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Underground Hydrogen Storage Sites Selection in Central Asia Using Fuzzy Logic

Final Report for Capstone Project

by

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Declaration

We, Adina Kenesbekova, Alina Samyratova, and Aizhan Tussipova, hereby declare that this report entitled “Underground Hydrogen Storage Sites Selection in Central Asia Using Fuzzy Logic” is the result of our own project work except for quotations and citations that have been duly acknowledged. We also declare that it has not been previously or concurrently submitted for any other degree at Nazarbayev University.

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Abstract

Global economic transition towards low-carbon economies and rising demands for clean energy identify the immediate need for efficient high-capacity energy storage facilities. Hydrogen as a highly prospective energy source faces the hurdle of cost-efficient and safe storage, particularly in large volumes. The study attempts to identify optimum underground hydrogen storage (UHS) sites in Central Asia utilizing the Fuzzy TOPSIS (The Technique for Order of Preference by Similarity to Ideal Solution) multi-criteria decision-making strategy with due regard for the innate uncertainty and subjectivity in the evaluations by the experts.

An initial list of nineteen technical, geological, and socio-economic criteria was generated through a comprehensive literature review. These were later condensed to six most significant factors - sealing efficiency, storage capacity, caprock permeability, cavern stability, storage cost, and hydrogen injection/withdrawal rate - based on expert questionnaires and fuzzy logic. Storage alternatives like salt caverns, aquifers, and depleted gas fields were considered, with depleted gas fields being most suitable due to their good geological conditions and infrastructure availability.

Subsequently, four gas-depleted fields in Kazakhstan and Uzbekistan were selected for detailed study. Sensitivity analysis using Computer Modelling Group (CMG) software was conducted where reservoir data were unavailable in an attempt to estimate missing parameters. An expert evaluation of two stages using Fuzzy TOPSIS identified the Kashagan field as the best place for UHS. Preliminary economic appraisal also established it as cost-effective.

This research provides a data-driven, systematic approach to UHS site selection in Central Asia and contributes valuable insights to the regional hydrogen economy development, supporting broader global energy transition objectives.

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Chapter I

Introduction

1.1 Hydrogen as a Key Energy Carrier

Climate change, driven mainly by the massive and prolonged exploitation of fossil fuels associated with greenhouse gas emissions, is among the most important environmental problems facing the international community [1]. Therefore, countries worldwide are switching from traditional fossil fuels to main renewable energy sources such as solar, wind and hydro power to combat the global climate crisis [2]. The transition towards sustainable energy is also driven by the need to strengthen energy security, as the scarcity of fossil fuel resources can no longer keep pace with rising demand. However, most renewables potential is constrained with primarily generating electricity, restricting their versatility as energy carriers in different applications [3]. Chemical fuels are still necessary because a large number of transportation vehicles cannot operate entirely on electricity.

In this regard, hydrogen is emerging as both energy carrier and chemical feedstock, offering a viable potential to deliver clean energy across multiple applications [4]. Reflecting that versatility, the demand for pure hydrogen has more than tripled globally, rising from about 20 million tons in 1975 to over 70 million tonnes in 2018 [5]. It can serve as a fuel or be converted to electricity using devices like fuel cells. As a zero-carbon gas, hydrogen emits no greenhouse gases during combustion, provided if it is produced from non-fossil fuel feedstocks [6]. Hydrogen has the potential to successfully decarbonize the entire fuel supply chain if it is widely used as an energy vector and a substitute for hydrocarbon fuels.

Hydrogen contains more energy per unit of weight (120 MJ/kg) than any other known substance (Table 1.1). However, its atomic structure, consisting of a single positively charged nucleus and one orbiting electron, makes it the lightest element with extremely low density at ordinary temperature and pressure conditions [7]. The secure and effective hydrogen storage is another important aspect in unlocking its potential as an energy source or fuel. The storage of hydrogen can occur in three phases: solid, liquid, and gas.

Table 1.1: Hydrogen's characteristics in comparison to other fuels[7]

Fuel	Boiling Point, [K]	Liquid density, [kg/m³]	Gas density, [kg/m³]	Energy per kilogram, [MJ/kg]
Hydrogen	20.3	71	0.08	120.0
Gasoline	350–400	702	4.68	44.4
Methanol	337	797	–	20.1
Methane	112	425	0.66	50.0
Propane	231	507	1.87	46.4

1.2 Green Energy Trends in Central Asia

Central Asian countries are richly endowed with both traditional (such as oil, natural gas, and coal) and renewable (such as wind, solar, and hydro) energy resources and possess a strategic location, which could substantially counterbalance the predominant use of hydrocarbons during the global transition to green energy. Recognizing this potential, Kazakhstan and Uzbekistan have launched a series of initiatives and investment programs to unlock the potential of renewable sources towards sustainable development [8]. In Kazakhstan, the Energy Minister has underscored the concept of hydrogen production as a cornerstone of the nation's carbon-neutrality strategy and a key means of meeting its international emissions-reduction obligations (Paris Agreement [9]) [10]. According to the concept, Kazakhstan expects to produce 25,000 tonnes of hydrogen by 2030, with a green hydrogen share of 50% of total volume. The development of this strategy also highlights the need for construction of facilities capable of securely storing hydrogen with a minimum capacity of 100,000 m^3 [10]. Similar objectives are being pursued by Uzbekistan. Due to a steady decline in domestic gas production [11], diversifying into other clean-energy sources has become a necessity rather than an option. This requirement is the driving force behind Uzbekistan's 2023 initiative, which was started with support from the private sector and USAID, to establish a national green-hydrogen hub with the goal of producing 3,000 tonnes of hydrogen annually [12].

In this regard, hydrogen storage is vital, necessitating the construction of safe, large-scale facilities that will sustain a long-term balance between supply and demand over time in those regions.

1.3 Hydrogen Storage Methods

There are different physical states and methods for storing hydrogen. Each of them has advantages, disadvantages and limitations:

Solid-State Storage: Metal hydrides are unusual types of material that retain hydrogen at high temperatures. Although solid-state storage is highly concentrated, it typically uses expensive and complicated materials. Furthermore, due to the slow release of hydrogen, it is not practical for rapid and effective energy delivery [13], [14].

Liquid Hydrogen Storage: At cryogenic temperatures, hydrogen liquefies and can be stored in a compact state. However, liquefaction requires a significant amount of energy - roughly 30% of the energy present in the hydrogen itself - to occur [15]. Liquid Organic Hydrogen Carriers (LOHCs) are another option for storing hydrogen, but this approach suggests that the dehydrogenation process is inefficient and energy-intensive [14].

Gaseous Storage: Compressed hydrogen can be preserved underground in geological formations or above ground in tanks [16], [17]. Bulk storage of hydrogen in cylinders takes up a tremendous amount of ground space, hence raising construction costs [13]. Storage of hydrogen in compressed form, with the benefits of easy operation and effective storage and release of hydrogen, was the most advanced and common technology for decades.

1.4 Underground Hydrogen Storage

Underground storage is typically a more secure and cost-effective solution for mass hydrogen storage (Fig.1.1). Various geological strata are utilized for gas storage with their own strengths for UHS [16], [17].

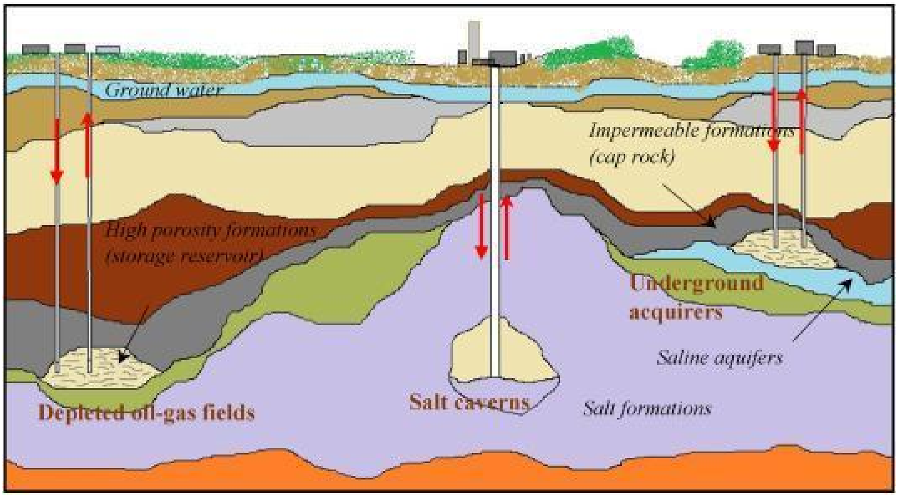

Figure 1.1. Underground H_2 Storage in Different Geological Formations [13].

- Because *salt caverns* have certain unique qualities, such as low permeability, high stability, and the ability to maintain hydrogen purity, they are among the most popular underground storage facilities for hydrogen. By dissolving salt deposits using fresh water and then pumping out the resulting brine, artificial cavities are thus formed within naturally occurring salt structures like salt domes or bedded salt layers. High geological tightness that reduces the risk of leakages, ability to perform a number of injection and withdrawal cycles annually, and secure, hermetic conditions that protect against contamination and ensure purity of hydrogen are some advantages of salt caverns [17]. However, since cavern development involves high costs and water consumption for leaching, their development and operation require considerable investment.

- *Aquifers*, a permeable and porous body of rock filled frequently with saline or freshwater water. Aquifers, rich in sedimentary basins throughout the world and constituted mostly of carbonate rocks or sandstone rocks, have been used effectively as reservoirs to store natural gas. Aquifers require two essential geological characteristics to be used as UHS facilities: impermeable cap rock, such as tight shale or mudstone, to stop hydrogen migration, and good injection reservoir characteristics. During storage, injected hydrogen pushes water out of the pore space, which comes back when the gas is generated due to the dynamic movement of the gas-water interface. Aquifers, however, need a huge volume of cushion gas, and because of the reservoir nature, there will be residual hydrogen. Among the key concerns are mineral or biochemical reactions, hydrogen migration through unmapped faults, and unknown cap rock tightness initially, necessitating large-scale and expensive testing.

