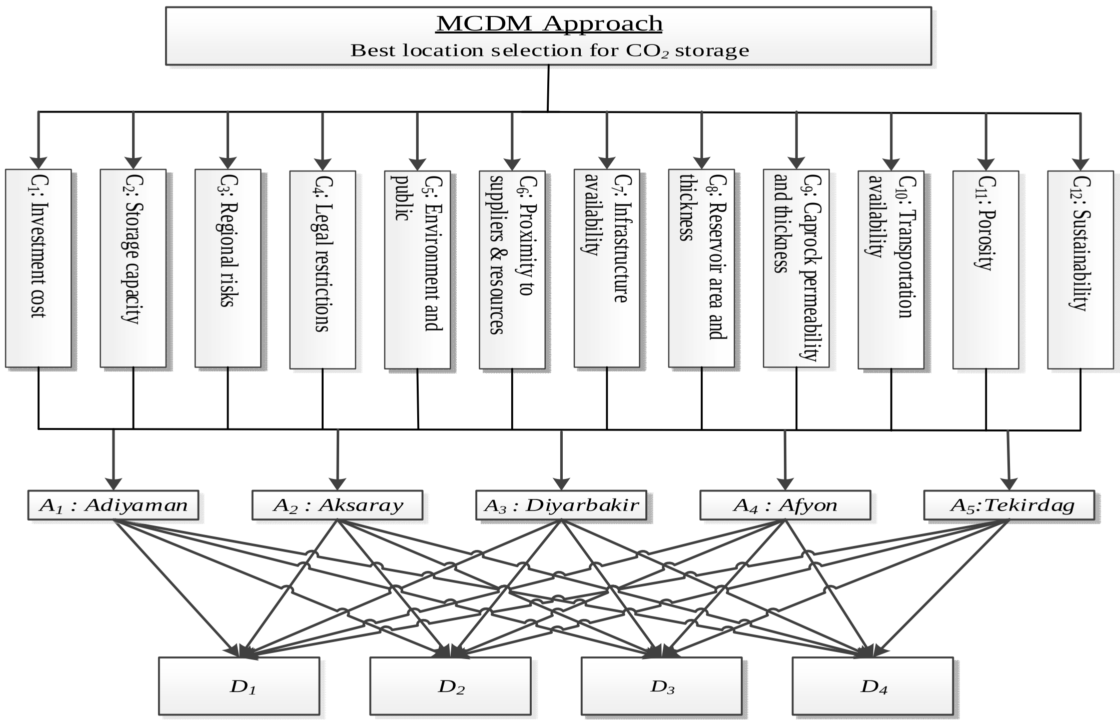

Fig. 2. The decision hierarchy of the location selection problem.

4.1. Fuzzy TOPSIS Solutions

The linguistic assessments for the twelve criteria are determined by the committee using rating scales (see Table 3), which also evaluate the five alternatives (locations) for each of the 12 criteria (using rating scales of Table 3). Tables 4 and 5 present the linguistic assessments for the criteria and alternatives. The aggregate weights of the 12 criteria are presented in Table 6.

Table 4
Linguistic assessments for the 12 criteria.

Decision makers	Criteria											
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
D1	H	VH	H	MH	L	MH	H	H	H	VH	H	MH
D2	MH	M	VH	H	M	M	VH	MH	VH	M	M	MH
D3	VH	MH	VH	H	M	VH	H	VH	H	MH	M	H
D4	VH	VH	VH	M	MH	H	VH	MH	VH	H	MH	M

Table 5
Linguistic assessments for the five alternatives.

Alternatives	Decision makers	Criteria											
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
A_1	D_1	VG	G	G	F	VG	G	G	G	G	F	G	G
	D_2	G	G	G	MG	G	MG	G	F	G	F	F	G
	D_3	MG	MG	VG	F	MG	F	F	MP	VG	MP	MP	F
	D_4	VG	MG	MG	F	MG	VG	MG	F	F	MP	F	F
A_2	D_1	MG	MG	F	F	G	G	MG	F	G	F	MP	G
	D_2	F	F	VP	VG	MG	MP	G	VG	MP	MP	MP	MG
	D_3	MP	MP	F	G	VG	F	G	G	F	P	P	F
	D_4	F	MP	VP	G	MG	MP	F	VG	F	F	F	G
A_3	D_1	VG	VG	MG	G	G	VG	VG	G	F	VG	MG	VG
	D_2	VG	G	G	F	G	MG	G	MG	G	VG	G	G
	D_3	G	G	VG	G	VG	G	G	MG	G	G	G	VG
	D_4	G	MG	VG	VG	VG	G	VG	G	MG	G	MG	VG
A_4	D_1	MP	P	VP	G	MG	VP	MG	MP	G	MP	G	VG
	D_2	F	VP	MP	G	F	MP	G	P	VG	F	VG	G
	D_3	F	VP	VP	VG	F	F	G	VP	F	F	MG	F
	D_4	MG	F	MP	G	G	F	G	P	MG	MP	F	G
A_5	D_1	G	F	F	VG	G	G	G	F	G	G	G	G
	D_2	G	F	MP	VG	VG	MG	VG	MG	G	MG	G	MG
	D_3	MG	MP	F	G	MG	F	MG	F	MG	F	F	G

	D_4	G	MP	G	G	MG	F	MG	MP	MG	G	MG	F

The fuzzy weights ($\tilde{w}_j$) for each criterion are computed by using Eq. (1). The aggregate fuzzy decision matrix for the alternatives is presented in Table 7.

