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APPLICATION OF MULTI-CRITERIA DECISION MAKING FOR GEOLOGICAL CARBON DIOXIDE STORAGE AREA IN TURKEY

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ABSTRACT

In contemporary era, carbon sequestration has become an important issue. Rapidly increasing population, higher life-standards and technological advancements consistently increase the amount of emissions, especially CO_2. Nowadays, the most promising solution is to minimize the carbon dioxide emissions with using carbon capture and storage (CCS) technologies for a better future. The problem is to choose the best location for CO_2 storage which is a crucial and challenging multicriteria decision problem. The objective of this paper is to determine the most appropriate city for carbon dioxide storage in Turkey, by demonstrating a successful implementation of Multi-criteria Decision Making (MCDM) tool. This study presents the use of MCDM method based on Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to assess the suitable location for CO_2 storage. For that purpose, 4 alternative locations were evaluated via 8 criteria which are determined according to the opinions of the experts with background information from the field. Towards this end, MCDM method, namely, TOPSIS, was utilized for the location evaluation. Consequently, this method detects Diyarbakır as CO_2 storage area which is also one of the most important city of Turkey for having finished oil reservoirs and for its geopolitical location.

Keywords: Carbon sequestration, Geological storage, Global warming, MCDM, TOPSIS

1. INTRODUCTION

The demand for natural resources and energy with the increase in population around the world is gradually increasing. The world's population has increased by 2.5 times since 1950, and the energy demand has increased seven-fold. Compared to the present, in 2030, it is expected to increase in a ratio ranging from 40 to 50% of the energy consumption worldwide, and to increase higher than 100% of this consumption in Turkey [1]

Considering the primary sources of energy, electric energy which is equivalent to 230 million barrels of oil energy is consumed in the world every day. About 200 million barrels of electrical energy are generated from fossil fuels. In the energy sector, petroleum, natural gas and coal are considered together, with the hydrocarbon weighted [2]. Increase in the usage of fossil fuels such as coal, petroleum and natural gas causes a major problem due to their destructive effects on the environment in different sectors. This damage directly related with the greenhouse gas (GHG) emissions such as carbon dioxide (CO_2), NO_x, SO_2, etc. However, the most common greenhouse gas is CO_2 due to the high amount of emission because of the combustion of hydrocarbon fuels. Global warming potential (GWP) was 35.3 Gt in 2014 because of carbon dioxide emission, there is a %55.6 increase only in the last 13 years [1]. Atmospheric carbon dioxide concentration has increased 27% from 315.71 ppm in 1958 to 400.26 ppm in 2015 [3] and average global temperature increased by about 0.8°C since 1880 [4]

According to United States Environmental Protection Agency; in the next century, atmospheric carbon dioxide concentration will be between 450-980 ppm and the temperatures will increase by 2.2-4.4°C [2]. According to the World Energy Outlook Report, CO_2 emission will increase 63% by 2030 from

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today's level, which is 90% higher than the 1990 CO_2 emission level. Thus, stronger actions/policies are required and expected from the governments, including generation and utilization of certain technology options to avoid massive CO_2 emission increases [5]

There are many revolutionary designs to decrease the amount of carbon dioxide emissions, but they are not feasible in most cases. The real question is how fossil fuels can be burned in more eco-friendly way. Nowadays, the most promising solution is using carbon capture and storage (CCS) technologies to minimize the carbon dioxide emissions for a better future. The whole process for CCS is to prevent the carbon dioxide release to atmosphere from exhaust gas of the burned fossil fuels such like coal and natural gas. 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 et al. (2010) [6]; Liao et al. (2014) [7]; Kissinger et al. (2014) [8]. CCS can make large reductions in greenhouse gas emissions, which involves capturing CO_2 in deep geological formations [9].

There are four main carbon capturing ways; from industrial processes, from flue gases produced by combustion of fossil fuels and biomass in air is referred to as post-combustion capture, from flue gases produced by oxyfuel combustion with pure oxygen instead of air or, by a physical or chemical absorption process, resulting in a hydrogen-rich fuel which can be used in many applications, such as boilers, furnaces, gas turbines, engines and fuel cells, is referred to as pre-combustion capture.