- *Depleted gas fields* hold the potential for UHS, based on their inherent geologic stability and previous use as hydrocarbon reservoirs. Due to their huge volume and the natural seal afforded by the impermeable cap rocks and structural traps that minimize the potential for hydrogen leakage, depleted gas fields offer a vast storage capacity. Although existing infrastructure, like pipelines and wells, can reduce initial expenditures, it might need to be modified to handle small molecular size of hydrogen and the probability for material embrittlement. Complexity in operations is introduced by the requirement for large-scale surveys and monitoring to maintain the cap rock tightness and control interactions with residual hydrocarbons [17].

1.5 Criteria for evaluating UHS Sites

Current UHS options are being considered for their economic and technical feasibility; however, the selection of the most appropriate sites requires a systematic assessment on the basis of certain criteria and sub-criteria. The parameters help to evaluate the relative suitability of each site, whose pertinence varies in terms of geological, technical, and socio-economic factors.

Geological aspects cover such factors as permeability of the reservoir, sealing, integrity of subsurface caprock, and overall subsurface stability. Technical aspects encompass technical elements such as rates of injection and withdrawal, storage efficiency, and safety needs of operations. Socio-economic aspects encompass such factors as CAPEX/OPEX costs, closeness to centers of demand, existence of infrastructure, regulatory requirements, and acceptance by the public.

Because it is challenging to separate these factors, the use of structured decision-making techniques is necessary to determine well-informed and credible site selection. The present study formulates a framework to select suitable UHS sites in Central Asia by employing the Fuzzy TOPSIS methodology - a Multi-Criteria Decision-Making (MCDM) technique combining traditional TOPSIS with fuzzy logic to handle ambiguity and subjectivity in expert opinions.

1.6 Problem Statement

The identification of suitable UHS locations in Central Asia is plagued by serious challenges posed by regional geology, safety, stability, and cost-effectiveness uncertainties. Current methods of evaluating the said parameters lack strength in terms of giving good ratings, complicating the decision-making process. This work is designed to address these issues with the introduction of a fuzzy logic system for enhancing the quality of optimal UHS site determination.

1.7 Objectives

The primary objectives of this research are:

1. To determine and evaluate potential underground hydrogen storage sites in Central Asia according to Fuzzy TOPSIS logic.
2. To develop a decision-support framework that integrates geologic, technical, and socio-economic factors for site selection.

Chapter II

Literature review

2.1 Global Hydrogen Storage Projects

The rise of hydrogen recognition for enabling decarbonization and renewable energy integration led to the development of UHS as a leading prospect among major energy storage solutions. Over recent years hydrogen storage projects operated and examined different subsurface reservoirs such as salt caverns along with empty hydrocarbon locations and aquifers after implementing natural gas storage tactics [18]-[20].

UHS technology has reached commercial success through multiple pilot and operational platforms established in Europe, North America and China which proved its technical viability. The international storage projects inform the development of hydrogen infrastructure in Central Asia since the region needs to establish its storage systems.

2.1.1 Case studies of UHS in other countries

The extensive deployment of fossil-based and industrial gases underground storage through UGS operations presents essential knowledge for developing UHS. Currently there exist more than 680 Underground Gas Storage (UGS) facilities which can be found worldwide in depleted gas reservoirs and aquifers and salt caverns [16]. The installation of facilities for storing gas underground provides multiple strengths such as increased safety because they are protected from natural disasters and attacks, from surface fires, also they require less space than aboveground storage facilities and are cheaper to build with more availability of geological formations for storage [21]. European hydrogen storage focuses on salt caverns as they offer excellent leakproofness and operational versatility according to research [19].

The United Kingdom

The storage of hydrogen within salt caverns started in the 1970s at Teesside, United Kingdom, through operations that handled around 1 million m^3 of hydrogen for industrial purposes [19]. Since the 1980s facilities located in Clemens Dome and Moss Bluff have shown the United States how hydrogen storage at safe levels can be managed successfully [19]. Salt cavern facilities demonstrate quick cycling operations to match the sudden changes between energy supply levels and customer demand patterns. Historically town gas mixtures received successful storage within aquifers and depleted gas fields. But Germany and France need to conduct thorough geological assessments to prevent hydrogen leakage and microbial consumption [19].

Storing hydrogen requires special solutions because of its physical characteristics. The groundwater tank experiences leakage through rock or salt barriers because of its high diffusivity and small molecular dimensions unless appropriate management measures are deployed. Efforts should concentrate on solving hydrogen-induced material degradation of pipelines, chemical reactions with surrounding rocks, and stopping hydrogen leakage through rock and salt barriers [22]. The storage process of UHS requires additional site testing and technological adjustments beyond what natural gas storage needs.

The United States of America

The researchers are conducting large-scale investigations to study the complete effects of hydrogen storage on underground rock structures. Research about blending natural gas with hydrogen at the American Department of Energy supports Power-to-Gas projects to determine petroleum reservoir stability, rock formation and well infrastructure component effects [23]. The spread of hydrogen exceeds the movement of all other substances and causes steel to become brittle alongside causing reservoir rock permeability variations according to laboratory experiments and site measurements at U.S. locations [23]. Laboratory testing demonstrates that permeability changes between 10% to 65% occur when rock samples encounter different lithologies while caprock samples reveal the greatest sensitivity to hydrogen damage [23].

Numerical modeling of saline aquifers revealed that hydrogen dissolves into formation water and results in the loss of 1.75% of total storage capacity throughout four years of cyclic operations [23]. The reliability of traditional casing and cement materials designed for natural gas usage faces challenges when performing under high hydrogen partial pressures which produces risks through gas leakage and hydrogen embrittlement [23]. Organizations must carefully choose underground rock formations and execute thorough geochemical tests and redesign well system components to achieve secure hydrogen storage operations which remain effective.

The republic of Poland

Lewandowska-Śmierzchalska et al. [24] implemented a UHS site selection evaluation system in Poland through the Analytic Hierarchy Process (AHP) which screened and ranked potential sites. The researchers examined three subterranean geological structures of salt caverns as well as aquifers and depleted hydrocarbon reservoirs using nine evaluation criteria that included assessments of storage capacity and tightness and infrastructure availability. The research data showed salt caverns receiving the highest score of 0.464 during the evaluation which made them the best option for UHS applications. Research showed depleted gas reservoirs obtaining the second ranking with 0.349 while aquifers stood as last with 0.187. The paper demonstrated that salt cavern storage is optimal for long-term, safe hydrogen containment because of their exceptional low permeability (10e-18 m^2 or less) and strong mechanical properties.

Despite preferring salt caverns the authors declared depleted gas fields as suitable solutions whenever salt deposits are not available. Depleted gas reservoirs present slightly less secure conditions for hydrogen leakage yet provide storage capacities larger than 1 billion m^3 together with proximity to gas infrastructure which decreases investment expenses. The analysis conducted by Lewandowska-Śmierzchalska et al. creates a quantitative method for selecting UHS sites by bringing together geological potential with operational and economic considerations [24].

The Republic of China

Research conducted by China proves that depleted oil and gas reservoirs provide the best option for hydrogen storage infrastructure operations. The extensive underground natural gas storage experience alongside mature oil and gas field collection across China creates ideal conditions for upcoming hydrogen storage projects. Research indicates that China operates 5,000 stable mature oil and gas fields which provide total storage capabilities of about 60 billion cubic meters of natural gas-equivalent storage capacity. The big storage potential enables China to build its hydrogen economy through this approach. The existing underground gas storage infrastructure has demonstrated implementation success over 10 years so it strengthens the feasibility of converting these sites into hydrogen storage facilities which are both technically viable and cost-effective [25].

2.1.2 Lessons learned for Central Asia

European and North American and Chinese UHS projects demonstrate essential lessons about developing hydrogen storage infrastructure in Central Asia through their accumulated experiences.

1. Recent case studies demonstrate geological compatibility serves as the main criterion when picking storage sites. Depleted gas reservoirs work well as replacement storage facilities in Western Kazakhstan because this area contains established oil and gas fields like Karachaganak and Tengiz [24], [26]. Such sites demonstrate excellent potential for hydrogen storage since China successfully integrates depleted oil and gas fields to store hydrogen particularly in areas with mature oil fields such as the Tarim Basin. The Chinese oil and gas industry proves that their 5,000 mature fields located in stable regions represent an effective large-scale hydrogen storage opportunity for Central Asia [26].

2. Existing well infrastructure and casing integrity was shown to be possible for reuse in both U.S. and European projects although researchers identified potential problems related to hydrogen embrittlement and leakage through time-damaged wellbore pipelines and steel casings [24], [26]. The numerous aging facilities of mature oil and gas fields throughout Central Asia require mandatory retrofit strategies combined with integrity testing before starting any hydrogen storage project. To guarantee well integrity in hydrogen storage operations extensive testing protocols must be implemented because Kazakhstan and Turkmenistan possess numerous aging wells.

3. Studies conducted both in aquifers and depleted reservoirs indicate that methanogenic bacteria along with other microbial communities potentially consume hydrogen substrate [17], [27]. Central Asia requires immediate attention on this issue because its numerous depleted reservoirs might harbor active microbial communities. Research on other hydrogen production projects shows that microbial activity causes hydrogen depletion patterns which requires strategic microbial control systems and advanced monitoring solutions for planning success.

4. The fermentation facilities located at Teesside and Moss Bluff displayed how keeping hydrogen pure becomes difficult due to contaminated cushion gas which mixes with leftover

hydrocarbons. The design phase of Central Asian projects requires integration of purification and gas separation systems which will enable end-use applications including fuel cells and ammonia production according to [17] and [23]. China's hydrogen production campaigns at depleted gas reservoirs revealed the necessity of implementing strong purification systems to remove natural gas residues as stated in [25].