Table 6
Aggregate fuzzy weights for criteria.

Criteria	Alternatives				Fuzzy
	D1	D2	D3	D4	Weights ($\tilde{w}_j$)
C_1	(0.70,0.90,1.00)	(0.50,0.70,0.90)	(0.90,1.00,1.00)	(0.90,1.00,1.00)	(0.75,0.90,0.98)
C_2	(0.90,1.00,1.00)	(0.30,0.50,0.70)	(0.50,0.70,0.90)	(0.90,1.00,1.00)	(0.65,0.80,0.90)
C_3	(0.70,0.90,1.00)	(0.90,1.00,1.00)	(0.90,1.00,1.00)	(0.90,1.00,1.00)	(0.85,0.98,1.00)
C_4	(0.50,0.70,0.90)	(0.70,0.90,1.00)	(0.70,0.90,1.00)	(0.30,0.50,0.70)	(0.55,0.75,0.90)
C_5	(0.10,0.30,0.50)	(0.30,0.50,0.70)	(0.30,0.50,0.70)	(0.50,0.70,0.90)	(0.30,0.50,0.70)
C_6	(0.50,0.70,0.90)	(0.30,0.50,0.70)	(0.90,1.00,1.00)	(0.70,0.90,1.00)	(0.60,0.78,0.90)
C_7	(0.70,0.90,1.00)	(0.90,1.00,1.00)	(0.70,0.90,1.00)	(0.90,1.00,1.00)	(0.80,0.95,1.00)
C_8	(0.70,0.90,1.00)	(0.50,0.70,0.90)	(0.90,1.00,1.00)	(0.50,0.70,0.90)	(0.65,0.83,0.95)
C_9	(0.70,0.90,1.00)	(0.90,1.00,1.00)	(0.70,0.90,1.00)	(0.90,1.00,1.00)	(0.80,0.95,1.00)
C_{10}	(0.90,1.00,1.00)	(0.30,0.50,0.70)	(0.50,0.70,0.90)	(0.70,0.90,1.00)	(0.60,0.78,0.90)
C_{11}	(0.70,0.90,1.00)	(0.30,0.50,0.70)	(0.30,0.50,0.70)	(0.50,0.70,0.90)	(0.45,0.65,0.83)
C_{12}	(0.50,0.70,0.90)	(0.50,0.70,0.90)	(0.70,0.90,1.00)	(0.30,0.50,0.70)	(0.50,0.70,0.88)

Table 7
The fuzzy decision matrix.

Criteria	Alternatives				
	A1	A2	A3	A4	A5
C_1	(7.50,9.00,9.75)	(3.00,5.00,7.00)	(8.00,9.50,10.0)	(3.00,5.00,7.00)	(6.50,8.50,9.75)
C_2	(6.00,8.00,9.50)	(2.50,4.50,6.50)	(7.00,8.75,9.85)	(0.75,1.50,3.00)	(2.00,4.00,6.00)
C_3	(7.00,8.75,9.75)	(1.50,2.50,4.00)	(7.50,9.00,9.75)	(0.25,1.00,2.50)	(3.50,5.50,7.25)
C_4	(3.50,5.50,7.50)	(6.50,8.25,9.25)	(6.50,8.25,9.25)	(7.50,9.25,10.0)	(8.00,9.50,10.0)
C_5	(6.50,8.25,9.50)	(6.50,8.25,9.50)	(8.00,9.50,10.0)	(4.50,6.50,8.25)	(6.50,8.25,9.50)
C_6	(6.00,7.75,9.00)	(3.00,5.00,6.75)	(7.00,8.75,9.75)	(1.75,3.25,5.00)	(4.50,6.50,8.25)
C_7	(5.50,7.50,9.00)	(5.50,7.50,9.00)	(8.00,9.50,10.0)	(6.50,8.50,9.75)	(6.50,8.25,9.50)
C_8	(3.50,5.50,7.25)	(7.00,8.50,9.25)	(6.00,8.00,9.50)	(0.25,1.25,3.00)	(3.00,5.00,7.00)
C_9	(6.50,8.25,9.25)	(3.50,5.50,7.25)	(5.50,7.50,9.00)	(6.00,7.75,9.00)	(6.00,8.00,9.50)
C_{10}	(2.00,4.00,6.00)	(1.75,3.50,5.50)	(8.00,9.50,10.0)	(2.00,4.00,6.00)	(5.50,7.50,9.00)
C_{11}	(3.50,5.50,7.25)	(1.25,3.00,5.00)	(6.00,8.00,9.50)	(6.00,7.75,9.00)	(5.50,7.50,9.00)
C_{12}	(5.00,7.00,8.50)	(5.50,7.50,9.00)	(8.50,9.75,10.0)	(6.50,8.25,9.25)	(5.50,7.50,9.00)

Table 8
The fuzzy normalized decision matrix.

