Application of the PROMETHEE and VIKOR methods for selecting the most suitable carbon dioxide geological storage option

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APPLICATION OF THE PROMETHEE AND VIKOR METHODS FOR SELECTING THE MOST SUITABLE CARBON DIOXIDE GEOLOGICAL STORAGE OPTION

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Abstract: CO_2 storage in geological formations is one of the leading solutions for mitigation of greenhouse gas emissions. Types of geological formations that can be used for CO_2 storage, that are discussed in this paper are: depleted oil and gas reservoirs, saline aquifers and injection CO_2 in partially depleted oil reservoirs for enhanced oil recovery (EOR–CO_2 method). In order to select the most suitable geological storage of CO_2, the ranking of these storage options was performed using two methods of multi criteria analysis, PROMETHEE and VIKOR.

This paper presents an overview of considered criteria (storage capacity, total storage costs, risk assessment costs, storage time dynamics, risk of CO_2 leakage from geological formation and risk of CO_2 leakage through the well), description of applied multi criteria analysis methods, selection of optimal CO_2 storage option and results of their application.

Keywords: PROMETHEE; VIKOR; multi criteria decision making; geological storage

1   INTRODUCTION

The concentrations of CO_2 in the atmosphere that are the main cause of global warming and climate change are constantly increasing, resulting from the combustion of fossil fuels during the process of electricity generation, certain industrial processes and transport. It is considered that one of the leading solutions for mitigation of CO_2 emissions is geological storage of CO_2, which includes three phases: capturing anthropogenic CO_2, transporting and injection into different types of geological formations such as: depleted oil and gas reservoirs, saline aquifers, unmined coal beds, injection CO_2 in partially depleted oil reservoirs for enhanced oil recovery (EOR–CO_2 method), as well as storage in salt caverns, basalt formations and oil or gas rich shale.

In order to select the most suitable geological storage of carbon dioxide, using two methods of multi criteria analysis, PROMETHEE and VIKOR, these storage options:

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depleted oil and gas reservoirs, saline aquifers and injection CO_2 in partially depleted oil reservoirs for enhanced oil recovery (EOR–CO_2 method) were ranked. Ranking of the geological formation is based on the following criteria: storage capacity, total storage costs, risk assessment costs, storage time dynamics, risk of CO_2 leakage from geological formation and risk of CO_2 leakage through the well.

2   OVERVIEW OF ANALYZED CRITERIA

The criteria that are considered in this paper in order to choose the optimal CO_2 storage option are geological, techno-economic parameters and risk factors.

All parameters are significant, but the most significant from the safety aspect, which is the most important characteristic of the geological storage, can be identified risk factors for migration and leakage of CO_2 (risk of CO_2 leakage from geological formation and risk of CO_2 leakage through the well).

Storage capacity

A number of methods have been developed to estimate the storage capacity based on different characteristics depending on the type of storage. Capacity assessment requires a multidisciplinary approach to the analysis of available data. The accuracy of the storage capacity assessment depends on the availability of data on the potential storage.

The analyzed parameters for estimating the storage capacity in depleted oil and gas reservoirs and during EOR-CO_2 process, include: original oil (or gas) in place, recoverable oil or gas reserves, porosity, reservoir rock volume, reservoir temperature and pressure, water saturation, potential water inflow, phase behavior of CO_2, solubility in water and possible spill point. The most important parameters for saline aquifers are: aquifer characteristics, water salinity, CO_2 solubility in water, as well as the presence of cap rocks continuity (Bachu,2002; Tomić, 2018).

The estimated storage capacity in depleted oil and gas reservoirs varies between 675 и 900 Gt CO_2 (Vishal, 2016). Storage capacity in saline aquifers is estimated at 1.000-10.000 Gt CO_2 (Cook, 2012), while the storage capacity during EOR-CO_2 process is the least and is 140 Gt (IEAGHG, 2009).

Total storage costs

Total storage costs include the costs related to the infrastructure for CO_2 capture and transportation, the costs of injection wells, as well as costs of field facilities whose value varies depending on storage option (Tomić, 2018).