5. Central Asia differs from Europe and North America because it does not have specific regulations for hydrogen storage despite their established natural gas storage laws. The absence of proper legislation prevents Central Asia from solving leakage liability together with monitoring standards and public safety issues [28]-[38]. Central Asia must learn from existing regulatory frameworks in Europe and North America to guarantee that its hydrogen storage facilities fulfill all safety requirements and environmental compliance standards.

6. International examples indicate the necessity of conducting pilot-scale storage trials because these tests help identify both geological behaviors and technical problems at localized sites prior to extended implementation. The region should choose one or two depleted oil fields to conduct their first pilot demonstrations with supporting geological modeling as well as well integrity testing alongside microbial analysis. The successful pilot tests conducted by China in oil and gas fields provide essential data for constructing large-scale hydrogen storage systems because they preview the later-stage methodology [25].

Central Asia shares geological characteristics like other regions that successfully employ underground hydrogen storage but must conduct region-specific assessments through pilot demonstrations due to these international examples. The region needs to study global examples before developing locally applicable strategies to ensure safe and effective hydrogen storage implementations.

2.2 Fuzzy Logic and Fuzzy TOPSIS in Decision-Making

Multiple decision systems (MCDM) involve AHP, ELECTRE and TOPSIS which remain popular tools for tackling challenging selection and ranking tasks that combine competing criteria [30]. Traditional MCDM approaches depend on precise quantitative information for their implementation, but decision problems usually lack such detailed data in real environments. Information that exists in practical scenarios is often incomplete or vague and imprecise because these characteristics make classical MCDM approaches less applicable [31]. Engineering and energy project criteria are typically presented in subjective expressions instead of measurable formats according to various studies [31].

Researchers solved these limitations by developing fuzzy extensions for MCDM methods thus producing Fuzzy Multi-Criteria Decision-Making (FMCDM) [32]. The integration of fuzzy logic within traditional decision making processes allows decision-makers to utilize linguistic variables (high, medium and low) instead of numerical values in evaluations through FMCDM systems. The incorporation of decision models with this approach enhances the ability to capture unpredictable human evaluation uncertainties leading to better evaluation results. The research community has established that FMCDM methods provide superior quality decision-making solutions than MCDM systems when dealing with environments with uncertainty [32].

Fuzzy TOPSIS stands as one of the most commonly used approaches in the field of FMCDM. Cognitive psychologists developed TOPSIS to find rankings by determining alternative distances from positive and negative ideal solutions through exact data analysis [31]. Jahanshahloo et al enhanced the method by using triangular fuzzy numbers to represent performance values and criteria weights to enable alternative ranking under conditions of uncertainty based on fuzzy decision matrix and fuzzy weight vector construction. Fuzzy TOPSIS demonstrates its versatility in multiple areas of application including facility selection and supplier evaluation as well as energy planning and project prioritization through which it proves its effectiveness for complex decisions which require handling vagueness [30].

2.2.1 Fundamentals of Fuzzy logic

The systematic structure of fuzzy logic enables systematic modeling of decision-making uncertainties as well as imprecise conditions. Fuzzy set theory allows elements to demonstrate partial set membership through membership degrees existing between 0 and 1 [31]. Every element in universe X has its corresponding membership value $\mu A(x) \in [0, 1]$ detected through the membership function $\mu A(x)$ that defines fuzzy set A.

Vague information can be transformed into practical mathematical expressions through simple parameterized shapes including triangular and trapezoidal fuzzy numbers [33]. The triangular fuzzy number displays linear upward and downward slopes extending from its summit value and the trapezoidal fuzzy number encompasses full membership between two distinct points.

The processing of linguistic assessments utilizing "high importance", "medium suitability" and "low risk" under fuzzy logic requires no binary classification requirements in decision-making applications. The combination offers superior expression of expert evaluations particularly in technical domains which present challenges for determining precise numerical data.

Fuzzy logic shows exceptional capability in handling vague as well as incomplete and imprecise information which makes it optimal for decision-making problems that heavily rely on human judgment. Fuzzy logic continues widespread adoption in current decision systems through frameworks that boost reliability during situations of uncertainty [31], [33].

2.2.2 Application of Fuzzy TOPSIS in energy projects

New TOPSIS benefits from fuzzy numbers that enable the assessment of decision matrices and criterion weights [33]. Fuzzy TOPSIS requires two main operational steps which start by having experts provide linguistic evaluations in a decision matrix before normalization and subsequent weight assignment [33]. The method then calculates the fuzzy best-case solution and the fuzzy worst-case solution and calculates the distances to these solutions using the vertex method. [31]. The ranking procedure follows the FPIS position with alternative scores to assess objective decision-making even with uncertain conditions.

Fuzzy TOPSIS stands as a successful decision-making approach which serves numerous energy-related sectors. Research shows that fuzzy TOPSIS proves beneficial for renewable energy planning and selection of energy system suppliers and sites for electric vehicle charging stations and facility placement under ambiguous conditions [30]. The combination of fuzzy TOPSIS with fuzzy AHP and fuzzy DEMATEL presents recent developments that boost decision-making accuracy within FMCDM problems [30]. This project utilizes fuzzy TOPSIS evaluation to rank different types of UHS facilities (salt caverns and aquifers alongside depleted gas fields) by finding consensus from experts through established multi-criteria analysis.

Chapter III

Methodology

3.1 Research Steps Overview

The methodological framework employed to assess and choose the most suitable UHS site for Central Asia is presented in Fig. 3.1 and described in detail below.

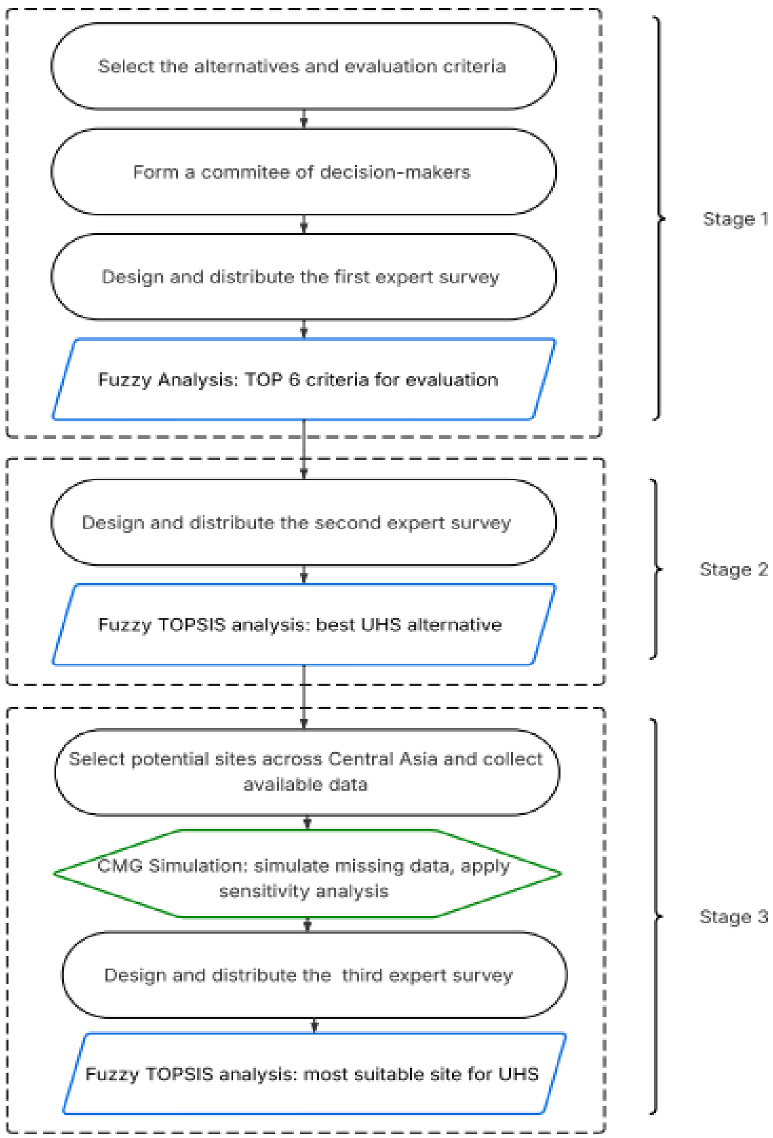

Figure 3.1. Research Process Flowchart

1. Select the alternatives (e.g. salt caverns, deep aquifers, depleted hydrocarbon spaces).

2. Select evaluation criteria based on geological, technical, and socio-economic factors.
3. Design and distribute the first questionnaire to three experts.
4. Analyze expert responses and select the top six most critical criteria using the Fuzzy method.
5. Prepare and distribute the second questionnaire to experts.
6. Apply Fuzzy TOPSIS methodology to rank the three storage alternatives.
7. Identify the best UHS alternative for Central Asia.
8. Select four UHS fields across Central Asia.
9. Collect available geological data for the selected fields.
10. Perform CMG simulations on selected fields.
11. Apply sensitivity analysis to estimate missing parameters.
12. Design and distribute the third questionnaire to experts.
13. Apply Fuzzy TOPSIS again to rank the fields.
14. Perform cost analysis for the most suitable field.

3.2 Identification and Refinement of Criteria

The objective of this section is to discuss how the criteria used to choose UHS sites were identified, refined, and ultimately structured from which the final decision making process was based.

3.2.1 Development of 19 initial criteria

An extensive review of previous research on underground hydrogen and other gases storage was conducted to identify the key criteria affecting suitable site selection. The authors of [34], [35] provided valuable insights on the division of all selected criteria into three main sectors: geological, technical, and socio-economic (see Table 3.1).