Criteria	Alternatives				
	A1	A2	A3	A4	A5
C_1	(0.31,0.33,0.40)	(0.43,0.60,1.00)	(0.30,0.32,0.38)	(0.43,0.60,1.00)	(0.31,0.35,0.46)
C_2	(0.62,0.82,0.97)	(0.26,0.46,0.67)	(0.72,0.90,1.00)	(0.08,0.15,0.31)	(0.21,0.41,0.62)
C_3	(0.03,0.03,0.04)	(0.06,0.10,0.17)	(0.03,0.03,0.03)	(0.10,0.25,1.00)	(0.03,0.05,0.07)
C_4	(0.35,0.55,0.75)	(0.65,0.83,0.93)	(0.65,0.83,0.93)	(0.75,0.93,1.00)	(0.80,0.95,1.00)
C_5	(0.65,0.83,0.95)	(0.65,0.83,0.95)	(0.80,0.95,1.00)	(0.45,0.65,0.83)	(0.65,0.83,0.95)
C_6	(0.62,0.79,0.92)	(0.31,0.51,0.69)	(0.72,0.90,1.00)	(0.18,0.33,0.51)	(0.46,0.67,0.85)
C_7	(0.55,0.75,0.90)	(0.55,0.75,0.90)	(0.80,0.95,1.00)	(0.65,0.85,0.98)	(0.65,0.83,0.95)
C_8	(0.37,0.58,0.76)	(0.74,0.89,0.97)	(0.63,0.84,1.00)	(0.03,0.13,0.32)	(0.32,0.53,0.74)
C_9	(0.68,0.87,0.97)	(0.37,0.58,0.76)	(0.58,0.79,0.95)	(0.63,0.82,0.95)	(0.63,0.84,1.00)
C_{10}	(0.20,0.40,0.60)	(0.18,0.35,0.55)	(0.80,0.95,1.00)	(0.20,0.40,0.60)	(0.55,0.75,0.90)
C_{11}	(0.37,0.58,0.76)	(0.13,0.32,0.53)	(0.63,0.84,1.00)	(0.63,0.82,0.95)	(0.58,0.79,0.95)
C_{12}	(0.50,0.70,0.85)	(0.55,0.75,0.90)	(0.85,0.98,1.00)	(0.65,0.83,0.93)	(0.55,0.75,0.90)

Table 9
The fuzzy weighted normalized decision matrix.

Criteria	Alternatives					FPIS (A*)	FPNS (A-)
	A1	A2	A3	A4	A5		
C_1	(0.23,0.30,0.39)	(0.32,0.54,0.98)	(0.23,0.28,0.37)	(0.32,0.54,0.98)	(0.23,0.32,0.45)	(1, 1, 1)	(0, 0, 0)
C_2	(0.40,0.66,0.88)	(0.17,0.37,0.60)	(0.47,0.72,0.90)	(0.05,0.12,0.28)	(0.13,0.33,0.55)	(1, 1, 1)	(0, 0, 0)
C_3	(0.02,0.03,0.04)	(0.05,0.10,0.17)	(0.02,0.03,0.03)	(0.09,0.24,1.00)	(0.03,0.04,0.07)	(1, 1, 1)	(0, 0, 0)
C_4	(0.19,0.41,0.68)	(0.36,0.62,0.83)	(0.36,0.62,0.83)	(0.41,0.69,0.90)	(0.44,0.71,0.90)	(1, 1, 1)	(0, 0, 0)
C_5	(0.20,0.41,0.67)	(0.20,0.41,0.67)	(0.24,0.48,0.70)	(0.14,0.33,0.58)	(0.20,0.41,0.67)	(1, 1, 1)	(0, 0, 0)
C_6	(0.37,0.62,0.83)	(0.18,0.40,0.62)	(0.43,0.70,0.90)	(0.11,0.26,0.46)	(0.28,0.52,0.76)	(1, 1, 1)	(0, 0, 0)
C_7	(0.44,0.71,0.90)	(0.44,0.71,0.90)	(0.64,0.90,1.00)	(0.52,0.81,0.98)	(0.52,0.78,0.95)	(1, 1, 1)	(0, 0, 0)
C_8	(0.24,0.48,0.73)	(0.48,0.74,0.93)	(0.41,0.69,0.95)	(0.02,0.11,0.30)	(0.21,0.43,0.70)	(1, 1, 1)	(0, 0, 0)
C_9	(0.55,0.83,0.97)	(0.29,0.55,0.76)	(0.46,0.75,0.95)	(0.51,0.78,0.95)	(0.51,0.80,1.00)	(1, 1, 1)	(0, 0, 0)
C_{10}	(0.12,0.31,0.54)	(0.11,0.27,0.50)	(0.48,0.74,0.90)	(0.12,0.31,0.54)	(0.33,0.58,0.81)	(1, 1, 1)	(0, 0, 0)
C_{11}	(0.17,0.38,0.63)	(0.06,0.21,0.43)	(0.28,0.55,0.83)	(0.28,0.53,0.78)	(0.26,0.51,0.78)	(1, 1, 1)	(0, 0, 0)
C_{12}	(0.25,0.49,0.74)	(0.28,0.53,0.79)	(0.43,0.68,0.88)	(0.33,0.58,0.81)	(0.28,0.53,0.79)	(1, 1, 1)	(0, 0, 0)

