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A Sustainable Approach for Site Selection of Underground Hydrogen Storage Facilities Using Fuzzy-Delphi Methodology

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A B S T R A C T

One of the consequences of rapid global population growth is the increase in the energy demand. Currently, the main source of energy for various applications is fossil fuels, which are not renewable and their utilization at large scales have caused a number of environmental issues such as global warming. Hydrogen is one of the main renewable energy sources; however, its utilization has not yet been sufficiently commercialized due to some existing technical issues. For large-scale underground Hydrogen storage facilities, selecting the most suitable set-up location is accounted to be a crucial factor in order to use Hydrogen as a promising and environmentally friendly energy carrier. This study aims to develop an expert judgment approach for the prioritization of criteria involving site selection of large-scale Hydrogen storage facilities to support development of modern cities and industries. In this regard, Fuzzy-Delphi methodology was used to prioritize the criteria and sub-criteria, which seemed to be most relevant for the underground Hydrogen storage site selection process. A comprehensive screening was performed in the literature and eighteen criteria from technical, economic, health, safety and environment (HST) and social points of view were extracted. A professional questionnaire was designed for the criteria prioritization and SPSS 25.0 was employed to analyse the achieved results. According to the gained results, the most important sub-criteria were identified as legal restrictions, reservoir permeability and porosity, and regional risks. Also, the findings demonstrated that HSE and technical issues of sustainability for the site selection of H_2 underground storage were more underscored in comparison to economic and social criteria. It is concluded that more in-depth studies are still needed to cover more aspects of sustainability regarding site selection for underground gas storages with special focus on social dimensions.

1. INTRODUCTION

According to the roadmap designed by the European Commission (2011), it has become mandatory for the European countries to promote renewable sources to provide their required energy by 2050 (Babonneau et al., 2016; Read et al., 2016). The main goal for this switch from fossil fuels to renewable energy sources, is to mitigate the release of CO_2 into the atmosphere (Crotogino et al., 2010; Türkseven Doğrusoy and Serin, 2015; Reuß et al., 2017). However, the utilization of the renewable energy sources (RES) is still limited due to the existing barriers. For instance, RES require a huge amount of investments and specific conditions to operate. Even thereafter, the preparation of the ideal conditions, RES will not be able to achieve the same efficiency level in comparison with fossil fuels (Kádár, 2014; Rocco, 2016). In addition, the produced electricity from RES must be utilized right away. This is mainly due to the existing technical limitations of RES storage techniques. Application of batteries for the RES storage has been proposed over the past decades as an effective method to deal with this problem. However, batteries are not widely applicable due to existing economic barriers.

To be able to provide the required energy for various applications such as energy supply for future smart cities, Hydrogen (H_2) storage has been accounted as a promising alternative. H_2 can be produced either by electricity or water electrolysis (Roumpedakis et al., 2018). Furthermore, when required, H_2 can again be converted to electricity at the high rate of efficiency with a minimum energy loss (European Commission, 2011; Hopper, 2017; Pesonen and Alakunnas, 2017; Sherif et al., 2003). Hence, Hydrogen energy can be considered satisfactory for the EU roadmap for clean and renewable energies development.

H_2 can be stored in gas or liquid forms. The storage of H_2 in liquid form necessitates some particular conditions such as low temperature, which will increase the total energy supply costs (Reuß et al., 2017). In order to overcome such issues, on board H_2 storage has been applied for the storage of gas-phase H_2 as an affordable approach (HyUnder, 2014; Pritchard and Rattigan, 2010). Moreover, like all of the renewable energy sources, the utilization of H_2 arises some limitations. One of the main obstacles on the way of H_2 use is that a large amount of H_2 is required to proceed with the energy production. H_2 is accounted as one of the lightest elements and contains low amount of energy density (Larsen et al., 2004). For instance, in comparison to gasoline, to produce the same amount of energy, four times more volume of H_2 is required (Tzimas et al., 2003). Generally, there are two types of onboard H_2 storages, including surface storage and underground storage techniques. In order to store H_2 above the ground, special tanks or reservoirs are required, which need high capital costs (Lord et al., 2014). Thus, underground H_2 storages are considered to be more economic options to this end (Amos, 1998). Geological storages aquifers, rock and salt caverns (Tzimas et al., 2003), abandoned mines (Evans et al., 2006), and natural gas reservoir (Hagemann et al., 2018) are among the applicable underground Hydrogen storage facilities. However, there are some barriers for the application of underground Hydrogen storage facilities. For instance, H_2 leakage is considered to be risky as the released H_2 can react to other minerals surrounding the storage and produce hazardous contaminants (Lord et al., 2014). Hence, some specifications are required to select the most appropriate sites for the establishment of underground Hydrogen storage facilities. Such specifications can be categorized into specific criteria and sub-criteria. The relative importance of such criteria and sub-criteria can determine the relative suitability of the desired sites. In this regard, adoption of the most suitable approaches to analyse and weigh the mentioned criteria and sub-criteria are vital. Fuzzy-Delphi methodology can be employed as a scientific-based analytical method for the prioritization of the important criteria in various fields of study (Jahanshahi et al., 2019; Kamali et al., 2015; Kamali et al., 2017).