Table 3.1: Criteria-Based UHS Site Selection Practices

Criteria	References
Technical Characteristics	[34], [35], [36]
Geological Properties	[34], [37]
Socio-economic Characteristics	[35], [36], [38]

An initial step towards establishing the criteria for selection of UHS sites, the first questionnaire was developed (Appendix A.1). The methodology targeted technical and economic factors that were critical factors in evaluating potential storage methods, and ensured that the analysis factored in a broad set of considerations. The importance of these and other criteria was to be gauged by expert input in order to establish a basis for future decisions and evaluations of alternative UHS.

The criteria were divided into three categories:

1. Geological criteria included reservoir characteristics (e.g., permeability, porosity, and storage volume) and geological characteristics (e.g., area, depth, and thickness).
2. Technical factors covered the requirements for operation, prevention of hydrogen leakage, maintaining pure and safe storage of hydrogen
3. Socio-economic considerations included storage costs, proximity to infrastructure, and legal and social restrictions. This initial set ensured comprehensive coverage of factors essential for successful hydrogen storage.

Previous studies have highlighted key technical factors of long-term reliability in underground gas storage, including storage capacity, geographical feature (depth, area, thickness), and reservoir porosity and permeability [34]-[36]. Economic factors such as development costs, initial investments, and infrastructure availability have also been extensively analyzed [34]-[38]. Building upon these findings, criteria and sub-criteria were extracted from existing literature, resulting in the development of 19 criteria to evaluate the most suitable sites for UHS.

3.2.2 First expert survey: rating importance of criteria

A structured questionnaire was distributed among three experts to rate the importance of each of the 19 identified criteria. The linguistic scale employed by experts ranged from "Extremely Low" to "Extremely High" importance. The collected responses were converted into fuzzy numbers, allowing for a nuanced treatment of expert uncertainty and subjectivity.

3.2.3 Selection of top 6 criteria

Based on the simple fuzzy logic top six criteria were defined from the first expert survey according to their high aggregated importance values. The resulting criteria are shown in Table 3.2.

Table 3.2: Criteria and Definitions.

Criteria		Definition	Criteria Type
C_1:	Sealing Effectiveness	The ability to prevent hydrogen leakage and ensure long-term containment.	Benefit
C_2:	Storage Capacity	The volume of hydrogen capable of being safely stored.	Benefit
C_3:	Caprock Permeability	The impermeability of the overlying geological layer, which is crucial for containment.	Cost
C_4:	Cavern Stability	The structural integrity of the storage site under varying pressures.	Benefit
C_5:	Storage Costs	The economic feasibility of initial setup and operational expenses.	Cost
C_6:	Hydrogen Injection and Withdrawal Rates	The volume of injected and produced hydrogen per day.	Cost

3.3 Evaluation of UHS Alternatives

This section's aim is to discuss how the most appropriate alternative for UHS sites in Central Asia were defined, describe the Fuzzy TOPSIS method and the second stage of the expert survey.

3.3.1 Second expert survey: rating 3 storage types

A second questionnaire was developed to evaluate three alternative UHS types - salt caverns, aquifers, and depleted gas fields - against the six selected criteria. Experts rated the performance of each alternative using a linguistic scale from "Very Poor" to "Very Good." Their responses were again translated into fuzzy numbers to reflect uncertainty in evaluations.

3.3.2 Fuzzy TOPSIS application to rank alternatives

The Fuzzy TOPSIS method was selected for its robustness in coping with uncertainty and for its systematic way of ranking infeasible alternatives [39]. The traditional TOPSIS compares the alternatives by calculating the distance from ideal solutions. Nevertheless, since expert evaluations are, of necessity, uncertain, traditional methods involve crisp, absolute weights and values, which are difficult to justify. To overcome the uncertainty and bias in the decision-making process, fuzzy TOPSIS extends the traditional approach by converting expert opinions expressed in linguistic terms ("high", "medium", and "low") to fuzzy numbers. Using this extension, there can be better expert evaluations of these alternatives and rank them accordingly [40]. Normally, without the use of fuzzy logic, evaluations made by human beings have to be binary, i.e., good-bad, yes-no or 0-1. However this black-white description in real life can be separated by many shades of gray, which should be taken into account for evaluations. This uncertainty, or vagueness may be accounted for using fuzzy logic [40].

Fuzzy sets can be represented as membership functions, where the function is defined as a number in the range 0 to 1 and denoted as, $\mu A(x)$. This implies that if an element x belongs to the set A, then the membership function $\mu A(x) = 1$, and if not, $\mu A(x) = 0$. The membership function can vary from a high to a low degree and it is continuous. There are many ways of defining the membership function, for example, using triangular or trapezoidal [41] formulations. The membership function used here is the trapezoidal fuzzy number defined as

$$\mu_{\tilde{n}}(x) = \begin{cases} 0, & x < n_1 \\ \frac{x-n_1}{n_2-n_1}, & n_1 \leq x \leq n_2 \\ 1, & n_2 \leq x \leq n_3 \\ \frac{x-n_3}{n_3-n_4}, & n_3 \leq x \leq n_4 \\ 0, & x > n_4 \end{cases}$$

It should be noted that in the following a fuzzy number will be identified by a tilde. For fuzzy trapezoidal numbers the following elementary operations can be defined [42], with some used in this work.

For two positive trapezoidal values *m* and *n*, and *r* a constant number, fundamental operations for TFNs are defined as

$$(\tilde{m} \oplus \tilde{n}) = (m_1 + n_1, m_2 + n_2, m_3 + n_3, m_4 + n_4)$$

$$(\tilde{m} \ominus \tilde{n}) = (m_1 - n_1, m_2 - n_2, m_3 - n_3, m_4 - n_4)$$

$$(\tilde{m} \otimes \tilde{n}) = (m_1 \times n_1, m_2 \times n_2, m_3 \times n_3, m_4 \times n_4)$$

$$(\tilde{m} \otimes r) = (m_1 \times r, m_2 \times r, m_3 \times r, m_4 \times r) \quad (1)$$

$$(\tilde{m} \oslash \tilde{n}) = (m_1/n_4,\ m_2/n_3,\ m_3/n_2,\ m_4/n_1)$$

$$(-\tilde{m}) = (-\tilde{m}_1,\ -\tilde{m}_2,\ -\tilde{m}_3,\ -\tilde{m}_4)$$

$$\left(\frac{1}{\tilde{m}}\right) = \left(\frac{1}{\tilde{m}_4}, \frac{1}{\tilde{m}_3}, \frac{1}{\tilde{m}_2}, \frac{1}{\tilde{m}_1}\right) \quad (2)$$

An equivalent method for the traditional TOPSIS analysis when finding the distance of the positive and negative ideals needs to be developed for fuzzy numbers. The method used here is the vertex method for the trapezoidal fuzzy numbers $\tilde{m} = (m_1, m_2, m_3, m_4)$ and $\tilde{n} = (n_1, n_2, n_3, n_4)$ defined [43], [44].

Vertex Method

The distance to the positive and negative ideal solutions is calculated to rank the options, with the Vertex method being employed for this purpose:

$$d_v(\tilde{m}, \tilde{n}) = \sqrt{\frac{1}{4}[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2 + (m_4 - n_4)^2]} \quad (3)$$

where $\tilde{m} = (m_1, m_2, m_3, m_4)$ and $\tilde{n} = (n_1, n_2, n_3, n_4)$ are two positive trapezoidal numbers.

Experts in the field decide on the MCDA problem. The following set of elements are necessary for MCDA problems: DMs (DM_1, DM_2, ..., DM_k), alternative (A_1, A_2, ..., A_m), decision criteria component for each alternative (C_1, C_2, ..., C_n), and a set of criteria values based on the decision criteria for each alternative. Linguistic expressions for priorities of each criterion and linguistic expressions for ratings are given in Tables 3.3 and 3.4.

Table 3.3: Translation of linguistic expressions of criteria into fuzzy numbers

Linguistic Expression	Abbreviation	Trapezoidal Fuzzy Number
Very High	VH	(0.8 0.9 1.0 1.0)
High	H	(0.7 0.8 0.8 0.9)
Middle High	MH	(0.5 0.6 0.7 0.8)
Middle	M	(0.4 0.5 0.5 0.6)
Middle Low	ML	(0.2 0.3 0.4 0.5)
Low	L	(0.1 0.2 0.2 0.3)
Very Low	VL	(0.0 0.0 0.1 0.2)

Table 3.4: Translation of linguistic expressions of alternatives into fuzzy numbers

Linguistic Expression	Abbreviation	Trapezoidal Fuzzy Number
Very Good	VG	(8 9 10 10)
Good	G	(7 8 8 9)
Middle Good	MG	(5 6 7 8)
Fair	F	(4 5 5 6)
Middle Poor	MP	(2 3 4 5)
Poor	P	(1 2 2 3)
Very Poor	VP	(0 0 1 2)

Then following is a series of steps used to rank the alternatives based on the criteria.

3. Methodology

i. Step 1

The expert evaluations of k decision-makers (DMs) on m *a*lternatives, along with priority weights of n criteria, are represented as $\tilde{x} = (a_{ijk}, b_{ijk}, c_{ijk}, d_{ijk})$ and $\tilde{w} = (w_{ij1}, w_{ij2}, w_{ij3}, w_{ij4})$, where $(i = 1,\ 2,\ ...,\ m; j = 1,\ 2,\ ..., n)$.