The fuzzy normalized decision matrices, constructed using Eq. (8) for the five alternatives are shown in Table 8. The $\tilde{r}_{ij}$ values from Table 5 and $\widetilde{w}_j$ values from Table 4 are utilized to calculate the fuzzy weighted decision matrix for the alternatives. For alternative A_1, the fuzzy weight of criterion C_2 (Storage capacity) is given by $\tilde{v}_{ij} = \tilde{r}_{ij}(.)\tilde{w}_j$ = (0.62, 0.82, 0.97)(.)(0.65, 0.80, 0.90) ≅ (0.40, 0.66, 0.88). Similarly, the fuzzy weights of five alternatives for the remaining criteria are calculated as summarised in Table 9.

Table 10
Distances *d*(Aj, A*) and d(Aj, A-) of the alternatives from fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS) (i,j=1,2,3,4,5).

Alternatives	FPIS & FNIS	Criteria												Total
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	
A_1	$d(A_1. A^*)$	0.70	0.41	0.97	0.61	0.61	0.44	0.37	0.56	0.28	0.70	0.64	0.54	6.809
	$d(A_1. A^-)$	0.31	0.67	0.03	0.47	0.47	0.63	0.71	0.52	0.80	0.37	0.43	0.53	5.952
A_2	$d(A_2. A^*)$	0.47	0.65	0.90	0.44	0.61	0.62	0.37	0.34	0.50	0.73	0.78	0.52	6.923
	$d(A_2. A^-)$	0.67	0.42	0.12	0.63	0.47	0.44	0.71	0.74	0.57	0.33	0.28	0.57	5.938
A_3	$d(A_3. A^*)$	0.71	0.35	0.97	0.44	0.56	0.38	0.22	0.38	0.34	0.34	0.50	0.39	5.586
	$d(A_3. A^-)$	0.30	0.72	0.03	0.63	0.51	0.70	0.86	0.72	0.75	0.73	0.59	0.69	7.220
A_4	$d(A_4. A^*)$	0.47	0.86	0.69	0.39	0.68	0.74	0.30	0.87	0.32	0.70	0.51	0.47	6.980
	$d(A_4. A^-)$	0.67	0.18	0.60	0.70	0.39	0.31	0.79	0.18	0.76	0.37	0.57	0.60	6.122
A_5	$d(A_5. A^*)$	0.67	0.68	0.95	0.37	0.61	0.52	0.31	0.59	0.31	0.47	0.53	0.52	6.518
	$d(A_5. A^-)$	0.34	0.38	0.05	0.71	0.47	0.55	0.77	0.49	0.79	0.61	0.56	0.57	6.299

Once the fuzzy decision matrix is constructed, the next step is to compute the fuzzy normalized decision matrix as depicted in Table 9. The fuzzy weighted normalized decision matrix for the five alternatives is calculated using Eq. (8). Afterwards, using Eqs. (9) and (10), the fuzzy positive ideal solution (FPIS, A^*) and negative ideal solution (FNIS, A^-) are detected, as provided in Table 10. Then, the Euclidean distance of each alternative from A^* and A^- can be computed using Eqs. (11), (12) and (13). Subsequently, the similarities to an ideal solution are found using Eq. (14). The values for each alternative for final ranking are shown in Table 11. Using the distances d_1^* and d_1^- , we calculate the closeness coefficients (CC_i) for all five alternatives using Eq. (14). For example, CC_1 for the alternative A_1 is as follows:

$$CC_1 = \frac{d_1^-}{d_1^* + d_1^-} = \frac{5.952}{5.952 + 6.809} \cong 0.466$$

Table 11
Closeness coefficients (CC_i) of the five alternatives.