The Fuzzy-Delphi methodology includes two separate and complementary procedures. Via the utilization of the Delphi methodology, the most suitable questionnaire is achieved. Furthermore, the affecting criteria in the questionnaire will be ranked by the application of the fuzzy set theory (Hsueh, 2015; Bouzon et al., 2016). The application of Fuzzy-Delphi methodology facilitates the prediction of the future outputs when the application of forecasting models is not possible (Aliev et al., 2004). Thus, in this study, the Fuzzy-Delphi approach was adopted to prioritize the main criteria and sub-criteria influencing the selection of the appropriate sites for setting up the underground Hydrogen storage facilities.

2. THEORETICAL BACKGROUND

Underground Hydrogen storage has been used since the beginning of the twenty-first century. However, very few studies with the sustainability perspectives have been performed to investigate the affecting criteria on the gas storage site selection process (Lewandowska-Śmierzchalska et al., 2018). Underground gas storage has numerous environmental, economic, and social benefits in addition to the energy supply security benefits (Deveci et al., 2015; Llamas and Cámara, 2014). In this regards, those few studies, considering the site selection of gas storage integrated with the sustainability objectives, have considered four main aspects of sustainability including: a). Technical (Lewandowska-Śmierzchalska et al., 2018; Tarkowski and Czapowski, 2018); b). Economic (Lewandowska-Śmierzchalska et al., 2018; Tarkowski and Czapowski, 2018); c). Health, safety and environment (HSE) (Tarkowski and Czapowski, 2018), and d). Social criteria. According to Llamas and Cámara (2014), technical criteria can also be taken into account as one of the most significant aspects affecting the selection of the Hydrogen underground storage site, due to the high costs and risk involved in the investigation techniques. Also, Lewandowska-Śmierzchalska et al. (2018)

indicated that technical dimensions should be considered with equal significance to environmental and economic criteria of the Hydrogen underground storage site selection.

Table 1. Identified criteria and sub-criteria for the site selection of the underground H_2 storage facilities extracted from the literature review.