After the capturing process, the greenhouse gas can be stored in underground reservoirs or stored in ocean or stored as carbonated mineral form. Especially, geological storage of CO_2 is the best way to extinguish the emissions released to atmosphere by capturing CO_2 from combustion chambers, transporting it to the injection facility by using a pipeline and storing CO_2 in geological formations. It is estimated that 99 % of the CO_2 will be injected and stayed for about 1000 years underground with geological storage.

There are some previous studies proposing a variety of solution methods to find the optimum location for CO_2 storage in geological reservoirs. For example, Grataloup et al. (2009) focused on-site selection for CO_2 underground storage in deep saline aquifers [10]. Another study addressed different aspects while considering potential CO_2 storage reservoirs, including safety and economic feasibility of each location [8]. Ramirez et al. (2010) studied a methodology to screen and rank Dutch reservoirs suitable for long-term large-scale CO_2 storage [11]. The screening was focused on gas, oil and aquifers fields. Llamas and Cienfuegos (2012) presented a methodology for the selection of site areas for CO_2 geological storage based on an analytic hierarchy process (AHP) [12]. Ertugrul and Karakasoglu (2008) compared MCDM methods for facility location selection [13]. The proposed methods were applied to a facility location selection problem of a textile company in Turkey. 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 [14]. 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.

The objective of this paper is to determine the most appropriate city for carbon dioxide storage in Turkey, by demonstrating a successful implementation of MCDM tool. MCDM techniques are gaining popularity in energy supply systems. MCDM techniques provide the means to solve such problems supporting decision makers with the best option from a set of alternatives with respect to different factors [15]. To evaluate the selected area for CO_2 storage, a comprehensive analysis is developed using some of the most prominently used MCDM technique, namely TOPSIS method. Based on the results of the analysis, the most appropriate and the least desirable set of actions are determined for CO_2 storage. Although the results are specifically developed for cities of Turkey, the techniques that are used in this work might be inspiring for the other countries around the world. Like many other countries in the world, the annual increase of CO_2 emission in Turkey is quite high.

2. METHODOLOGY

In literature, Deveci, M., et al. (2015) made a comparison of five cities Adiyaman, Aksaray, Diyarbakir, Afyon and Tekirdag in Turkey by choosing twelve criteria [16] Another studies from the world; Grataloup et al. (2009) studied possible site location selection for Paris Basin for CO_2 underground storage in deep saline aquifers [10]. Ramirez et al. (2010) gave a methodology to screen and rank CO_2 reservoirs suitable for storage application [11].

Our approach is like theirs in terms of involving several economic criteria (such as initial investment cost, operation cost, transportation cost) rather than combining them all under the roof of a single “economic” criterion. However, we find that their “benefit” criteria can be accounted for within the “cost” criteria, thereby creating a single matrix of criteria which need to be minimized. Basically, cost criteria and benefit criteria were distinguished in TOPSIS. Best solution for benefits criteria is close to ideal positive cost criteria; while best solution for cost criteria, is close to ideal negative. TOPSIS is developed for solving multiple decision-making problems by considering two reference points of the ideal positive solution and the ideal negative solution simultaneously, best solution is the one that close to the ideal positive solution and far away from the negative ideal solution.

2.1. Background information

Geological storage of CO_2 is a way to eliminate the emissions released to atmosphere by capturing CO_2 from combustion chambers, transporting it to the injection facility by using a pipeline and storing CO_2 in geological formations. Three main geological storage areas are commonly used for CO_2 storage. First one is injection into suitable depleted oil and gas reservoirs left from fuel production, second one is saline aquifers that are unsuitable for using as water source and last one is injection to un-minable coal and basalt deposits. But this study is only focused on suitable oil and gas reservoirs for CO_2 storage.

According to the number of wells some areas were considered to choose the best option for CO_2 storage capacity (as seen in Table 1). The number of wells gives information about possible storage zones and capacity of geological reservoirs which is related with criteria 1 (C1). Turkey has five oil and natural gas well zones in which four of these places highly used for petroleum extracting and one is for natural gas. Injecting CO_2 into petroleum reservoirs is a better option to use in enhanced oil recovery. Therefore, in this study, four areas were determined as potential storage zones as seen in Table 1.

Table 1. Number of wells in four areas [17]

Areas	**Well numbers**
Adıyaman	**185**
Diyarbakır	**271**
Batman-Siirt	**209**
Mardin-Şırnak	**81**

In this project, three closest plants were also considered for every storage zone. Less than 20MW capacity plants were eliminated due to their low carbon dioxide amount (as seen in Table 2). Criteria 2 which is source proximity can be determined by using average distance to the storage zones.