Alternatives	d_i^*	d_i^-	CC_i	Ranking
A_1	6.809	5.952	0.466	4
A_2	6.923	5.938	0.462	5
A_3	5.586	7.220	0.564	1
A_4	6.980	6.122	0.467	3
A_5	6.518	6.299	0.491	2

The closeness coefficient for each location considered for CO_2 storage is shown in Table 11, yielding a final ranking of $A_3 > A_5 > A_4 > A_1 > A_2$. A_3 is the best among the five alternatives because it has the largest closeness coefficient (CC_i), while A_2 is the worst alternative.

4.1.1. Sensitivity Analysis

In here, we examine the impact of criteria weights on the location selection for CO_2 storage using Fuzzy TOPSIS through sensitivity analysis (Awasthi et al., 2011). We have performed 17 experiments with different weight settings for the criteria (using rating scales of Table 3). In the first seven experiments, the weights of all criteria are set to (0.9,1,1), (0.7,0.9,1), (0.5,0.7,0.9), (0.3,0.5,0.7), (0.1,0.3,0.5), (0,0.1,0.3) and (0,0,0.1). Then in the following experiments from 8–13, the weight of one criterion is set to the lowest (or highest) value, while the remaining weights are set to the highest (or lowest) value. For example, in experiment 11, the criterion C_1 has the highest weight (0.7,0.9,1) while the remaining criteria have weight (0.5,0.7,0.9).

The results from the sensitivity analysis are provided in Table 12 along with the settings used during each experiment and illustrated in Fig. 3. The location A_3 still turns out to be consistently the best alternative in all 17 experiments. This observation confirms that the location decision is relatively insensitive to the criteria weights while using Fuzzy TOPSIS.

Table 12
Experiments for sensitivity analysis.

Experiment Number	CC_i					Description
	A_1	A_2	A_3	A_4	A_5	
1	0.567	0.556	0.700	0.556	0.602	All criteria weights = (0.9,1,1)
2	0.520	0.513	0.632	0.515	0.551	All criteria weights = (0.7,0.9,1)
3	0.440	0.436	0.530	0.441	0.466	All criteria weights = (0.5,0.7,0.9)
4	0.335	0.333	0.401	0.339	0.354	All criteria weights = (0.3,0.5,0.7)
5	0.227	0.228	0.268	0.233	0.240	All criteria weights = (0.1,0.3,0.5)
6	0.127	0.129	0.147	0.133	0.134	All criteria weights = (0,0.1,0.3)
7	0.042	0.043	0.048	0.044	0.044	All criteria weights = (0,0,0.1)

8	0.523	0.516	0.635	0.519	0.553	Weight of criteria 1= (0.9,1,1) Weight of remaining criteria = (0.7,0.9,1)
9	0.526	0.515	0.639	0.516	0.553	Weight of criteria 2 = (0.9,1,1) Weight of remaining criteria = (0.7,0.9,1)
10	0.563	0.555	0.694	0.551	0.597	Weight of criteria 11 = (0.7,0.9,1) Weight of remaining criteria = (0.9,1,1)
11	0.449	0.442	0.540	0.444	0.473	Weight of criteria 6 = (0.7,0.9,1) Weight of remaining criteria = (0.5,0.7,0.9)
12	0.347	0.345	0.414	0.349	0.366	Weight of criteria 5= (0.5,0.7,0.9) Weight of remaining criteria = (0.3,0.5,0.7)
13	0.149	0.150	0.173	0.156	0.157	Weight of criteria 7= (0.3,0.5,0.7) Weight of remaining criteria = (0,0.1,0.3)
14	0.453	0.451	0.545	0.457	0.479	Weight of criteria 1 & 8 = (0.7,0.9,1) Weight of remaining criteria = (0.5,0.7,0.9)
15	0.270	0.256	0.315	0.281	0.287	Weight of criteria 9 & 11 = (0.5,0.7,0.9) Weight of remaining criteria = (0.1,0.3,0.5)
16	0.467	0.459	0.565	0.465	0.491	Weight of criteria 3. 6 & 12 = (0.9,1,1) Weight of remaining criteria = (0.5,0.7,0.9)
17	0.502	0.495	0.629	0.511	0.550	Weight of criteria 1. 2 & 5 = (0.3,0.5,0.7) Weight of remaining criteria = (0.9,1,1)