Criteria	Sub-criteria	Definition/ Description	References
Technical	Geology	Defined as the suitability of the structure and the properties of the local rocks for constructing the Hydrogen storage facility.	Deveci, 2018; Simon et al., 2015; Tarkowski and Czapowski, 2018
	Depth	Defined as the depth required for the Hydrogen storage facility.	Deveci, 2018; Lewandowska-Śmierzchalska et al., 2018
	Area	As an indicator to calculate the Hydrogen storage capacity, required or available in the geological field.	Deveci et al., 2015; Hsu et al., 2012; Lewandowska-Śmierzchalska et al., 2018
	Thickness	Defined as the thickness of the reservoir required for Hydrogen storage.	Deveci, 2018; Deveci et al., 2015; Hsu et al., 2012; Lewandowska-Śmierzchalska et al., 2018
	Caprock thickness	Defined as the necessity of having caprocks with sufficient thickness for the safe storage of Hydrogen.	Hsu et al., 2012; Chadwick et al., 2008; Llamas and Cámara, 2014; Ramírez et al., 2010; Sainz-Garcia et al., 2017
	Caprock permeability	Defined as the sealing properties capacity of a caprock, which enables successful sealing in the reservoirs.	Hsu et al., 2012; Chadwick et al., 2008; Llamas and Cámara, 2014; Ramírez et al., 2010; Sainz-Garcia et al., 2017
	Reservoir permeability and porosity	Defined as the porosity of the reservoir that reflects the potential volume available for Hydrogen storage.	(Deveci, 2018; Deveci et al., 2015; Hsu et al., 2012; Lewandowska-Śmierzchalska et al., 2018)
	Storage capacity	Defined as the total capacity required for Hydrogen storage reservoir.	Deveci, 2018; Deveci et al., 2015; Hsu et al., 2012; Llamas and Cámara, 2014; Lord et al., 2014; Reitenbach et al., 2015
Economics	Labour	Describes the costs attributed to the human resources required for the operation of Hydrogen storage facilities.	Deveci et al., 2015
	Proximity to suppliers & resources	Defined as the distance to roads, power line, and accessibility of raw materials.	Deveci et al., 2015
	Infrastructure availability	Defined as the technological availabilities in terms of basic infrastructures in the area.	Deveci et al., 2015
	Storage cost	Defined as the total costs of Hydrogen storage in terms of capturing, transportation, injection, and storage.	Deveci, 2018; Hsu et al., 2012; Deveci et al., 2015
	Initial investment	The initial investment required to construct an underground Hydrogen storage facility.	Deveci, 2018; Deveci et al., 2015
Health, Safety and Environment (HSE)	Regional risks	Describes the potential risks in the region regarding the occurrence of natural disasters such as earthquakes.	Deveci, 2018; Deveci et al., 2015; Llamas and Cámara, 2014
	Legal restrictions	Defined as the applicable environmental legislation such as the required distance to protected areas, as well as the applicable occupational health and safety legislation.	Deveci et al., 2015; Llamas and Cámara, 2014
Social	Social acceptance	Describes the overall perception of the local communities for the construction of a Hydrogen storage facility.	Deveci et al., 2015
	Job creation	Defined as the new job opportunities created by the construction and implementation of the facility.	Jahanshahi et al., 2019
	Local culture	Describes the local culture properties that may need special protection.	Llamas and Cámara, 2014

The key issues addressed in the previous studies regarding the technical aspects of sustainability in underground gas storage are categorized as follows: capacity of storage (Hsu et al., 2012; Ramírez et al., 2010; Reitenbach et al., 2015; Simon et al., 2015), geological structure (such as depth, area, thickness, and tightness) (Hsu et al., 2012; Lewandowska-Śmierzchalska et al., 2018), and reservoir porosity and permeability (Chadwick et al., 2008; Deveci, 2018). The economic aspect, which can be considered in the site selection of underground gas storage, has impressively been considered in several studies performed by some researchers (Deveci et al., 2015; Simon et al., 2015; Tarkowski and Czapowski, 2018). Lord et al. (2014) addressed the costs associated with the development and application of H_2 storage facilities and stressed that the current limiting factor for widespread adoption of Hydrogen storage is the lack of economically feasible infrastructures. Moreover, as asserted by Tarkowski and Czapowski (2018), the costs of building underground reservoirs are much lower than the costs of building traditional reservoirs with the same capacity on the ground. The most frequent parameters associated with the economic aspects of sustainability, which have been addressed in underground gas storage studies, are various, such as labour cost (Deveci et al., 2015), initial investments (Simon et al., 2015), and the availability of basic infrastructure (Deveci et al., 2015). Table 1 reveals the most important parameters mentioned in the literature for the site selection of H_2 underground facilities.