Fuzzy criteria values obtained from these expert evaluations based on indicators are represented as $\tilde{x} = (a_{ijk}, b_{ijk}, c_{ijk}, d_{ijk})$ where

$$a_{ij} = a_{ijk}, \quad b_{ij} = \frac{1}{K}\sum_{k=1}^{K}\left(b_{ijk}\right) \tag{4}$$

$$c_{ij} = \frac{1}{K}\sum_{k=1}^{K}\left(c_{ijk}\right), \quad d_{ij} = d_{ijk} \tag{5}$$

ii. Step 2

Priority weights of decision criteria are $\tilde{w} = (w_{ij1}, w_{ij2}, w_{ij3}, w_{ij4})$, where

$$w_{j1} = w_{jk1}, \quad w_{j2} = \frac{1}{K}\sum_{k=1}^{K}\left(w_{jk2}\right) \tag{6}$$

$$w_{j3} = \frac{1}{K}\sum_{k=1}^{K}\left(w_{jk3}\right), \quad w_{j4} = w_{jk4} \tag{7}$$

iii. Step 3

The decision problem is presented in matrix form as

$$\begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{13} & \tilde{x}_{13} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \tilde{x}_{23} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \tilde{x}_{m3} & \cdots & \tilde{x}_{mn} \end{bmatrix} \tilde{W} = [\tilde{w}_1, \tilde{w}_2, ..., \tilde{w}_n] \tag{8}$$

where $\tilde{x} = (a_{ijk}, b_{ijk}, c_{ijk}, d_{ijk})$ and $\tilde{w} = (w_{ij1}, w_{ij2}, w_{ij3}, w_{ij4})$ are two fuzzy numbers, $\tilde{D}$ is a fuzzy decision matrix, and $\tilde{W}$ represents a fuzzy weight matrix.

iv. Step 4

Decision criteria can be separated as cost and benefit. Therefore, a normalized fuzzy decision matrix is obtained as $R^{\sim} = \{r^{\sim}_{ij}\}_{m\times n}$. Here B and C symbolize the benefit and cost criteria, respectively:

$$r^{\sim}_{ij} = \left[\frac{a_{ij}}{d^{*}_{j}}, \frac{b_{ij}}{d^{*}_{j}}, \frac{c_{ij}}{d^{*}_{j}}, \frac{d_{ij}}{d^{*}_{j}}\right], \quad d^{*}_{j} = d_{ij}, \quad j \in B \tag{9}$$

$$r^{\sim}_{ij} = \left[\frac{a^{-}_{j}}{d_{ij}}, \frac{a^{-}_{j}}{c_{ij}}, \frac{a^{-}_{j}}{b_{ij}}, \frac{a^{-}_{j}}{a_{ij}}\right], \quad a^{-}_{j} = a_{ij}, \quad j \in C \tag{10}$$

The weighted normalized fuzzy decision matrix is needed, since each decision criterion might have different priority weights. This matrix is constructed as:

$$V^{\sim} = [v^{\sim}_{ij}]_{m\times n}, \quad i = 1, 2,..., m; \quad j = 1, 2,..., n \tag{11}$$

$$v_{ij} = r^{\sim}(.)w^{\sim}_{j} \tag{12}$$

Here, Fuzzy Positive Ideal Solution (FPIS, A^{*}) and Fuzzy Negative Ideal Solution (FNIS, A^{-}) are expressed as:

$$A^{*} = (v^{*}_{1}, v^{*}_{2},..., v^{*}_{n}), A^{-} = (v^{-}_{1}, v^{-}_{2},..., v^{-}_{n}) \tag{13}$$

Let $i = 1, 2, ..., m$ and $j = 1, 2, ..., n$.

$$v^{\sim *}_{j} = max(v_{ij4}), v^{\sim -}_{j} = min(v_{ij1}) \tag{14}$$

The distance between two fuzzy numbers, denoted as d_{v}, is calculated using the vertex method, allowing for the determination of distances to the FPIS and FNIS for each country:

$$d^{*}_{i} = \sum_{j=1}^{m} d_{v}(v^{\sim}_{ij}, v^{*}_{j}), \quad i = 1, 2, ..., m \tag{15}$$

$$d^{-}_{i} = \sum_{j=1}^{m} d_{v}(v^{\sim}_{ij}, v^{-}_{j}), \quad i = 1, 2, ..., n \tag{16}$$

v. Step 5

Once the distances are determined, the closeness coefficient (*CC_i*) for comparing the attributes is computed as follows:

$$CC_i = \frac{\alpha d_i^- + (1+\alpha) d_i^*}{d_i^* + d_i^-}, \quad i = 1,\ 2,\ \ldots,\ m \tag{17}$$

Here, $0 \le \alpha \le 1$. The attribute weights are sorted from highest to lowest. After testing the range of α values from 0 to 1, the final evaluation rankings were compared.

3.3.3 Identification of optimal storage type

Following the ranking of the alternatives, the option with the highest closeness coefficient - ranked first - was selected as the optimal storage type based on expert evaluations. Calculations were initially performed using Microsoft Excel, followed by further analysis conducted with MATLAB software.

3.4 Selection of Specific UHS Fields

This section describes the selection of depleted gas fields in Central Asia, namely in Kazakhstan and Uzbekistan. Following by collection and estimation of geological data using CMG software.

3.4.1 Selection of 4 depleted gas fields in Central Asia

After the identification of depleted gas fields as the preferred storage alternative, four candidate fields in Kazakhstan and Uzbekistan were selected. This selection was based on availability of public data of these four fields. The selected fields were:

- Tengiz Field
- Kashagan Field
- Karachaganak Field
- Gazli Field

3.4.2 Collection of geological data

Depleted gas fields were historically owned and operated by oil and gas commercial organizations, resulting in geological and technical data being classified as highly confidential. Some information for the four selected fields was gathered from scientific publications, government databases, and field development reports [23], [25], [26]. Geological data such as reservoir permeability, lithology, reservoir pressure, and temperature were collected. However, this data was insufficient to fully characterize the storage potential of the sites.

3.4.3 CMG simulation: sensitivity analysis

Criteria such as storage capacity and injection and withdrawal rates are valuable only if they were used in terms of hydrogen storage. Since there was not any experience in storing the hydrogen in Central Asia, this data had to be simulated in CMG software. Sensitivity analyses served as the estimation of injection and production rates under different scenarios.

3.5 Final Evaluation of Selected Fields

This section aims to explain the final steps of UHS site selection, including the third stage of expert survey, second Fuzzy TOPSIS analysis and cost estimations for the derived gas field.

3.5.1 Third expert survey: rating 4 fields

A third questionnaire was distributed among the same group of experts (see Appendix A.3). The experts evaluated the four selected fields based on five refined criteria:

1. Sealing Effectiveness
2. Storage Capacity
3. Caprock Permeability
4. Cavern Stability
5. Hydrogen Injection and Withdrawal Rates

It is significant to note that the criterion “Storage Costs” was intentionally excluded from the third stage expert survey. The principal reason for making this decision was to simplify the process of evaluation and focus the analysis on geological and technical parameters that determine the gas fields' viability for UHS. Then, the evaluation again used a linguistic scale, converted into fuzzy numbers for analysis.

3.5.2 Fuzzy TOPSIS application: ranking of fields

The fuzzy TOPSIS method was re-applied in UHS site selection. The closeness coefficient was calculated for each site using MATLab software, and the option with the highest one was marked as the most suitable site for UHS in Central Asia.

3.5.3 Cost Analysis

At this stage the costs for potential hydrogen storage operation at the chosen gas field were identified. The cost analysis included capital (CAPEX) and operational expenditures (OPEX).

Chapter IV

Results

4.1 Weighting of Initial Criteria

Based on expert input, the initial set of 19 criteria, covering technical, socio-economic, and geological aspects, was proposed. Decision makers used a scale from "Extremely Low" to "Extremely High" priority to rank these criteria. The results showed that criteria such as sealing effectiveness, storage capacity, and cavern stability received the highest importance ratings across all experts. In contrast, factors like depth, area, and caprock thickness were deemed less critical.

The expert feedback resulted in the selection of six key criteria, which were evaluated most critical for assessing the suitability of UHS sites:

1. Sealing Effectiveness
2. Storage Capacity
3. Caprock Permeability
4. Cavern Stability
5. Storage Costs (CAPEX/OPEX)
6. Hydrogen Injection and Withdrawal Rates

These six criteria reflect the interdisciplinary requirements for successful UHS deployment. Fig. 4.1 summarizes the final rankings and importance levels of all 19 criteria.

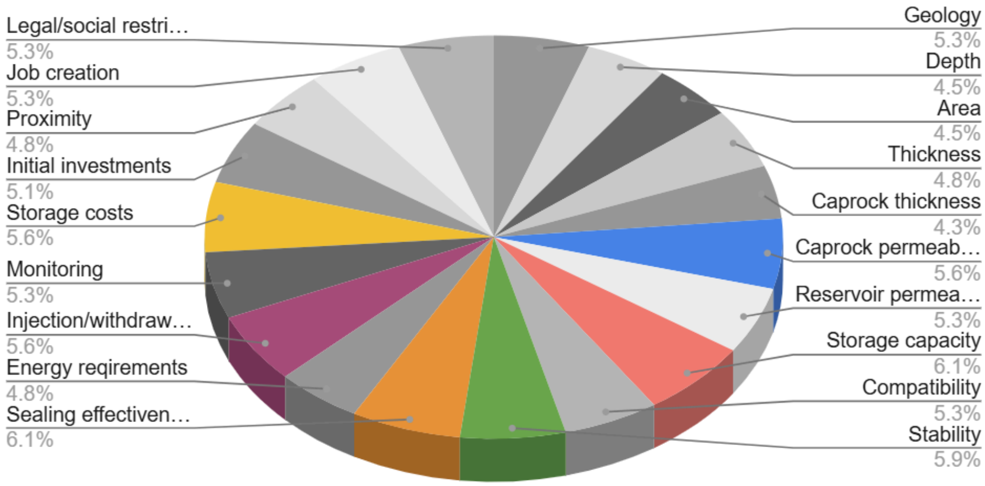

Figure 4.1. Importance levels of 19 criteria

The high prioritization of sealing effectiveness and storage capacity underscores the importance of safety and scalability in hydrogen storage. Conversely, criteria with relatively low rankings, such as depth, area and caprock thickness or impact on local population, were deprioritized due to their lesser influence on the overall feasibility of UHS. By narrowing down the criteria, the study ensures that the subsequent analysis is both focused and relevant to the unique geological and operational conditions of Central Asia.