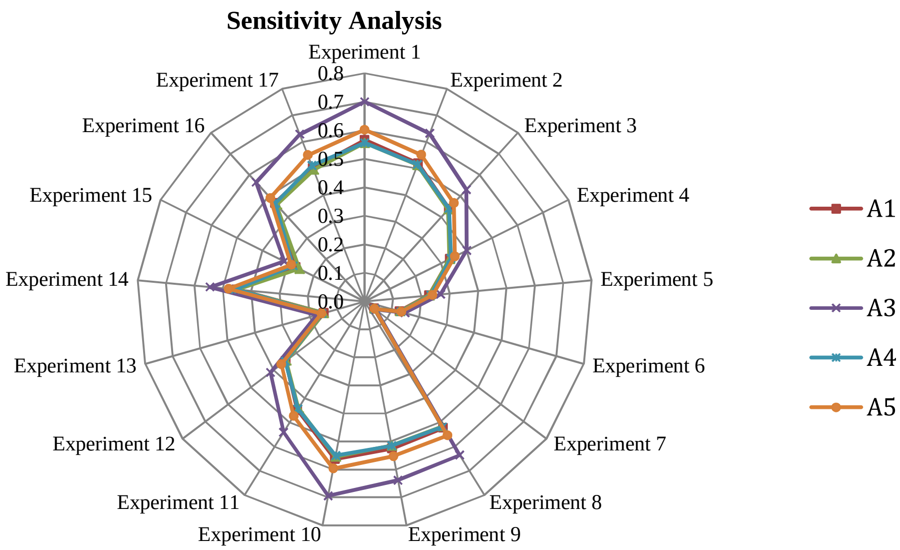

Fig. 3. Results of sensitivity analysis.

4.2. Fuzzy ELECTRE I Solutions

This table shows the distance between two actions *p* and *r* with respect to each criterion calculated using the Hamming distance method. Note that in Table 13, the first number and the second in each cell represent $d(max(\tilde{v}_{pj},\tilde{v}_{rj}),\tilde{v}_{rj})$ and $d(\max(\tilde{v}_{pj},\tilde{v}_{rj}),\tilde{v}_{pj})$, respectively.

Table 13
The distances between any two alternatives *p* and *r* with respect to each criterion (for the first six criteria).

C_1	X_{11}	X_{21}	X_{31}	X_{41}	X_{51}	C_2	X_{12}	X_{22}	X_{32}	X_{42}	X_{52}
X_{11}	-	(0, 0.25)	(0.01, 0)	(0, 0.25)	(0, 0.03)	X_{12}	-	(0.02, 0)	(0.02, 0)	(0.13, 0)	(0.03, 0)
X_{21}	-	-	(0.26, 0)	(0, 0)	(0.22, 0)	X_{22}	-	-	(0, 0)	(0.10, 0)	(0.01, 0)
X_{31}	-	-	-	(0, 0.26)	(0, 0.04)	X_{32}	-	-	-	(0.10, 0)	(0.01, 0)
X_{41}	-	-	-	-	(0.22, 0)	X_{42}	-	-	-	-	(0, 0.10)
X_{51}	-	-	-	-	-	X_{52}	-	-	-	-	-
C_3	X_{13}	X_{23}	X_{33}	X_{43}	X_{53}	C_4	X_{14}	X_{24}	X_{34}	X_{44}	X_{54}
X_{13}	-	(0, 0.05)	(0, 0)	(0, 0.45)	(0, 0.01)	X_{14}	-	(0, 0)	(0, 0)	(0, 0)	(0.01, 0)
X_{23}	-	-	(0.05, 0)	(0, 0.40)	(0.04, 0)	X_{24}	-	-	(0, 0)	(0, 0.01)	(0.01, 0)
X_{33}	-	-	-	(0, 0.45)	(0, 0.02)	X_{34}	-	-	-	(0, 0.01)	(0.01, 0)
X_{43}	-	-	-	-	(0.44, 0)	X_{44}	-	-	-	(0, 0)	(0.01, 0)
X_{53}	-	-	-	-	-	X_{54}	-	-	-		-
C_5	X_{15}	X_{25}	X_{35}	X_{45}	X_{55}	C_6	X_{16}	X_{26}	X_{36}	X_{46}	X_{56}
X_{15}	-	(0, 0)	(0, 0)	(0.01, 0)	(0, 0)	X_{16}	-	(0.01, 0)	(0, 0)	(0.05, 0)	(0, 0.01)
X_{25}	-	-	(0, 0)	(0.01, 0)	(0, 0)	X_{26}	-	-	(0, 0.02)	(0.04, 0)	(0, 0.02)
X_{35}	-	-	-	(0.01, 0)	(0, 0)	X_{36}	-	-	-	(0.06, 0)	(0, 0.01)
X_{45}	-	-	-	-	(0, 0.01)	X_{46}	-	-	-	-	(0, 0.07)
X_{55}	-	-	-	-	-	X_{56}	-	-	-	-	-

Table 14
The concordance matrix.

	Alternatives				
	A_1	**A_2**	**A_3**	**A_4**	**A_5**
A_1	-	(4.2, 5.4, 6.2)	(2.4, 2.8, 3.0)	(3.6, 4.6, 5.4)	(3.0, 3.9, 4.5)
A_2	(4.4, 5.6, 6.4)	-	(2.8, 3.5, 3.8)	(3.0, 3.8, 4.4)	(3.7, 4.7, 5.4)
A_3	(5.1, 6.7, 8.0)	(5.3, 6.9, 8.0)	-	(4.6, 6.0, 7.1)	(4.6, 6.0, 7.1)
A_4	(4.5, 5.7, 6.5)	(5.3, 6.7, 7.5)	(3.0, 3.6, 3.9)	-	(3.4, 4.2, 4.7)
A_5	(4.8, 6.2, 7.2)	(4.6, 6.1, 7.1)	(3.0, 3.6, 3.9)	(4.2, 5.4, 6.3)	-
$\tilde{\tilde{X}}$	(3.96, 5.05, 5.80)				

Table 14 shows the concordance matrix obtained by using Eq. (18). Also Table 15 shows the discordance matrix obtained by using Eq. (21). Boolean matrices *G* and *H* are show in Table 16. The global matrix is shown in Table 17.