The social aspects of sustainability have recently gained some attention in some of the studies on the topic of gas underground storage. However, compared to the technical, HSE and economic criteria, the social aspect has been considered to have less importance (Atanda, 2019; Mapar et al., 2017). As defined by Mani et al. (2014), "*social criteria of sustainability are considered as a human code of conduct which needs to be achieved in an equitable, inclusive and prudent manner*". The recent studies have already addressed various social aspects while considering potential gas underground storage, including areas under cultural protection (Llamas and Cámara, 2014), social acceptability (Chadwick et al., 2008; Deveci et al., 2015) and the ability of this practice to create new jobs (Jahanshahi et al., 2019). Jahanshahi et al. (2019) pointed out that the capability of creating new jobs can also be considered as a social factor with an enormous impact on the development of energy facilities. Llamas and Cámara (2014) also proposed a new approach to solve the problems related to the selection of gas storage sites by considering the social criteria. However, it was asserted that the social aspects of sustainability, namely the social acceptance of the implementation are interlinked with the economic aspects and should be considered in an integrated approach along with other gas underground storage issues. On the other hand, as a new approach of sustainability, health, safety and environmental (HSE) aspects are seen as parallel challenges of sustainable development (Mapar et al., 2017). Sustainability approaches will be more robust when integrated with the HSE aspects (Mapar et al., 2017). These merged aspects have recently acquired adequate dominance at occupational level (Cunningham et al., 2010; IPIECA et al., 2015; Koskela, 2014). Some studies in the field of underground gas storage indicated that there are interlinking associations between environmental legislation and work health and safety (Deveci et al., 2015). Hsu et al. (2012) investigated the criteria of selection of the most appropriate gas storage locations and stated that, while deciding the best gas storage reservoir, regional risks are needed to be taken into account as one of the main affecting criteria. Ramírez et al. (2010) also explained that risk factors associated with underground gas storage also influence the suitability of a reservoir and asserted that it is important to take risk aspects into account as it will result in more realistic valuations of total gas storage potential. Also, according to Damen et al. (2006) risk assessment is a first step in a strategy-forming process to set-up management and control measures to minimise the risks of underground gas storage.

Table 1 represents the 18 most robust criteria extracted from the literature review for the site selection of the underground Hydrogen storage.

3. METHODOLOGY

3.1. Fuzzi-Delphi methodology

Delphi methodology is a useful tool employed to identify and prioritize criteria in a group, and in particular, questionnaires that are conducted to collect expert opinions (Kamali et al., 2019). This method is very popular among researchers in various fields (Okoli and Pawlowski, 2004). In the case of this method, respondents are selected based on their level of expertise and their skills in the field chosen to be analysed. In our study, the analysis regarding the site selection of the underground H_2 storage was performed by using expert opinions in the field to rank the specific criteria. The expert panel was selected carefully, consisting of academic and non-academic experts with adequate knowledge in the field (Chang et al., 2000; Doyon et al., 1971; Kamali et al., 2019; Yousuf, 2007) combined with other 15 specialists, researchers and experts. There are a number of reports in the literature that argue for the effective application of the Fuzzy-Delphi methodology to make sustainability relevant decisions in various scientific fields (Hsu et al., 2010; Sánchez-Lezama et al., 2014; Tahriri et al., 2014).

In this study, a professional questionnaire was developed based on 18 identified criteria (see Table 1). Moreover, Fuzzy-Delphi approach was applied to categorize the criteria and sub-criteria along with their impact on Hydrogen site selection and rank them from the least to the most significant. Fuzzy numbers were defined as a set of numbers representing fuzzy space in the real R number, often used to explain unknown information in the decision-making process and for reaching conclusions (Ban and Coroianu, 2012).

Based on the selected approach, each fuzzy number in triangular form has been represented by three numbers as the following: $A = (a_1, a_2, a_3)$.

Membership functions that could interpret this profile were in accordance with the following equations (Gani and Assarudeen, 2012):

$$y = m(x) = \begin{Bmatrix} 0 & x < a_1 \\ \frac{x-a_1}{a_2-a_1} & a_1 \le x \le a_2 \\ \frac{a_3-x}{a_3-a_2} & a_2 \le x \le a_3 \\ 0 & x > a_3 \end{Bmatrix} \quad \text{Eq. 1}$$

According to Table 2, in order to develop the questionnaire, a fuzzy scale, containing seven linguistic variables, and the respective triangular fuzzy numbers were used. The numeral mean (Eq. 2) (Hsu et al., 2010) was used to compute the fuzzy gravity of criteria, where L, M, and U expressed the fuzzy number ingredients. Eq. (3) was also used to defuzzy the values. Moreover, all criteria were defuzzied using Eq. (1) and defuzzied numbers were used to rank the criteria.

$$L_j = Min_i\{L_{ij}\}, M_j = \frac{1}{n}\sum_{i=1}^{n} M_{ij}\ , U_j = Max_i\{U_{ij}\} \quad \text{Eq. 2}$$

$$df = \frac{1}{4}(L + 2M + U) \quad \text{Eq.}$$

Table 2. Linguistic variables and the relevant fuzzy scales used to rank the criteria for the site selection of H_2 underground storage.