Based on Hendriks (2002) if we neglect the capture and transportation costs, the most probably estimated storage costs, for „onshore" saline formations in Europe, located at

depth of 2 km, are 2,7 euro/t CO_2 stored. Offshore storage is more expensive than onshore storage. For offshore saline aquifers at the same depths, the most probable value is 7,3 euro/t CO_2 stored. Storage costs for onshore depleted oil and gas fields are 1,6 euro/tCO_2 stored, and for offshore formations the most probable value is 5,7 euro/tCO_2 stored.

Primary purpose of EOR-CO_2 projects are additional oil production, and therefore storage of CO_2 during the EOR-CO_2 process requires lower costs compared to storing in other formations. Storage costs for EOR-CO_2 at depths up to 2 km are reduced to minimum. The costs of storage depending on the actual oil price, as well as the depth of the storage reservoir (Hendriks, 2002).

Risk assessment costs

Risk assessment costs are significantly lower in researched storage, where a large number of reservoir and fluid data is available, which is the case for the storage of CO_2 in depleted hydrocarbon reservoirs and during the EOR-CO_2 process. Insufficient research of saline aquifers increases the risks of storage, and therefore the costs of risk assessment are very high. In order to reduce risks, large investments are needed in researching, collecting and analyzing the necessary data (IPCC, 2005).

Storage time dynamics

Storage time dynamics relates to the probability that a particular geological formation will become a geological storage in the near future. Aquifers are found in almost all sediments that are widespread around the world, and possess the largest storage capacities. It is believed that these geological formations need to be further explored, and exploit their potential.

After completing primary oil recovery, resorts to secondary oil production (waterflooding, ie. injection of water or gas) and tertiary (enhanced) oil recovery (EOR), therefore the reservoirs remain longer in production, so it cannot be said that a large number of depleted reservoirs will become a geological storage in the near future (IPCC, 2005).

Risk of CO_2 leakage from geological formation

The existence of impermeable barriers, i.e. cap rocks is a very important parameter for ensuring a long term CO_2 storage (Mortezaei, 2018). For this reason, cap rocks should have the following characteristics: to be laterally homogeneous, with low permeability and porosity which means that there is a high value of capillary entry pressure and to be ductile and resistant to high injection pressure (Rutqvist, 2012).

From the beginning of the CO_2 injection process, available monitoring methods are used at certain time intervals to monitor the CO_2 movement. If CO_2 leakage is detected,

appropriate remediation techniques are used depending on the type of leakage, in order to prevent further leakage to the surface (IPCC, 2005).

Insufficient research of saline aquifers i.e. a small number of reservoir data increases the risks of storage, as opposed to storage in depleted oil and gas reservoirs and during EOR-CO_2 process.

Figure 1 shows the possible leakage pathways for injected CO_2 into saline aquifers:

- CO_2 leaks through the cap rock due to injection pressure increase above the capillary pressure,
- Presence of faults enables CO_2 leakage into a freshwater aquifers,
- Leakage through natural fractures,
- Injected CO_2 goes up due to the presence of fault,
- CO_2 leakage through poorly plugged abandoned well,
- Due to natural water flow into the stored formation, saline water dissolves at the water/ interface and transports it out of closure,
- CO_2 migration through the spill point of the storage geological formation.
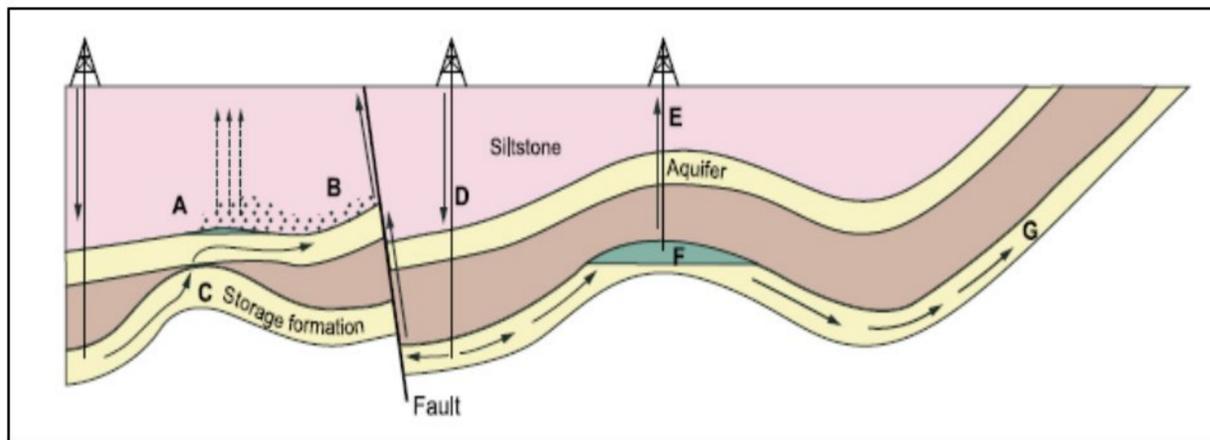
Figure 1 Possible leakage paths (IPCC, 2005)