Table 15
The discordance matrix.

	Alternatives				
	A_1	A_2	A_3	A_4	A_5
A_1	-	0.18	1.00	0.28	0.82
A_2	1.00	-	1.00	0.26	1.00
A_3	0.77	0.32	-	0.28	0.57
A_4	1.00	1.00	1.00	-	1.00
A_5	1.00	0.34	1.00	0.24	-
$\bar{Y}$	0.70				

Table 16
Boolean matrices G and H.

	Alternatives				
	A_1	A_2	A_3	A_4	A_5
A_1	-	1	0	0	0
A_2	1	-	0	0	0
A_3	1	1	-	1	1
A_4	1	1	0	-	0
A_5	1	1	0	1	-

(a) G based on the minimum concordance

	Alternatives				
	A_1	A_2	A_3	A_4	A_5
A_1	-	1	0	1	0
A_2	0	-	0	1	0
A_3	0	1	-	1	1
A_4	0	0	0	-	0
A_5	0	1	0	1	-

(b) H based on minimum discordance level

Table 17
The global matrix.

	Alternatives				
	A_1	A_2	A_3	A_4	A_5
A_1	-	1	0	0	0
A_2	0	-	0	0	0
A_3	0	1	-	1	1
A_4	0	0	0	-	0
A_5	0	1	0	1	-

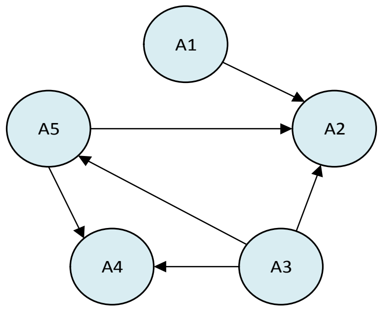

Fig. 4. The decision graph for the numerical example.

Finally, the decision graph is formed and shown in Fig. 4. As shown in this figure, location A_3 is categorized as the first ranking option, because three arcs originate from the nodes A_3. That means that A_3 is preferred over A_2, A_5 and A_4. Moreover, location A_5 is categorized as the second best option. A_2 and A_4 are ranked as the last two locations, because all actions are dominated by A_2 and A_4. According to Table 18, A_3 is selected as the best location among five location alternatives for the CO_2 storage.

Table 18
Final ranking.

Alternatives	Submissive alternatives	Final ranking
A_1	A_2	3
A_2	-	-
A_3	A_2, A_4, A_5	1
A_4		-
A_5	A_2, A_4	2

4.3. Fuzzy VIKOR Solutions

The fuzzy best and worst values are determined using equations (27) and (28) and they are indicated in Table 19 as follows.

Table 19
Fuzzy best values ($\tilde{f}_i^*$) and fuzzy worst values ($\tilde{f}_i^-$).

Criteria	$\tilde{f}_i^*$	$\tilde{f}_i^-$
C_1	(8.00,9.50,10.0)	(3.00,5.00,7.00)
C_2	(7.00,8.75,9.75)	(0.75,1.50,3.00)
C_3	(7.50,8.75,9.75)	(0.25,1.00,2.50)
C_4	(8.00,9.50,10.0)	(3.50,5.50,7.50)
C_5	(8.00,9.50,10.0)	(4.50,6.50,8.25)
C_6	(7.00,8.75,9.75)	(1.75,3.25,5.00)
C_7	(8.00,9.50,10.0)	(5.50,7.50,9.00)
C_8	(7.00,8.50,9.25)	(0.25,1.25,3.00)
C_9	(6.50,8.25,9.25)	(3.50,5.50,7.25)
C_{10}	(8.00,9.50,10.0)	(1.75,3.50,5.50)
C_{11}	(6.00,8.00,9.50)	(1.25,3.00,5.00)
C_{12}	(8.50,9.75,10.0)	(5.00,7.00,8.50)

Using equations (29) and (30) the distances of the alternatives to the best and worst values are calculated and they are indicated in Table 20 (a) as follows. $\tilde{S}^*$, $\tilde{S}^-$, $\tilde{R}^*$ and $\tilde{R}^-$ values found using equations (31) and (32) and $\tilde{Q}_i$ values calculated by being located in its place in the equation (33) are indicated in Table 20 (b).

Table 20
Index values.