Linguistic variable	Fuzzy Scale (L, M, U)	$df = \frac{1}{4}(L+2M+U)$
Extremely High	(0.9,1.0,1.0)	0.975
Very High	(0.7,0.9,1.0)	0.875
High	(0.5,0.7,0.9)	0.7
Fair	(0.3,0.5,0.7)	0.5
Low	(0.1,0.3,0.5)	0.3
Very Low	(0.0,0.1,0.3)	0.125
Extremely Low	(0.0,0.0,0.1)	0.025

The panel members were asked to specify the importance of each proposed sub-criterion based on the fuzzy scale revealed in Table 2.

After the revision and extraction of results from the first round, the average outputs were sent to the panel of experts and after reaching a consensus in the second round, results were interpreted to represent the most important sub-criteria for selecting the most suitable sites for the implementation of the underground Hydrogen storage facilities.

3.2. Analysis of the results

SPSS v.2.0.0 was used for the data analysis. It should be taken into account that the numbers, which were input into the program, were defuzzied based on output responses. The outputs were analysed using the descriptive-analytic method. Cronbach's alpha was used to check and analyse the internal consistency of the answers provided by experts. The method employed is one of the methods of joints calculating internal consistency (reliability) which is generally used to evaluate the reliability of the time scale of questions (Béland et al., 2016). In this method, responses are examined and, finally, the coefficient is given to the answers. This coefficient has to be between 0 and 1. If the coefficient value is closer to 1, it means that the response is more reliable (Gottems et al., 2018). If the Cronbach's alpha coefficient is greater than 0.7, it means that the questionnaire can be accounted to be reliable for further analysis (Pinto et al., 2014). The Kolmogorov-Smirnov (KS) test was also used to examine and analyse the non-matching responses and to check whether parameters were parametric (Zhang and Chen, 2018). In the present paper, so as to examine the responses more precisely, Shapiro-Wilk test was used to check whether data were normal (it should be noted that the sample size was less than 2000).

4. RESULTS AND DISCUSSION

Table 3 represents the importance of each sub-criteria (shown as *df* column) extracted from the second-round questionnaire by applying the fuzzy scales (see also Table 2). The applied questionnaire utilized in this study can be found in the "Supplementary Information" section.

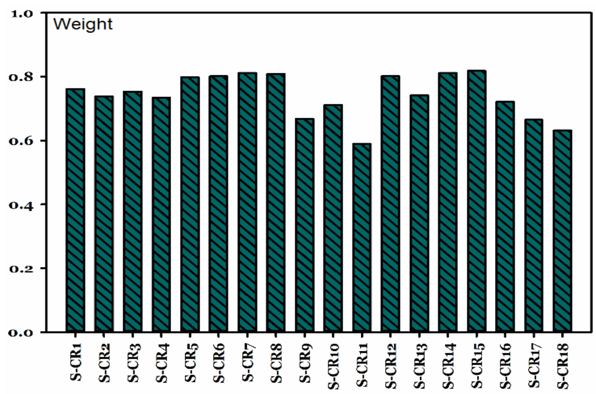

Fig. 3. Calculated weights of the sub-criteria for the site selection of underground Hydrogen storage.

Cronbach's alpha test was used to analyse the responses and the analysis was completed by using SPSS software. Finally, the obtained coefficient was 0.767. Since this value was greater than 0.7, the responses were consistent and reliable (Table 4).

The Kolmogorov-Smirnov and Shapiro-Wilk tests were used for parametric analysis and non-parametric analysis for output responses. Given that all outputs were less than 0.05, the responses were non-normalized and non-parametric.

Table 3. Linguistic variables and the relevant fuzzy scales employed to rank the criteria used for the site selection of H_2 underground storage.