Risk of CO_2 leakage through the well

The greatest risk of CO_2 leakage is the possibility of migration through active or abandoned wells because they represent a direct connection between the land surface and deep subsurface (IPCC, 2005). It is important to ensure well integrity in order to keep CO_2 safe inside the formation.

Modern well technology, and wells completion with corrosion-resistant materials, significantly reduces the risks of CO_2 migration. Since there is no existing infrastructure in saline aquifers, the use of new equipment reduces risks to a minimum.

Possible leakage pathways through an active and an abandoned well can be (Figure 2): through deterioration (corrosion) of the casing, between the cement and the outside of

the casing, in cement fractures, between the cement and the formation. In an active well CO_2 can also leakage through deterioration (corrosion) of the tubing and around the packer, and in an abandoned well through the cement plug and between the cement and the inside of the casing (Mortezaei, 2018).
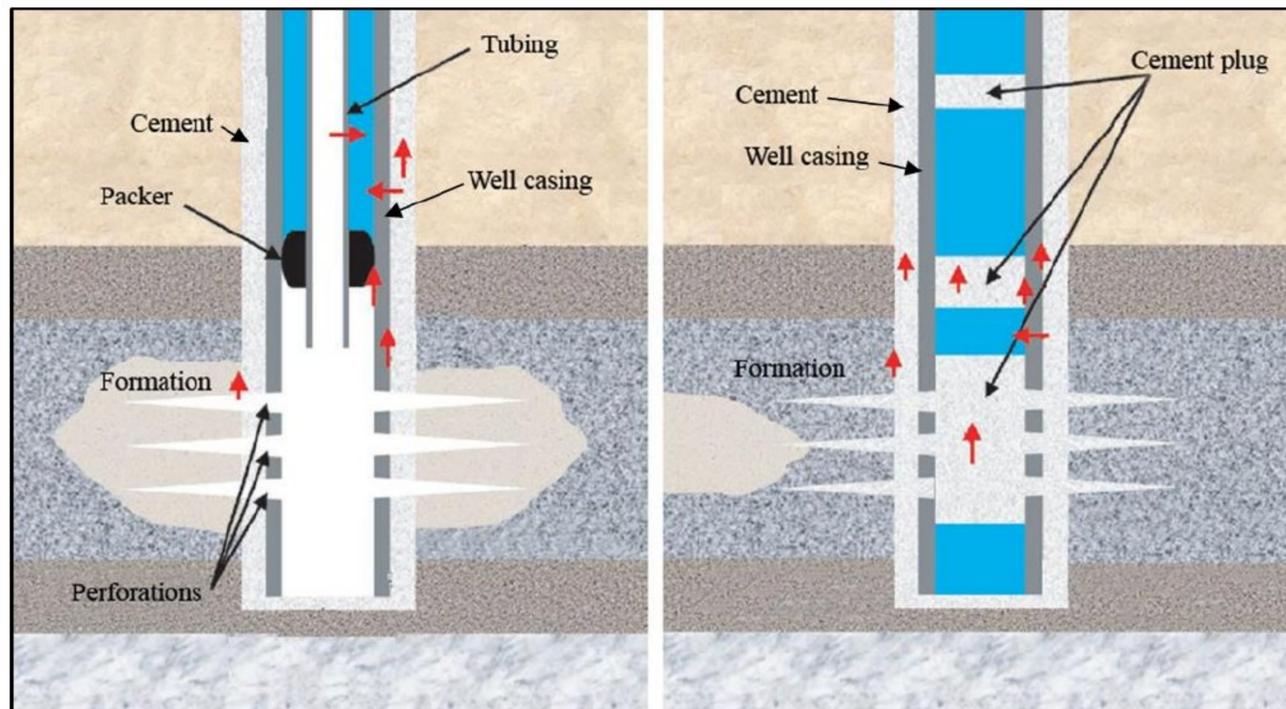
Figure 2 Possible leakage pathways in an active (left) and an abandoned (right) well
(adopted from Mortezaei, 2018)