Alternatives	$\tilde{S}_j$	$\tilde{R}_j$
A_1	(3.480,4.339,4.748)	(0.800,0.950,1.000)
A_2	(5.769,7.030,7.548)	(0.800,0.950,1.000)
A_3	(0.546,0.550,0.357)	(0.183,0.234,0.270)
A_4	(5.336,6.594,7.129)	(0.850,0.975,1.000)
A_5	(3.343,3.651,3.002)	(0.429,0.573,0.583)

(a) $\tilde{S}_j$ and $\tilde{R}_j$

	Values
Min $\tilde{S}^*$	(0.546,0.550, 0.357)
Max $\tilde{S}^-$	(5.769,7.030,7.548)
Min $\tilde{R}^*$	(0.183,0.234,0.270)
Max $\tilde{R}^-$	(0.850,0.975,1.000)

(b) $\tilde{S}^*$, $\tilde{S}^-$, $\tilde{R}^*$ and $\tilde{R}^-$ values

Triangular fuzzy numbers are simplified and alternatives are listed according to "$\tilde{Q}_i$" index. The minimum value of this index indicates the best alternative. Then, the values of Q_i, S_i and R_i in are calculated for alternatives as presented in Table 21.

Table 21
Ranking of alternatives according to Q_i index.

Alternatives	Q_i			Q_i		S_i		R_i	
	l	m	u	Index	Ranking	Index	Ranking	Index	Ranking
A_1	0.74	0.78	0.81	0.77	3	4.19	3	0.92	3
A_2	0.96	0.98	1.00	0.98	5	6.78	5	0.92	3
A_3	0.00	0.00	0.00	0.00	1	0.48	1	0.23	1
A_4	0.96	0.97	0.97	0.97	4	6.35	4	0.94	4
A_5	0.45	0.47	0.40	0.44	2	3.33	2	0.53	2

The ranking of the alternative locations by Q_i, S_i and R_i in decreasing order is shown in Table 22. We can conclude that A_3 alternative is the best location for CO_2 storage; on the other hand, A_5, A_1, A_4 and A_2 are less suitable locations than A_3 alternative.

Table 22
The ranking of the alternatives.

	Ranking Alternatives
Q_i	$A_3 > A_5 > A_1 > A_4 > A_2$
S_i	$A_3 > A_5 > A_1 > A_4 > A_2$
R_i	$A_3 > A_5 > A_1 = A_2 > A_4$

4.4. Comparison of results from the MCDM methods

The results from the proposed fuzzy methodologies are provided in Table 23. The best location for storing CO_2 emissions in Turkey is determined as A_3 (*Diyarbakir*) regardless of the fuzzy multi-criteria decision making method used.

Table 23
Result of proposed methodologies.

Alternatives	Fuzzy TOPSIS	Fuzzy ELECTRE	Fuzzy VIKOR
A_1	4	3	3
A_2	5	-	5
A_3	1	1	1
A_4	3	-	4
A_5	2	2	2

The ranking of alternatives obtained from fuzzy TOPSIS is $A_3 > A_5 > A_4 > A_1 > A_5$, while $A_3 > A_5 > A_1$ is obtained by fuzzy ELECTRE, which is a similar result although they are based on different decision schemes. Closeness coefficient is used as a basis for determining the ranking order for TOPSIS. In VIKOR, the aggregate functions are always closest to the ideal values. It is not surprising that ranking result from ELECTRE is similar to VIKOR, since they are based on similar decision schemes which consider maximum group of utility and minimum individual regret. A balance between a maximum group utility of the majority, obtained by concordance that represents the utility measure S_i and a minimum of individual regret of the opponent, obtained by discordance that represents the regret measure R_i is ensured by the compromise solution of ELECTRE method. However, the computational effort required by ELECTRE is more than the VIKOR method (Anojkumar et al., 2014).

5. Conclusion

This study presents the use of fuzzy MCDM methods based on TOPSIS, ELECTRE and VIKOR to assess the suitable location for CO_2 storage. A real case example from Turkey is illustrated for evaluating the results of the proposed model by these three methods. Since the three methods that are used for ranking in our problem give similar results, these methods can also give successful results for CO_2 location selection. All those methods detects A_3 *(Diyarbakir)* as the best alternative for CO_2 storage location in Turkey based on the set of criteria. Diyarbakir is also one of the most important cities of Turkey for having finished oil reservoirs and for its geopolitical location.

The main aim of this study was to investigate how fuzzy TOPSIS, fuzzy ELECTRE I and Fuzzy VIKOR can be utilized to solve the facility location selection problem for CO_2 storage. The proposed solutions based on the determined set of criteria are general and reusable; hence, they can be applied to the same problem in other countries than Turkey. It is important to keep in mind that the other multi criteria decision methods (fuzzy AHP, fuzzy ANP, fuzzy PROMETHEE, Fuzzy DEMATEL etc.) and/or their combinations can also be used as effective solutions to the facility location selection problems.

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