Criteria	Sub-Criteria		Fuzzy Scale (L, M, U)	*df*
Technical	S-CR1	Geology	(0.3, 0.873, 1.0)	0.7617
	S-CR2	Depth	(0.3, 0.827, 1.0)	0.7383
	S-CR3	Area	(0.3, 0.857, 1.0)	0.7536
	S-CR4	Thickness	(0.3, 0.820, 1.0)	0.7350
	S-CR5	Caprock thickness	(0.3, 0.847, 1.0)	0.7983
	S-CR6	Caprock permeability	(0.3, 0.853, 1.0)	0.8017
	S-CR7	Reservoir permeability and porosity	(0.3, 0.873, 1.0)	0.8117
	S-CR8	Storage capacity	(0.3, 0.867, 1.0)	0.8083
Economics	S-CR9	Labour	(0.3, 0.687, 1.0)	0.6683
	S-CR10	Proximity to suppliers & resources	(0.3, 0.773, 1.0)	0.7117
	S-CR11	Infrastructure availability	(0.3, 0.680, 1.0)	0.5900
	S-CR12	Storage cost	(0.3, 0.853, 1.0)	0.8017
	S-CR13	Initial investment	(0.3, 0.833, 1.0)	0.7417
Health, safety and environment (HSE)	S-CR14	Regional risks	(0.3, 0.873, 1.0)	0.8117
	S-CR15	Legal restrictions	(0.3, 0.887, 1.0)	0.8183
Social	S-CR16	Social acceptance	(0.3, 0.793, 1.0)	0.7217
	S-CR17	Job creation	(0.3, 0.680, 1.0)	0.6650
	S-CR18	Local culture	(0.3, 0.713, 1.0)	0.6317

Table 4. Results of Case Processing Summary (SPSS 25.0 software) for the analysis of the site selection for H_2 underground storage.

Analysis		N	(%)	No. of items	Cronbach's Alpha
Cases	Valid	18	100	15	
	Excluded	0	0	0	
	Total	18	100	15	0.767

Table 5. Results of the normality test performed on the data gained from the responses based on the criteria and sub-criteria for the site selection of H_2 underground storage.

Criteria	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
S-CR1	0.448	15	0.000	0.615	15	0.000
S-CR2	0.369	15	0.000	0.773	15	0.002
S-CR3	0.414	15	0.000	0.707	15	0.000
S-CR4	0.303	15	0.001	0.847	15	0.016
S-CR5	0.339	15	0.000	0.776	15	0.002
S-CR6	0.306	15	0.001	0.794	15	0.003
S-CR7	0.308	15	0.000	0.795	15	0.003
S-CR8	0.338	15	0.000	0.786	15	0.002
S-CR9	0.435	15	0.000	0.627	15	0.000
S-CR10	0.298	15	0.001	0.838	15	0.012
S-CR11	0.281	15	0.002	0.865	15	0.028
S-CR12	0.269	15	0.005	0.770	15	0.002
S-CR13	0.254	15	0.010	0.858	15	0.022
S-CR14	0.308	15	0.000	0.795	15	0.003
S-CR15	0.334	15	0.000	0.782	15	0.002
S-CR16	0.269	15	0.005	0.864	15	0.028
S-CR17	0.302	15	0.001	0.806	15	0.004
S-CR18	0.288	15	0.002	0.828	15	0.009

In the previous step, it was found that our responses were non-parametric. Regarding the non-parametricity of the answers, it was necessary to analyze the uniformity in the perception of respondents to the questionnaire. Kruskal-Wallis test was used in this regard. In this test, the output number should be greater than 0.05, so that the respondents' perception of the criteria is the same. The calculated test coefficient was determined to be 0.055. This coefficient represented that all respondents had a similar understanding of the questionnaire. This test was used to compare the mean of two or more groups of samples. The hypotheses of this test were based on statistical comparison of the existence or non-existence of differences between groups and based on responses. If the program output for this test was less than 0.05, there would be a difference between the respondents' perception regarding the questions and criteria (Maimaiti et al., 2019).

Table 6. Kruskal-Wallis Test (SPSS 25.0 software) performed on the gained results from the responses to the questionnaire for the site selection of H_2 underground storage.

Test Statistics	Answer
Kruskal-Wallis H	23.329
df	14
Asymp. Sig.	0.055

Table 7 and Fig.4 demonstrate the final ranking of the sub-criteria at the overall scale.

Table 7. Final ranking of the sub-criteria for the site selection of underground Hydrogen storage.