3   MULTI CRITERIA DECISION MAKING (MCDM) METHODS

This section presents the theoretical basis of PROMETHEE and VIKOR methods.

PROMETHEE

The PROMETHEE (The Preference Ranking Organization METHod for Enrichment of Evaluations) is an outranking method (Papathanasious, 2018). There are 4 variants of the PROMETHEE method: PROMETHEE I for partial ranking of the alternatives, PROMETHEE II for complete ranking of the alternatives (Medić, 2017), PROMETHEE III for ranking based on intervals, and PROMETHEE IV for continuous case (Brans, 2005).

Below is a brief description of the PROMETHEE II method.

The PROMETHEE procedure is based on mutual comparison of every pair of alternatives on each criterion (Medić, 2017).

In order to rank the alternatives, PROMETHEE method introduces the **preference function** P(a,b), for alternative a and b. Alternatives a and b are evaluated according to

criteria functions. Alternative a is better than alternative b according to criterion f, if $f(a) > f(b)$. The preference function is defined as follows (Opricović, 1998):

$$P(a,b) = \begin{cases} 0, if\ f(a) \le f(b) \\ P(f(a) - f(b)), if\ f(a) > f(b) \end{cases} \tag{1}$$

$$d = f(a) - f(b) \tag{2}$$

Brans and Mareschal (2005) proposed six types of generalized criteria:

1. Usual criterion
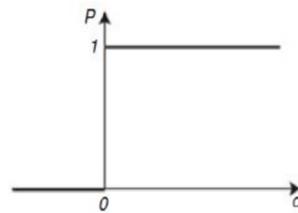
$$P(a,b) = \begin{cases} 0, if\ d \le 0 \\ 1, if\ d > 0 \end{cases}$$

2. Quasi criterion
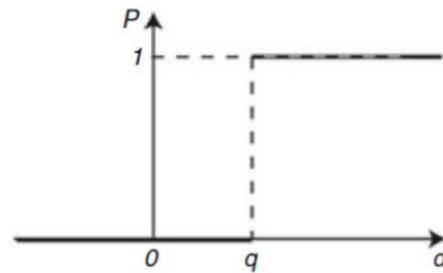
$$P(a,b) = \begin{cases} 0, if\ d \le q \\ 1, if\ d > q \end{cases}$$

3. Criterion with linear preference
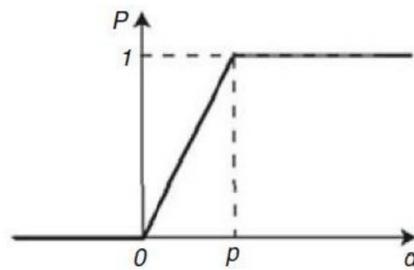
$$P(a,b) = \begin{cases} 0, if\ d \le 0 \\ \dfrac{d}{p}, if\ 0 < d \le p \\ 1, if\ d > p \end{cases}$$

4. Level criterion
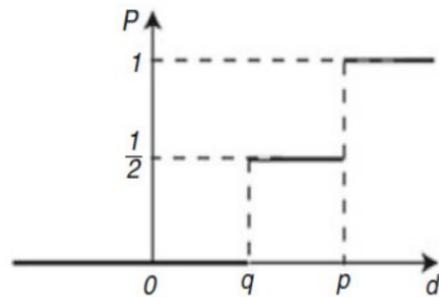
$$P(a,b) = \begin{cases} 0, & if\ d \le q \\ \dfrac{1}{2}, & if\ 0 < d \le p \\ 1, & if\ d > p \end{cases}$$