Table 2. Closest power plants to the storage zones

Storage Zones	Three Closest Power Plants	Distance to Storage Zone	Average distance (km)
Adıyaman	Afşin-Elbistan B Coal PP	126km	86
	AKSA Şanlıurfa Natural Gas PP	74km	
	ODAŞ Şanlıurfa Natural Gas PP	57km	
Diyarbakır	Mardin-1,2 Fuel Oil Plant	83km	110
	AKSA Şanlıurfa Natural Gas PP	134km	
	ODAŞ Şanlıurfa Natural Gas PP	114km	
Batman-Siirt	Mardin-1,2 Fuel Oil Plant	74km	71
	İdil Fuel Oil Plant	54km	
	Silopi Coal PP	85km	
Mardin-Şırnak	Mardin-1,2 Fuel Oil Plant	76km	55
	İdil Fuel Oil Plant	19km	
	Silopi Coal PP	69km	

Maximum electricity production in power plants directly related with CO_2 emissions. Therefore, comparison between the selected power plants depends on this parameter to clarify the maximum supply from the plant to the atmosphere. The emission of CO_2 per unit of electrical energy generated is 900 g CO_2/kWh from coal combustion and 400g CO_2/kWh from natural gas combustion. Increased use of natural gas is important to greenhouse gas reduction because natural gas emits about half the amount of carbon dioxide than coal for the same energy produced (as seen in Table 3). Table 3 can be considered to determine the maximum supply from the power plants which helps us to clarify the criteria 3 and 4 (C3 and C4). Closest power plants which are given in Table 3, are only in operation except the others in Table 2. So, we must take consider only these power plants in Table 3 for CO_2 emissions to the atmosphere.

Table 3. Closest Power Plants with their capacity, used fuel, annual generation and CO_2 release [18]

Closest Power Plants	Installed Capacity (MW)	Used Fuel	Generation (GWh/year)	Kg's of CO_2 release per kWh
Afşin-Elbistan B	1440	Coal	1430	0.9
Afşin-Elbistan A	1355	Coal	1029	0.9
Silopi	405	Asphaltene	2204	0.9
ODAŞ Şanlıurfa	140	Natural Gas	566	0.4
AKSA Şanlıurfa	147	Natural Gas	540	0.4

Geological topography of Turkey is very young and that creates constant changes in tectonic plates. Tectonic activity is an important parameter to choose an appropriate injection site. Seismic zones map of Turkey in Figure 1 published by the Ministry of Public Works and Settlement in 1996, which is also approved by the Council of Ministers, and used geographic information system analysis to divide Turkey into 4 regions as follows. On the seismic zones map of Turkey, first-degree seismic zone is taken as region 1, second-degree seismic zone is taken as region 2, third-degree seismic zone is taken as region 3, fourth-degree and fifth-degree seismic zones are taken as region 4 [19]. Adıyaman and Diyarbakır are in region 2, Batman-Siirt region is in region 1-2 and Mardin-Şırnak is in region 2-3. This map can be considered to determine the possible safety zones for CO_2 storage and clarify criteria 5 (C5).

In literature, total cost for integrated CCS system in US$/ton based on the current technology. Capture cost has the highest share for all power plants as seen in Table 4. Total cost per metric ton of CO_2 is the highest for new natural gas combined cycle plants. According to table 4 from the literature, experts have decided to give high points to Adıyaman and Diyarbakır, low points to the other regions for criteria 6 (C6).

Table 4. Total cost for integrated CCS system [20]

US$/ton	Pulvarized Coal	Integrated gas combined cycle (IGCC)	Natural gas combined cycle (NGCC)
CO_2 capture cost	65.9	52.3	214
Transportation Cost	3.5	3.5	3.5
Storage Cost	3.2	3.2	3.2
Total Cost	72.6	59	220.7