4.2 Evaluation of Storage Alternatives

As one of the main steps of Fuzzy TOPSIS analysis, the six criteria were weighted based on decision-makers' assessment of their relative importance in the UHS selection process. Table 4.1 represents the linguistic assessment of criteria by 3 decision-makers.

Table 4.1: Linguistic assessment of 6 criteria

Decision makers	**Criteria**					
	C_1	C_2	C_3	C_4	C_5	C_6
D_1	VH	MH	H	M	L	ML
D_2	VH	H	M	ML	L	VL
D_3	VH	M	VH	H	MH	MH

The assigned weights are presented in Table 4.1 and Fig. 4.2, sealing effectiveness and caprock permeability being given highest importance due to their fundamental roles in ensuring operational safety. The weighted criteria served as the foundation for assessing the performance of each alternative.

Table 4.2: Weightage of criteria

Criteria		**Trapezoidal Fuzzy Number (a_1, a_2, a_3, a_4)**	**Weightage** $df = \frac{1}{4}(a_1 + a_2 + a_3 + a_4)$
C1	Sealing effectiveness	0.8 0.9 1.0 1.0	0.925
C2	Storage capacity	0.4 0.633 0.667 0.9	0.650
C3	Caprock permeability	0.4 0.733 0.767 1.0	0.725
C4	Cavern Stability	0.2 0.533 0.567 0.9	0.550
C5	Storage costs	0.1 0.333 0.367 0.8	0.400
C6	Injection and withdrawal rates	0.0 0.3 0.4 0.8	0.375

The results of the study highlight the socio-economic, technological, and geological advantages of utilizing depleted gas fields for UHS in Central Asia.

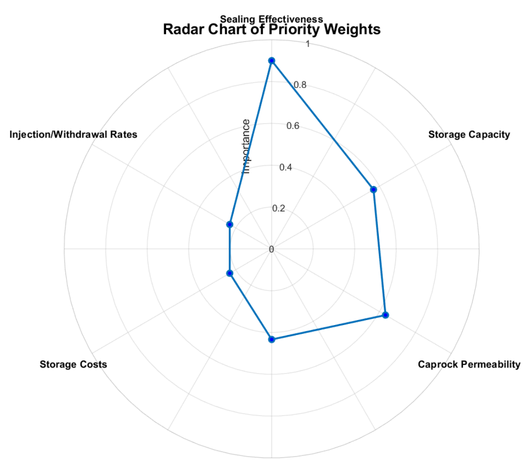

Figure 4.2. Criteria prioritization for depleted gas fields

Subsequently, three different storage options - depleted gas fields, aquifers, and salt caverns - were evaluated against the six key criteria derived from the first stage of survey. Second stage of expert surveys was conducted to assess the performance of each alternative relative to these criteria, the example of the questionnaire is shown in Appendix A.2. A structured decision-making framework was employed to assign weightages to the criteria and evaluate the alternatives based on their suitability for UHS in Central Asia. Experts - decision-makers have assessed three alternatives using linguistic values (shown in Table 4.3). Following steps 1-4 for Fuzzy TOPSIS logic, the normalized fuzzy decision matrix was derived (shown in Table 4.4).

Table 4.3: Linguistic assessments of three alternatives

Alternatives (Storage types)	**Decision makers**	**Criteria**					
		$\mathbf{C_1}$	$\mathbf{C_2}$	$\mathbf{C_3}$	$\mathbf{C_4}$	$\mathbf{C_5}$	$\mathbf{C_6}$
$\mathbf{A_1}$	$\mathbf{D_1}$	VG	F	VG	VG	G	VG
	$\mathbf{D_2}$	VG	F	VG	P	F	MP
	$\mathbf{D_3}$	VG	VG	VG	VG	G	G
$\mathbf{A_2}$	$\mathbf{D_1}$	G	VG	G	G	VG	G
	$\mathbf{D_2}$	VG	G	VG	VG	VG	VG
	$\mathbf{D_3}$	G	VG	F	G	VG	G
$\mathbf{A_3}$	$\mathbf{D_1}$	F	G	F	F	MP	F
	$\mathbf{D_2}$	G	VG	G	G	G	G
	$\mathbf{D_3}$	F	G	F	F	F	G

Table 4.4: The normalized fuzzy decision matrix

Criteria	Alternatives (Storage types)		
	A_1	**A_2**	**A_3**
C_1	(0.8, 0.9, 1.0, 1.0)	(0.6, 0.767, 0.867, 1.0)	(0.4, 0.567, 0.667, 0.9)
C_2	(0.4, 0.633, 0.733, 1.0)	(0.6, 0.833, 0.933, 1.0)	(0.6, 0.767, 0.867, 1.0)
C_3	(0.4, 0.4, 0.444, 0.5)	(0.4, 0.5, 0.571, 1.0)	(0.444, 0.6, 0.706, 1.0)
C_4	(0.1, 0.633, 0.733, 1.0)	(0.6, 0.767, 0.867, 1.0)	(0.4, 0.567, 0.667, 0.9)
C_5	(0.4, 0.633, 0.733, 0.9)	(0.8, 0.9, 1.0, 1.0)	(0.2, 0.5, 0.6, 0.9)
C_6	(0.2, 0.273, 0.316, 1.0)	(0.2, 0.231, 0.261, 0.333)	(0.222, 0.273, 0.316, 0.5)

The analysis demonstrated that depleted gas fields had the highest closeness coefficient and ranked as first, while salt caverns ranked second and aquifers ranked third (see Table 4.5 and Fig 4.3).

Table 4.5: Final ranking of alternatives of underground hydrogen storage

Alternative	Fuzzy Scale	Final Ranking
A1 - Salt Caverns	0.54378	2
A2 - Depleted Gas Fields	0.61997	1
A3 - Aquifers	0.38688	3

The TOPSIS analysis identified depleted gas fields as the most suitable UHS alternative in Central Asia, outperforming aquifers and salt caverns in terms of overall criteria satisfaction (see Fig. 4.3). This finding underscores the practical advantages of utilizing existing infrastructure and favorable geological conditions, aligning with the region's potential for hydrogen storage development. Each alternative was assessed for its ability to meet the criteria, considering the geological and technical context of Central Asia. The evaluations highlighted the following:

- Depleted Gas Fields: These registered fine performance in caprock permeability, sealing efficiency, and storage capacity due to their prevailing geology and infrastructure.

- Aquifers: Although aquifers have a moderate storage capacity, aquifers were plagued by sealing efficiency and hydrogen injection/withdrawal rates concerns, so aquifers are not as preferred in mass hydrogen storage.

- Salt Caverns: Due to their good sealing properties and high withdrawal rates, salt caverns were acceptable but less common in Central Asia restricted their viability.

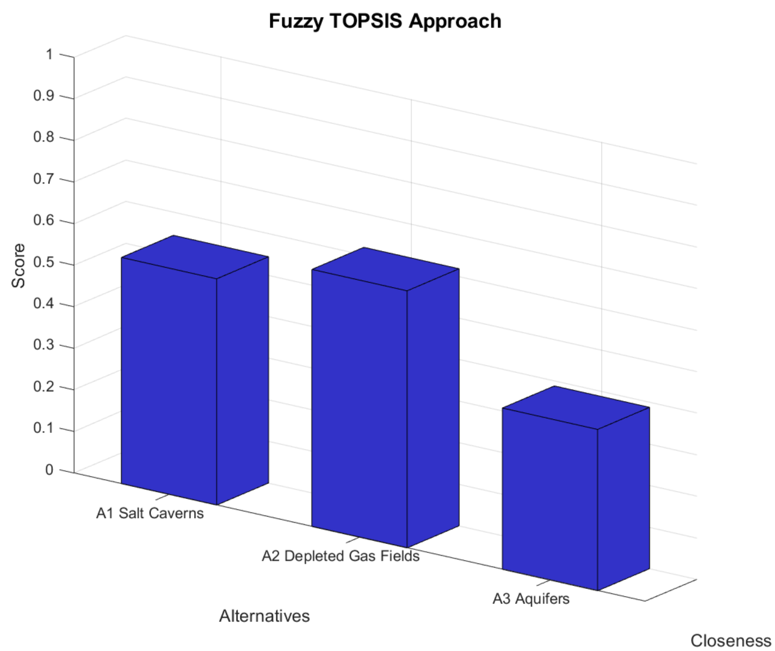

Figure 4.3. Ranking of the Three Alternatives Based on Fuzzy TOPSIS Analysis

4.3 Assessment of Selected Gas Fields

This section aims to provide the result of the second-stage Fuzzy TOPSIS method applied to evaluate the potential of four depleted gas fields in Central Asia for underground hydrogen storage. It includes the analysis of the geological and technical data, CMG simulation for forecasting operational parameters, and the Fuzzy TOPSIS ranking for identifying the most suitable field for storage. Furthermore, a preliminary economic evaluation of the Kashagan field is presented to establish the commercial feasibility and expense of hugescale hydrogen storage.

4.3.1 Data summary

Following the selection of depleted gas fields as the most optimal storage alternative, Central Asian depleted gas fields were examined for potential suitability. Only four gas fields (Tengiz, Kashagan, Karachaganak gas fields - in Kazakhstan, and Gazli gas field - in Uzbekistan) were selected due to the availability of data and accessibility. Publicly available geological and technical data were collected from scientific publications, government databases, and development reports [18], [19], [47], [48]. This data is demonstrated in Table 4.6.