5. Criterion with linear preference and indifference area
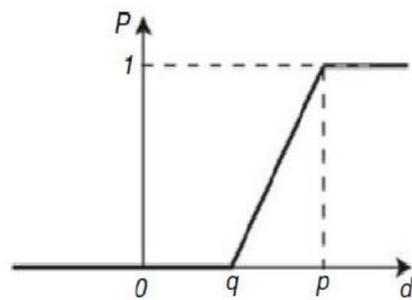
$$P(a,b) = \begin{cases} 0, & if\ d \le q \\ \dfrac{d-q}{p-q}, & if\ q < d \le p \\ 1, & if\ d > p \end{cases}$$

6. Gaussian criterion
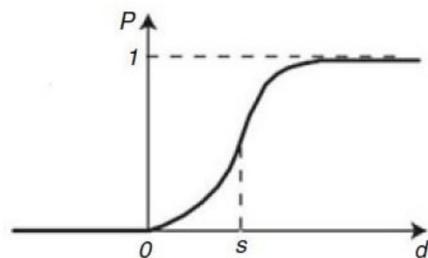
$$P(a,b) = \begin{cases} 0, & if\ d \le 0 \\ 1 - e^{-\frac{d^2}{2s^2}}, & if\ d > 0 \end{cases}$$

The multicriteria preference index of alternative a over alternative b is calculated in the following way (Brans, 2005; Papathanasious, 2018):

$$\prod(a,b) = \sum_{i=1}^{n} P_i(a,b) w_i \qquad (3)$$

Where w_i is the weight of i-th criterion.

Outranking flows (Medić, 2017):

The positive outranking flow of alternative a_j expresses how an alternative a_j is outranking all the others.

$$\phi_j^+\left(a_j\right)=\sum_{m=1}^{1}\prod\left(a_j,a_m\right) \qquad (4)$$

The negative outranking flow of alternative a_j expresses how an alternative a_j is outranked by all the others.

$$\phi_j^-\left(a_j\right)=\sum_{m=1}^{1}\prod\left(a_m,a_j\right) \qquad (5)$$

Based on positive and negative outranking flows, the net flow is defined as follows:

$$\phi_j\left(a_j\right)=\phi_j^+\left(a_j\right)-\phi_j^-\left(a_j\right) \qquad (6)$$

Alternative a_j is better than alternative a_k, if $\phi_j > \phi_k$ is ranked higher on the list.

VIKOR

A multicriteria compromise ranking method VIKOR (the acronym: VIšekriterijumsko KOmpromisno Rangiranje, in Serbian) was first introduced by S. Opricović and was developed for multicriteria optimization of complex systems (Papathanasious, 2018; Opricović, 2004). This method has to provide compromise solutions in terms of non-commensurable and conflicting criteria (Papathanasious, 2018; Opricović, 2007). Compromise solutions is the closest to the ideal one, where the ideal solution is determined based on the best values of criteria. (Opricović, 2007; Papathanasious, 2018; Marković, 2013)

The compromise ranking procedure has the following steps (Marković, 2013; Medić, 2017; Opricović, 2007; Papathanasious, 2018):

Step 1: Determine the best x_i^* and the worst values x_i^- of all criteria functions:

$$
\begin{aligned}
x_i^* &= \max_j x_{ij} \\
x_i^- &= \max_j x_{ij}
\end{aligned}
\qquad (7)
$$

Step 2: Calculate the values of pessimistic solution S_j and expected solution R_j by the relations:

$$S_j = \sum_{i=1}^{n} w_i \frac{x_i^* - x_{ij}}{x_i^* - x_i^-}$$

$$R_j = \max_i \left[w_i \frac{x_i^* - x_{ij}}{x_i^* - x_i^-} \right]$$

(8)

where w_i is weight of criteria and expresses the preference of a decision-maker.