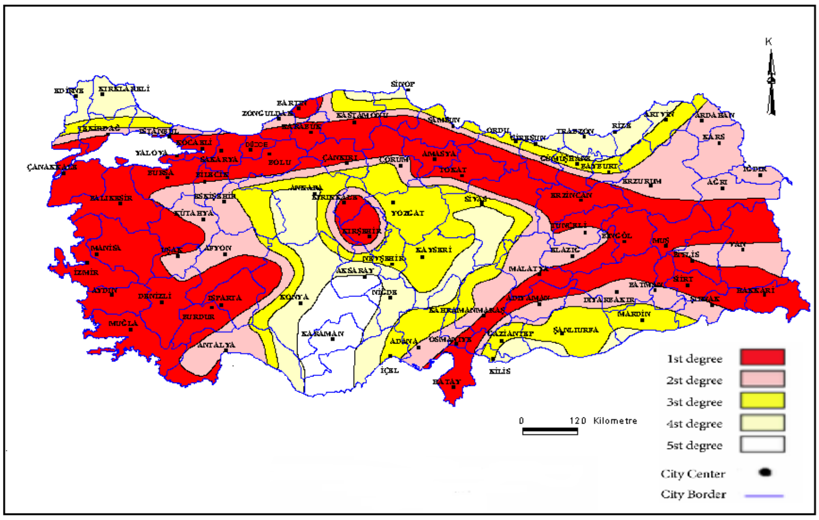

Figure 1. Seismic zones map of Turkey [19]

According to the socio-economic development in South Eastern Anatolia region, the order of cities is Diyarbakır > Adıyaman > Batman-Siirt > Mardin-Şırnak. Therefore, this information gives an idea about transportation availability (C7) and infrastructure availability criteria (C8) [21].

2.2. Case Study

This study presents a model using a method for selecting candidate sites for underground CO_2 geological storage in Turkey. A committee of decision makers (D1, D2, D3 and D4) with background information was formed to select the best alternative using 8 criteria as provided in Table 4. Four alternative locations for depleted reservoirs (depleted oil and gas reservoirs) are determined by using background information about different locations in Turkey: Adıyaman, Diyarbakır, Mardin-Şırnak and Batman-Siirt. They were evaluated by MCDM method named TOPSIS. Structure of CO_2 storage area selection with MCDM method is shown in Figure 2.

In summary, the evaluation criteria that are selected in our model are “Cost”, “Transportation availability”, “Infrastructure availability”, “Regional risks”, “Environmental contribution”, “Storage capacity” “Source proximity”, “Maximum Supply” which has a more detailed version of the general sets of technical, environmental/social and economic criteria as seen in Table 5.

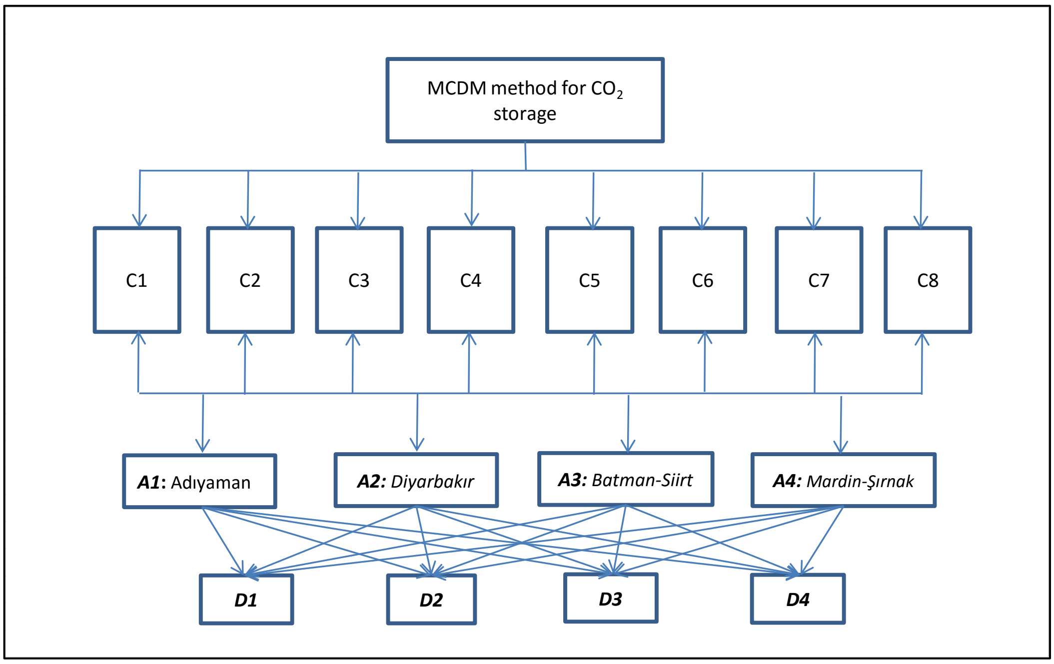

Figure 2. Best location selection for CO_2 storage with MCDM method

Table 5. Main and sub-criteria of carbon dioxide storage in geological reservoir with their type and definitions