Table 4.6: Four gas fields: geological and technical data

	Sealing Type	**Caprock Permeability, mD**	**Cavern Stability**
Tengiz Gas Field [26]	Carbonate cap with minor faulting	10	82.7 MPa, 109 ℃
Kashagan Gas Field [26]	Thick evaporite/salt layers	3	77.6 MPa, 100 ℃
Karachaganak Gas Field [23]	Fractured dolomite and limestone	10-14.5	59.5 MPa, 80 ℃
Gazli Gas Field [27]	Claystone & evaporite/anhydrite	1491	7.2 MPa, 90 ℃

Table 4.6 presents significant geological and technical characteristics of four selected gas fields in Kazakhstan and Uzbekistan. The Tengiz and Kashagan fields possess low caprock permeability (3–10 mD) and high cavern stability and are therefore preferable from the geological perspective. Although the Karachaganak field possesses relatively high permeability (10–14.5 mD) and lower stability, it is nevertheless economically viable due to its structure. The Gazli field, with its strongly permeable caprock (1491 mD), was included for its strategic location and complementary geological features.

Based on their types of sealing, caprock permeability, and cavern stability, the above four gas fields were selected among others in Kazakhstan and Uzbekistan to be investigated in detail because they possess the most favorable technological and geological conditions for underground hydrogen storage.

4.3.2 CMG simulations

The gaps remained in critical operational data, namely storage capacity and injection and withdrawal rates. Sensitivity analyses were performed using CMG simulations to estimate these missing parameters. In the sensitivity test the primary variable parameters during the simulations were the injection and withdrawal rates, and controllable factors included the gas saturation coefficient and pressure profiles (Appendix B.1-B.4).

It is important to note that the CMG simulations did not replicate the actual geometries of the selected depleted gas reservoirs, as such detailed data was not available. The sizing of reservoirs kept assumable and the same for four gas fields (9000 blocks: 30*30*10 with dimensions 200m*200m*165m correspondingly). The storage capacity was automatically calculated by the simulation software based on assumed reservoir geometry and the specified injection and production rates. The simulation period was set at 50 years to reflect a realistic long-term storage scenario.

For the simulations, a predefined daily injection and production rate was established to ensure that reservoir pressure remained within safe operational limits, specifically below the critical pressure threshold. Gas saturation was also carefully considered in the sensitivity analysis, as it directly influences the reservoir's ability to accommodate injected hydrogen and affects the overall storage efficiency.

The results of the simulations, including the estimated injection and withdrawal rates and the calculated storage capacities for the four selected gas fields, are summarized in Table 4.7.

Table 4.7: Operational parameters taken from the CMG simulations

	Storage Capacity, Sm^3	Injection and production rates, 10^6 Sm^3/day
Tengiz Gas Field	$6.559 \cdot 10^{11}$ Sm^3	INJ - 60 $\cdot 10^6$ m^3/day, PROD - 50 $\cdot 10^6$ m^3/day
Kashagan Gas Field	$6.559 \cdot 10^{11}$ Sm^3	INJ - 60 $\cdot 10^6$ m^3/day, PROD - 50 $\cdot 10^6$ m^3/day
Karachaganak Gas Field	$3.665 \cdot 10^{11}$ Sm^3	INJ - 60 $\cdot 10^6$ m^3/day, PROD - 50 $\cdot 10^6$ m^3/day
Gazli Gas Field	$3.059 \cdot 10^{10}$ Sm^3	INJ - 100 $\cdot 10^6$ m^3/day, PROD - 50 $\cdot 10^6$ m^3/day

4.3.3 Fuzzy TOPSIS ranking: best field selection

At this stage the four fields were evaluated over five criteria by decision makers, then, these assessments were analyzed using Fuzzy TOPSIS methodology (shown in Tables 4.8 and 4.9).

Table 4.8: Linguistic assessments of four selected gas fields

Alternatives (Gas Fields)	**Decision makers**	**Criteria**				
		C1	**C2**	**C3**	**C4**	**C5**
A1	**D1**	MG	G	MG	VG	G
	D2	G	G	G	G	G
	D3	F	MG	MP	MG	G
A2	**D1**	VG	VG	G	VG	G
	D2	VG	VG	VG	VG	VG
	D3	VG	G	F	MG	G
A3	**D1**	F	MG	F	G	G
	D2	F	G	G	MG	MG
	D3	F	MG	MP	F	G
A4	**D1**	G	MP	VP	P	MG
	D2	MG	MG	F	MP	MG
	D3	G	F	VP	MP	G

Table 4.9: The normalized fuzzy decision matrix

Criteria	**Alternatives (Gas Fields)**			
	A1	**A2**	**A3**	**A4**
C1	(0.4, 0.633, 0.667, 0.9)	(0.8, 0.9, 1.0, 1.0)	(0.4, 0.5, 0.5, 0.6)	(0.5, 0.733, 0.767, 0.9)
C2	(0.5, 0.733, 0.767, 0.9)	(0.7, 0.867, 0.933, 1.0)	(0.5, 0.667, 0.733, 0.9)	(0.2, 0.467, 0.533, 0.8)
C3	0	0	0	0
C4	(0.5, 0.767, 0.833, 1.0)	(0.5, 0.8, 0.9, 1.0)	(0.4, 0.633, 0.667, 0.9)	(0.1, 0.267, 0.333, 0.5)
C5	(0.556, 0.625, 0.625, 0.714)	(0.5, 0.577, 0.6, 0.714)	(0.556, 0.652, 0.682, 1.0)	(0.556, 0.682, 0.749, 1.0)

As a result, the Kashagan gas field was ranked first, emerging as the most appropriate location for storing hydrogen underground, followed by Tengiz, Karachaganak, and then Gazli gas fields. The ranking is demonstrated in Table 4.10 and Fig 4.4.

Table 4.10: Final ranking of depleted gas fields of underground hydrogen storage

Alternative	Fuzzy Scale	Final Ranking
A1 - Tengiz gas field	0.55906	2
A2 - Kashagan gas field	0.88749	1
A3 - Karachaganak gas field	0.42234	3
A4 - Gazli gas field	0.32333	4

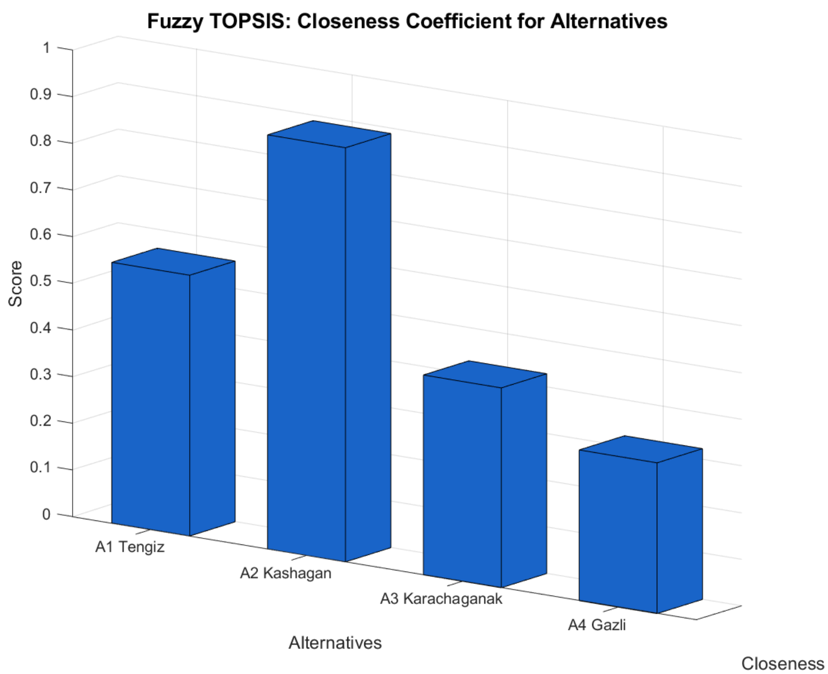

Figure 4.4. Final Ranking of Gas Field Candidates for UHS

4.3.4 Kashagan gas field performance and storage costs

After selecting the Kashagan field as the leading candidate, a preliminary economic analysis was conducted. The author in [19] provided the costs associated with hydrogen storage for

2021. Using the Consumer Price Index (CPI) adjustments, these costs were updated to reflect values for the current year, 2025 [20], [49]. Based on these calculations, capital expenditures (CAPEX) for hydrogen storage were estimated at 2.85 USD per kilogram of H_2, while operational expenditures (OPEX) were estimated at 0.17 USD per kilogram of H_2.

Assuming a workable hydrogen volume of 50×10^6 standard cubic meters (Sm^3), the total storage costs were calculated as follows:

$$Mass\ of\ H_2 = Workable\ gas\ volume \cdot Density\ of\ H_2 = 4\,494\,000\ kg\ of\ H_2$$

$$CAPEX = Mass\ of\ H_2 \cdot CPI\ of\ 2.33 = 4\,494\,000 \cdot 2.85 = 12\,807\,900\ \$/kg\ of\ H_2$$

$$OPEX = Mass\ of\ H_2 \cdot CPI\ of\ 0.14 = 4\,494\,000 \cdot 0.17 = 763\,980\ \$/kg\ of\ H_2$$

$$Total = CAPEX + OPEX = 13\,571\,880\ \$/kg\ of\ H_2$$

The total amount of hydrogen in a commercial volume of 50×10^6 Sm^3 was estimated at about 4,494,000 kg. According to this mass, the CAPEX for hydrogen storage at Kashagan field accounted to be about 12.8M USD, while the OPEX was about 764,000 USD. Therefore, the overall cost to store the specific amount of hydrogen is about 13.57 million USD.