Step 3: Determine the values Q_j (compromise solution):

$$Q_j = v \frac{S_j - S^-}{S^* - S^-} + (1 - v) \frac{R_j - R^-}{R^* - R^-}$$

(9)

Where:

$$S^- = \min_j S_j ; S^* = \max_j S_j$$

$$R^- = \min_j R_j ; R^* = \max_j R_j$$

Where v ($0 \leq v \leq 1$) is introduced as a weight of the strategy of the maximum group utility, whereas $1 - v$ is the weight of the individual regret. When $v > 0,5$, this represents a decision-making process that could use the strategy of maximum group utility, or "by consensus" when $v \approx 0,5$, or "with veto" when $v < 0,5$ (Opricović, 2007). Also, v depends on number of criteria (n): $v=0,5$ if $n \leq 4$, $v=0,6$ if $5 \leq n \leq 10$, $v=0,7$ if $n \geq 11$ (Opricović, 1998).

Step 4: Alternatives are ranked based on the values of R_j, S_j and Q_j. The first on the ranking list is the alternative whose values R_j, S_j and Q_j are the least, and it represents the best alternative. Alternative a_j is better than alternative a_k, if $Q_j < Q_k$ and is ranked higher on the list.

VIKOR is very useful method, specifically in situation when decision-maker is not able or doesn't know to express preference for criteria at the beginning of system design (Opricović, 2004).

4 COMPARATIVE ANALYSIS OF PROMETHEE AND VIKOR METHODS ON AN EXAMPLE

Based on PROMETHEE and VIKOR models, selection of the most suitable formation for storage CO_2 was performed. Several alternatives have been evaluated, such as: storage CO_2 in depleted oil and gas reservoirs, saline aquifers, and partially depleted oil reservoirs for enhanced oil recovery (EOR-CO_2 method). The selection of the optimal geological formation is based on the following criteria: storage capacity, total storage

costs, risk assessment costs, storage time dynamics, risk of CO_2 leakage from geological formation and risk of CO_2 leakage through the well. Preference presents the importance of each criteria expresses by the decision-maker, in this case the most important criteria are risk of CO_2 leakage from geological formation and through the well.

The initial and the quantified decision-making matrix are shown in Table 1 and Table 2.

Table 1 The initial matrix of decision making

	Saline aquifers	EOR-CO_2	Depleted oil and gas reservoirs
Storage capacity	5500	140	787,5
Total storage costs	Highest	Lowest	Intermediate
Risk assessment costs	Highest	Lowest	Lowest
Storage time dynamics	Highest	Intermediate	Lowest
Risk of CO_2 leakage from geological formation	Highest	Lowest	Lowest
Risk of CO_2 leakage through the well	Lowest	Highest	Intermediate

Table 2 The quantified decision-making matrix

	Saline aquifers	EOR-CO_2	Depleted oil and gas reservoirs	Preference	Max/ Min:
Storage capacity	5,5	0,14	0,7875	0,05	Max
Total storage costs	3	1	2	0,2	Min
Risk assessment costs	3	1	1	0,2	Min
Storage time dynamics	3	2	1	0,05	Max
Risk of CO_2 leakage from geological formation	3	1	1	0,25	Min
Risk of CO_2 leakage through the well	1	3	2	0,25	Min

PROMETHEE

The values of the preference function, the preference index and complete ranking of alternatives are shown in Table 3, Table 4 and Table 5.

Table 3 Values of the preference function

C_1 type I (max)			C_2 type I (min)		
a_1, a_s	x	$P_1(a_1, a_s)$	a_1, a_s	$x = c_2(a_1) - c_2(a_s)$	$P_2(a_1, a_s)$
s=2	5,5-0,14=5,36	1	s=2	2	0
s=3	5,5-0,7875=4,7125	1	s=3	1	0
a_2, a_s		$P_1(a_2, a_s)$	a_2, a_s		$P_2(a_2, a_s)$
s=1	0,14-5,5=-5,36	0	s=1	-2	1
s=3	0,14-0,7875=-0,6475	0	s=3	-1	1
a_3, a_s		$P_1(a_3, a_s)$	a_3, a_s		$P_2(a_3, a_s)$
s=1	0,7875-5,5=-4,7125	0	s=1	-1	1
s=2	0,7875-0,14=0,6475	1	s=2	1	0