Main Criteria	Sub-Criteria	Definition	Criteria Type
Technical	Storage capacity (C1)	The capacity of the underground geological formations (number of wells)	Benefit
	Source proximity (C2)	Distance to thermal power plants (km to CO_2 resources)	Benefit
	Maximum Supply (C3)	kg CO_2 /kWh (from powerplants)	Benefit
Environmental /Social	Environmental contribution (C4)	Social (human health) and environmental contributions.	Benefit
	Regional risks (C5)	Risks in the region (like earthquake risk, natural risk, etc.)	Cost
Economical	Cost (C6)	Initial for the investment, maintenance cost, transportation cost	Cost
	Transportation availability (C7)	Quality of transportation and distribution infrastructure.	Benefit
	Infrastructure availability (C8)	Technological quality and availability of basic infrastructure, pressure and flow systems.	Benefit

3. RESULTS AND DISCUSSION

The assessments for the eight criteria are determined by experts from the field with background information which also evaluate the four alternatives (locations) for each of the 8 criteria. This study presents a model using a method for selecting candidate sites for underground CO_2 geological storage in Turkey. The next step is to determine the best storage area according to the selected criteria and form a "decision matrix" to be used in TOPSIS method. To this end, again a combination of expert opinions and the relevant literature is used, and a "criteria vs methods" matrix is formed as in Table 5 initially. A scale of 1 to 10 is used, where one corresponds to the situation where the method has little impact on the criterion, while 10 corresponds to the situation where the method has high impact on/high relation with the criterion. The decision matrix is then formed using Table 5, the storage areas in different cities and the point score of each city according to each criterion.

Four alternative locations for depleted reservoirs (depleted oil and gas reservoirs, aquifer reservoirs, salt cavern reservoirs, coal mine and mined cavern) are determined by experts: Adiyaman (A1), Diyarbakir (A2), Mardin-Şırnak (A3) and Batman-Siirt (A4). The TOPSIS method starts with the decision matrix in Table 6. Next, a standard decision matrix is computed by using the elements of decision matrix, and the weighted standard decision matrix is developed by multiplying the values in the standard decision matrix with the weight value of that criterion. Since [22] suggests assigning equal weights to each evaluation criterion to reduce social conflicts and increase fairness, we used equal weights for each criterion.

Table 6. Decision matrix

Alternatives	C1	C2	C3	C4	C5	C6	C7	C8
Adıyaman (A1)	**185**	86	10	7	8	8	9	7
Diyarbakır (A2)	**271**	110	8	7	9	10	7	8
Batman-Siirt (A3)	**209**	71	6	9	7	7	6	6
Mardin-Şırnak (A4)	**81**	55	6	5	6	5	5	6

Table 7. Normalized decision Matrix

Alternatives	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.46555	0.51802	0.65094	0.49010	0.52750	0.51856	0.65122	0.51465
A2	0.68197	0.66258	0.52076	0.49010	0.59344	0.64820	0.50650	0.58817
A3	0.52595	0.42766	0.39057	0.63013	0.46157	0.45374	0.43414	0.44113
A4	0.20384	0.33129	0.39057	0.35007	0.39563	0.32410	0.36179	0.44113

TOPSIS method is conducted; a normalized decision matrix and a weighted normalized decision matrix are developed based on the decision matrix presented in Table 6.

The next step in TOPSIS methodology is to compute the ideal (A^*) and the negative ideal (A^-) solutions. TOPSIS method assumes that each evaluation criterion has an increasing or decreasing trend. That is, in a cost-minimization problem as ours, to form the positive ideal solution set (negative ideal solution set), the minimum (maximum) value in each column of the weighted standard decision matrix should be selected. The normalized and weighted normalized decision matrix of the 8 criteria are presented in Table 7 and Table 8, respectively.