Criteria	Sub-Criteria	Criteria Ranking	$df = \frac{1}{4}(L+2M+U)$
HSE	Legal restrictions	1	0.8183
Technical	Reservoir permeability and porosity	2	0.8117
HSE	Regional risks		
Technical	Storage capacity	3	0.8083
Technical	Caprock permeability	4	0.8017
Economic	Storage cost		
Technical	Caprock thickness	5	0.7983
Technical	Geology	6	0.7617
Technical	Area	7	0.7536
Economic	Initial investment	8	0.7417
Technical	Depth	9	0.7383
Technical	Thickness	10	0.7350
Social	Social acceptance	11	0.7217
Economic	Proximity to suppliers & resources	12	0.7117
Economic	Labour	13	0.6683
Social	Job creation	14	0.6650
Social	Local culture	15	0.6317
Economic	Infrastructure availability	16	0.5900

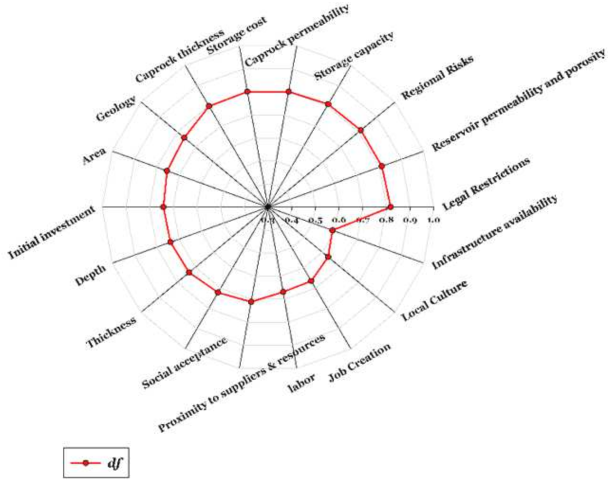

Fig. 4. Final ranking of the sub-criteria for the site selection of Hydrogen underground storage.

Regarding Figure 4, the vector of de-fuzzy ranks based on the Fuzzy-Delphi calculations showed that "legal restrictions" (S-CR15), with a decisive advantage over the others (df: 0.8183), appeared as the most important sub-criteria while selecting the H_2 underground storage site. In addition, "reservoir permeability and porosity", "regional risks", and "storage capacity" were ranked next in importance among the studied parameters (see also Table 7). It is noticeable in Table 1 and Figure 4 that both sub-criteria associated with HSE criterion were classified in the top three ranks, demonstrating the panel of experts to be heavily in favour of the HSE criteria and considered them among the most important aspects of sustainability in the site selection of H_2 underground storage. This might be due to the direct impact of HSE issues on the target groups whose life could be affected by the H_2 underground storage sites directly, for instance because of the potential risks of occurrence of disasters, namely earthquakes or natural fires. These findings were in line with the criteria suggested in the international standard ISO 37120 related to indicators for city services and quality of life (ISO, 2014), indicating emergency issues and fire protection as some of the most essential services to meet the responsibility of the involved parties to protect the life and well-being of their target groups in compliance with the sustainability goals (Mapar et al., 2017). These findings could be also compared with the objectives of Deveci et al. (2015) who demonstrated the importance of the risk of explosion in the underground gas storage to be significant, and that it could be considered as an independent and key category besides the technical, economic and social criteria. This study could be accounted to be successful to highlight the role of HSE aspects of sustainability.

Moreover, most sub-criteria located in the middle level of Table 1 (see ranks 5 to 10) belonged to

"Technical aspects", which demonstrated that the technical issue of sustainability regarding the H_2 underground storage was ranked second in comparison with other HSE, social and economic aspects, while playing an important role in the site selection of H2 underground storage. These findings were partially in line with the study of Chadwick et al. (2008), who analysed the underground gas storage in the Mid Norway and illustrated that a proper technical investigation was deemed to be helpful to rationalize these issues. Therefore, it was clear that the HSE and the technical issues of sustainability for the site selection of H_2 underground storage were more underscored, since all the HSE sub-criteria gained the first and second ranks of the total, whereas, most of the technical sub-criteria were allocated ranks of 5 to 10 (the middle level), while the social and economic criteria were positioned on the lowest ranks (between 11 and 16) (Table 3). On the other hand, the social sub-criteria (see Fig. 4 and Table 1) were placed at the lowest levels along with the economic sub-criteria (ranks 11 to 16).

Although the social sub-criteria were ranked the lowest, it is of high importance to notice that this study was successful in involving the social aspects of sustainability in the underground gas storage, since, overall, the panel were in favour of the role of social sub-criteria in the site selection and its related sub-criteria in the study. The findings of the present study could also be compared with the gaps indicated in the second sections of this study. Regarding the results presented in the studies of Atanda (2019) and Mapar et al. (2017), in which the attention to the social aspects of sustainability in different fields of studies was found to be lower in comparison with the economic issues, our findings showed that, the social and economic aspects of sustainability on the H_2 underground storage were ranked approximately the same.