Table 3 Values of the preference function - *continued*

C_3 type I (min)			C_4 type I (max)		
a_1, a_s	$x = c_3(a_1) - c_3(a_s)$	$P_3(a_1, a_s)$	a_1, a_s	$x = c_4(a_1) - c_4(a_s)$	$P_4(a_1, a_s)$
s=2	2	0	s=2	1	1
s=3	2	0	s=3	2	1
a_2, a_s		$P_3(a_2, a_s)$	a_2, a_s		$P_4(a_2, a_s)$
s=1	-2	1	s=1	-1	0
s=3	0	0	s=3	1	1
a_3, a_s		$P_3(a_3, a_s)$	a_3, a_s		$P_4(a_3, a_s)$
s=1	-2	1	s=1	-2	0
s=2	0	0	s=2	-1	0

Table 3 Values of the preference function - *continued*

C_5 type I (min)			C_6 type I (min)		
a_1, a_s	$x = c_5(a_1) - c_5(a_s)$	$P_5(a_1, a_s)$	a_1, a_s	$x = c_6(a_1) - c_6(a_s)$	$P_6(a_1, a_s)$
s=2	2	0	s=2	-2	1
s=3	2	0	s=3	-1	1
a_2, a_s		$P_5(a_2, a_s)$	a_2, a_s		$P_6(a_2, a_s)$
s=1	-2	1	s=1	2	0
s=3	0	0	s=3	1	0
a_3, a_s		$P_5(a_3, a_s)$	a_3, a_s		$P_6(a_3, a_s)$
s=1	-2	1	s=1	1	1
s=2	0	0	s=2	-1	1

Table 4 The preference index

	a_1	a_2	a_3
a_1	0	0,35	0,35
a_2	0,65	0	0,25
a_3	0,9	0,3	0
ϕ^-	0,775	0,325	0,3

Table 5 Complete ranking of alternatives

	ϕ^+	ϕ	**Rank**
Saline aquifers	0,35	-0,425	**3**
EOR-CO_2	0,45	0,125	**2**
Depleted oil and gas reservoirs	0,6	0,3	**1**

VIKOR

Max and min values of all criteria, calculated values of S_j and R_j, and complete ranking of alternatives (for $v = 0,5$) are shown in Table 6, Table 7 and Table 8.

Table 6 Max and min values of all criteria

	c_1	c_2	c_3	c_4	c_5	c_6
MAX	5,5	3	3	3	3	3
MIN	0,14	1	1	1	1	1
MAX-MIN	5,36	-2	-2	2	-2	-2

Table 7 Calculated values of S_j and R_j

	S_j - SUM	R_j -MAX
Saline aquifers	0,4	0,25
EOR-CO_2	0,075	0,05
Depleted oil and gas reservoirs	0,06896	0,1
MAX	0,4	0,25
MIN	0,06896	0,05

Table 8 Complete ranking of alternatives (v_1=0,5)

v_1=0,5		
	Q_j	Rank
Saline aquifers	1	**3**
EOR-CO_2	0,009123	**1**
Depleted oil and gas reservoirs	0,125	**2**

5   DISCUSSION AND CONCLUSION

In this paper a multi criteria analysis of selection the most suitable CO_2 geological storage formation was carried out by means of a comparative analysis of PROMETHEE and VIKOR methods. The selection of the most suitable option for storage of CO_2 based on the given criteria was made.

The complete ranking of geological formations for the storage of carbon dioxide using the PROMETHEE method show that storage in the depleted oil and gas reservoirs is in

the first place. In the second place there is EOR-CO$_2$ method and finally, storage in saline aquifers.

By applying VIKOR method, ranking of the alternatives is as follow: EOR-CO$_2$ method, storage in the depleted oil and gas reservoirs and storage in saline aquifers. The only difference is in reverse order of EOR-CO$_2$ and depleted oil and gas reservoir compared to results of PROMETHEE method.

Ranking of the alternative may vary depending on the approach and method used, which means that the decision-maker have to decide which method is the most appropriate for solving the problem.

Acknowledgment

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