Table 8. Weighted normalized decision matrix

Alternatives	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.05819	0.06475	0.08137	0.06126	0.06594	0.06482	0.08140	0.06433
A2	0.08525	0.08282	0.06509	0.06126	0.07418	0.08103	0.06331	0.07352
A3	0.06574	0.05346	0.04882	0.07877	0.05770	0.05672	0.05427	0.05514
A4	0.02548	0.04141	0.04882	0.04376	0.04945	0.04051	0.04522	0.05514

Finally, the alternatives are evaluated using TOPSIS method. TOPSIS is developed by Yoon and Hwang in 1980 [23] as an alternative to ELECTRE method and based on the principle of proximity of decision points to the ideal solution. Ideal solution is the best performance on each criterion; however, in general different solutions produce the ideal solution under each criterion, rendering to reach the ideal solution by selecting a single decision alternative impossible. Therefore, the decision maker proceeds with selecting the closest alternative to the ideal solution. Towards that end, the vector of "Positive Ideal Solution (PIS)", which maximizes profit criterion and the vector of "Negative Ideal Solution (NIS)" which maximizes cost criterion are developed. According to TOPSIS, best alternative should be closest to PIS, and farthest from the NIS [24] The PIS and NIS that are developed based on the previous steps are shown in Table 8. The positive ideal solution (PIS) set and the negative ideal solution (NIS) set that are developed based on the previous steps of the TOPSIS algorithm are shown in Table 9.

Table 9: PIS and NIS values

Criteria	**PIS**	**NIS**
Storage capacity	0.085246634	0.025479621
Source proximity	0.065817217	0.03949033
Maximum Supply	0.083451858	0.050071115
Regional risks	0.024592415	0.073777246
Cost	0.058114889	0.087172334
Environmental contribution	0.076497537	0.045898522
Transportation availability	0.069904665	0.038835925
Infrastructure availability	0.070803205	0.044252003

Next, the deviations of each decision point from the ideal and negative ideal solutions are computed via using Euclidian Distance Approach; and the relative proximity of each decision alternative to the ideal solution (C_i^*) is computed using the ideal and negative ideal separation measures. Here, C_i^* takes a value between 0 and 1; and the closer C_i^* value to 1 is, the closer the decision alternative is to the ideal solution; whereas the closer C_i^* value to 0 is, the closer is the decision alternative to the ideal solution [25]. Applying the appropriate formulas, the values of S_i^*, S_i^- and C_i^*; the result regarding the preferences of the alternatives are presented in Table 10.

Table 10: Final Computations and Ranking According to TOPSIS

Alternatives	**Positive Ideal Discrimination Measures (S_i^*)**	**Negative Ideal Discrimination Measures (S_i^-)**	**Closeness to Ideal Solution (C_i^*)**	**Ranking**
A1	0.04453703	0.070942854	0.614330838	2
A2	0.03885668	0.090357772	0.699285365	1
A3	0.07252811	0.048810603	0.402267344	3
A4	0.09815458	0.042859109	0.303935807	4

The ranking of alternatives obtained from fuzzy TOPSIS is A2> A1 > A3 > A4. Closeness coefficient is used as a basis for determining the ranking order for TOPSIS. We can conclude that *A2* alternative is the best location for CO_2 storage; on the other hand, *A1, A3* and *A4* are less suitable locations than *A2* alternative.

4. CONCLUSION

This study presents the use of MCDM method based on TOPSIS to assess the suitable location for CO_2 storage. A case study from Turkey is illustrated for evaluating the results of the proposed area by this method. The method can give successful results for CO_2 location selection. This method detects *A2 (Diyarbakır)* as the best alternative for CO_2 storage location in Turkey based on the set of criteria. *Diyarbakır* selected area 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 TOPSIS 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, it can be applied to the same problem in other countries than Turkey. We also show how these regions can be evaluated from all perspectives including economical, technical, environmental and social, by mathematical MCDM techniques. It is important to keep in mind that the other multi criteria decision methods (PROMETHEE I and II, etc.) and/or their combinations can also be used as effective solutions to the location selection problems. One limitation of the method described in this paper is the fact that MCDM methods depend heavily on expert opinion; as the weights attributed to each criterion play an important role in the result. Therefore, these solution procedures need a complimentary sensitivity analysis, which does not exist in MCDM by their nature. One way to handle this problem could be using mathematical programming procedures and conducting a sensitivity analysis to see how robust the results are for different ranges of parameter values. Our future research agenda includes this kind of an analysis procedure.

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