The findings of this study also attempted to resolve the concern of Etxteberria et al. (2015) over the exclusion of social issues from the sustainability criteria set in most studies. The findings emphasized a more explicit criterion to reflect the "social" aspect of sustainability in setting up the most suitable locations for underground gas storage. However, more in-depth studies are needed to more extensively approach different aspects of social sustainability when deciding on the location of underground gas storage.

Regarding the economic sub-criteria, it was obvious that the storage costs (ranked 4^{th}) and initial investment (ranked 8^{th}) gained much more attention than the "proximity to suppliers & resources", "labour" and "infrastructure availability" (ranked 12, 13 and 16). We could conclude that to gain much more success on continuous improvement of the underground gas storage site selection, the initial investment costs should be investigated by more in-depth analyses, before and beyond other cost-benefit analyses of the H_2 underground storage program. As mentioned above, we noted that the implementation of underground H_2 storage has not yet been commercialized. Thus, the achieved results can be applied to facilitate the investigation in regards with notifying the area in which more investments are required.

Consequently, the involved parties such as governments, relevant stakeholders, and researches with the proper insight can be more encouraged to apply and utilize the H_2 underground storage in large scales. In addition, underground H_2 storages seem to be an appropriate choice due to the large amount of investments required for building the over ground storages for H_2 and the requirements of tanks for the sequestration; and, the results obtained regarding the proper locations for the commercial implementation of such storages can be easily sought by using methodologies such as GIS-fuzzy methods (Khavarian-Garmsir and Rezaei, 2015).

Moreover, the obtained results gained from this study can be applied as a model in order to predict the destiny of such storages and prevent the occurrence of undesirable hazardous events. Also, one of main reasons negatively affecting the implementation of the underground gas storages is the lack of relevant standards for building, adjustments, and the use of these facilities (IEA Greenhouse Gas R&D Programme, 2003; Reitenbach et al., 2015). These results can also be utilized for the formation of the respective regulations and standards.

5. CONCLUSIONS

This study was performed to identify the most important criteria and sub-criteria involved in the selection of the most suitable sites for the establishment of underground Hydrogen facilities.

A Fuzzy-Delphi methodology was employed to prioritize the identified criteria and sub-criteria. According to the results achieved, legal restrictions were identified as the most important criterion. Reservoir permeability and porosity and regional risks were also identified as the next priorities. HSE and technical criteria were also considered as the most important and main criteria.

The results can clearly demonstrate that the governmental approach can considerably affect the selection of the most suitable sites for the establishment of the Hydrogen underground storage facilities. Also, there are some technical barriers such as lack of standards and regulations for building, adjustments, and utilizations of such facilities, which should be overcome to promote their commercial implementation.

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SUPPLEMENTARY MATERIAL

The questionnaire conducted in this research to rank the criteria for the site selection of the underground Hydrogen storage is revealed below.

Main criteria	Sub-criteria	Extremely low	Very low	Low	Fair	High	Very high	Extremely high
Technical	Geology	☐	☐	☐	☐	☐	☐	☐
	Depth	☐	☐	☐	☐	☐	☐	☐
	Area	☐	☐	☐	☐	☐	☐	☐
	Thickness	☐	☐	☐	☐	☐	☐	☐
	Caprock thickness	☐	☐	☐	☐	☐	☐	☐
	Reservoir permeability and porosity	☐	☐	☐	☐	☐	☐	☐
	Storage capacity	☐	☐	☐	☐	☐	☐	☐
Economic	Labour	☐	☐	☐	☐	☐	☐	☐
	Proximity to suppliers &resources	☐	☐	☐	☐	☐	☐	☐
	Infrastructure availability	☐	☐	☐	☐	☐	☐	☐
	Storage costs	☐	☐	☐	☐	☐	☐	☐
	Initial investment	☐	☐	☐	☐	☐	☐	☐
Health, Safety, and Environment (HSE)	Regional risks	☐	☐	☐	☐	☐	☐	☐
	Legal restrictions	☐	☐	☐	☐	☐	☐	☐
Social	Social acceptance	☐	☐	☐	☐	☐	☐	☐
	Job creation	☐	☐	☐	☐	☐	☐	☐
	Local culture	☐	☐	☐	☐	☐	☐	☐