This demonstrates that it would be possible to use the field for large scale hydrogen storage at a reasonable cost, benefiting from the available infrastructure and thereby limiting initial investment. The cost estimates provided here are ballpark in nature, based on standard assumptions regarding gas density and price indexes - actual costs may vary according to specifics of field development, field productivity, infrastructure developments and market conditions.

Chapter V

Discussion

5.1 Interpretation of Key Findings

This section aims to explain and interpret the key findings, reasons why depleted gas fields and namely Kashagan gas field were evaluated as the best options for UHS in Central Asia.

5.1.1 Why depleted gas fields are the best option

The conclusions of this study identify the technical, economic, and geological advantages of using depleted gas fields for UHS in Central Asia as:

Storage Capacity: Abandoned gas fields also have enormous storage capacity, whose volumes range from a few hundred to thousands of cubic meters based on their geology and previous utilization. Abandoned gas fields can store extremely high volumes of hydrogen and therefore are suitably geared to meet the growing energy needs of Central Asia as well as help transition to alternative energy [45].

Sealing Effectiveness and Permeability of Caprock: Utilizing naturally formed containment properties during hydrocarbon production, depleted gas fields provide a secure and well-established storage method for hydrogen, with less leakage risk [46].

Cost Efficiency: Existing infrastructure, such as wells and pipelines, reduces the need for huge capital investment [46]. This cost advantage makes depleted gas fields an attractive option compared to other storage alternatives, particularly in regions of constrained budgets.

Availability: Central Asia is replete with depleted gas fields, the legacy of its bountiful oil and gas production history. Their ubiquity offers practical and scalable solutions to hydrogen storage that do not involve extensive geological search or new infrastructure [45].

Salt caverns offer maximum sealing and operating flexibility but with low availability in Central Asia to render them not as immediately available for use. Aquifers with moderate storage capacity are accompanied by risk issues over hydrogen leakage and injection/withdrawal ineffective rates, rendering them vulnerable to technical improvement requirements.

5.1.2 Specific advantages of Kashagan gas field

The Kashagan gas field has several advantages that make it a highly feasible candidate for hydrogen underground storage. To begin with, its vast reservoir capacity provides ample room for storing enormous amounts of hydrogen, which is required for mass-scale energy storage facilities. The infrastructure that has already been developed in the field, including pipelines and processing plants, reduces the need for major new investment, making it an economic solution for storage. In addition, Kashagan's positive geological properties, such as its sealing effectiveness and stable caprock, ensure prolonged safety and containment of stored hydrogen. Further, the field's proximity to large energy infrastructure and accessibility enhance its potential for incorporation into existing energy systems. Finally, the field's operational history, such as previous successful gas extraction, demonstrates that it has the necessary technical ability to effectively manage hydrogen injection and withdrawal operations. These together provide Kashagan a suitable choice for hydrogen storage in the region.

5.2 Comparison with Literature

This study demonstrates through expert surveys and fuzzy TOPSIS analysis that depleted gas fields stand as the ideal choice for UHS in Central Asia because they surpass aquifers and salt caverns according to the assessment criteria. The outcome matches international UHS patterns in certain geographical situations yet deviates in others.

5.2.1 Consistency of results with global UHS sites

Scientific research shows that salt caverns represent the best geological storage solution for hydrogen storage through underground operations because they provide superior sealing performance with minimal permeability and high operational flexibility [17]. Salt formation hydrogen storage projects have been successfully executed at German and Teesside sites in the United Kingdom as well as at several European sites [17]. The HyUnder project which receives European Union funding names salt caverns as the most dependable geological option for hydrogen storage [17]. Success at the Clemens Dome facility and Moss Bluff location in the

United States verifies that domal salt formations represent a safe and technically viable solution for hydrogen storage [17]. All major international technical standards identify salt caverns as the most suitable storage option for situations that meet geological requirements.

Depleted gas fields prove to be the most feasible storage solution in Central Asia according to findings that match global observations. The limited supply of international preferred salt caverns in the region leads depleted fields to function as the premier hydrogen storage method [23]. Under U.S. Department of Energy Power-to-Gas research programs scientists proved that depleted gas fields retain hydrogen storage strength when managed properly even when natural gas and hydrogen mix in systems [23].

The depleted gas field selection for our study matches worldwide storage preferences because geological suitability controls what options become available for installation. Depleted hydrocarbon reservoirs stand as an approved solution for major hydrogen storage when salt formations prove scarce or economically impractical in storage regions.

5.2.2 New insights specific to Central Asia

The geological environment in Central Asia stands apart from that of Europe and North America. Kazakhstan and the surrounding region possess a large number of depleted oil and gas fields which include the Kashagan field, but have restricted locations for salt formations suitable for cavern development.

The research demonstrates that Central Asian UHS projects will benefit from using depleted gas reservoirs through various advantages:

- The current facilities from oil and gas projects enable companies to decrease their cost for both initial expenses and operational maintenance costs.
- Adequate sealing capability originates from thick caprocks which are well described through reservoir model data obtained from the field.
- Storage capacity has been confirmed through numerous decades of hydrocarbon extraction operations.

Latest surveys about Central Asian aquifers show they carry high risks from microbial hydrogen consumption and leaking problems and weak caprock protection because of weak water management and inadequate monitoring practices in this region [17], [23]. The Central Asian region should use its depleted gas reservoirs as the optimal solution for hydrogen storage since Europe predominantly utilizes salt caverns. The solution applies to local settings through utilization of existing geological and industrial resources rather than adopting foreign salt cavern approaches.

The fuzzy TOPSIS process verified that essential factors include both storage capacity and proximity to infrastructure and caprock integrity, yet emphasizes economic and infrastructure aspects in Central Asia above European priorities.

5.3 Limitations and Risks

The aim of this section is to declare and discuss the challenges and limitations encountered in the evaluation of UHS sites. It points out the small expert sample size, uncertainties in data, and technical risks associated with the modeling methodology and assumptions applied in the research. The section warns against the interpretation of results due to these limitations.

5.3.1 Small expert sample size

The small group of experts participating in each phase of evaluation represents a crucial drawback of this project. The assessment of storage alternatives and ranking of gas fields and criteria importance assessment involved only three experts in the surveys. The limited number of involved experts affords excellent experience in hydrogen storage processes and reservoir engineering alongside energy systems but creates higher chances for biased results and weakens statistical strength in findings. Better reliability and generalization of findings would emerge when more experts participate from varying industrial sectors and locations.

5.3.2 Data uncertainties and technical risks

The important drawbacks stem from unclarities in both the technical modeling approach as well as the source data:

- Many of the essential geological and operational data needed for the selected fields required gathering from public literature combined with academic publications and general field development reports. Field characterizations suffered from accuracy problems since access to current or industry-confidential datasets remained unavailable.

- The CMG simulation models required various assumptions because statistical data was insufficient for proper implementation. Reliable results from CMG simulations were only possible by using generalized rectangular reservoir shapes (6000m × 6000m × 1650m) instead of actual field-specific shapes. The assumptions made throughout lead to forecasting uncertainties when calculating injection and withdrawal rates along with storage capacity predictions.

- The storage of hydrogen entails technical challenges because materials face brittleness degradation, leaks can emerge through fault lines, microorganisms can consume stored hydrogen, and permeability may suddenly change with time. The study did not perform actual simulations or field tests of these risks which researchers had recognized in their literature review. The operational outcome at Kashagan might vary from the predicted data.

The combination of Fuzzy TOPSIS and CMG modeling produces an effective method for initial UHS site selection but users should derive conclusions carefully due to restrictions from expert size, data consistency and model simulation parameters.

5.4 Recommendations for Future Research

This work offers a starting point for the assessment of UHS site selection in the CA region, which will require further refinement, validation, and augmentation. In future, some important topics are recommended for further research, so as to improve the reliability, accuracy and practicality of the findings.

5.4.1 Increasing the number of expert evaluations

One of the main limitations of this study was the relatively small number of expert participants in the evaluation process. Expanding the expert pool in future research is essential to increase the reliability and statistical strength of the findings. Particularly, it is recommended to incorporate a broader range of experts like geologists, reservoir engineers, materials scientists, economists, and regulatory experts, both from Central Asia and globally. Larger and more comprehensive expert surveys would provide a broader range of perspectives, reduce individual bias, and result in more comprehensive assessments of site selection criteria, storage alternatives, and risks.

Additionally, conducting Delphi studies or multi-round surveys can ease the process of achieving consensus among experts and also improve the quality and consistency of the assessment results further.

5.4.2 Running full-scale field tests and simulations

Although this study applied CMG-based sensitivity analyses to quantify hydrogen storage parameters, large-scale field trials are necessary to validate simulation results and address actual field technical uncertainties. Future activities must focus on the design and deployment of pilot projects at selected depleted gas fields, such as Kashagan, to monitor hydrogen injection, storage, and withdrawal in actual field conditions.

These pilot-scale experiments would provide important data regarding hydrogen behavior within rock units, such as potential leakage, interactions with remaining hydrocarbons, caprock integrity, and microbial activity. Field data would be used to calibrate and validate simulation models, resulting in more accurate predictions of storage performance and operating risks.

Additionally, future modeling activities should involve higher-resolution geological information, variable reservoir structures, and more advanced multi-phase flow modeling to capture the intricate dynamics of the underground hydrogen storage.

Overall, a combination of bigger-scale specialist feedback and on-site validation will be required to further refine secure, effective, and economically viable hydrogen storage facilities in Central Asia.

Chapter VI

Conclusion

This study set up a systematic, formalized approach to the evaluation and selection of UHS sites in Central Asia, focusing on addressing the region's unique geological, technical, and economic issues. Through integrating expert opinion with the Fuzzy TOPSIS multi-criteria decision-making method, the study aimed at defeating uncertainties involved in traditional assessment approaches and enabling more reliable and transparent decision-making.

An initial set of nineteen evaluation criteria was initially established by way of a wide literature review and professional consultation and included geological, technical, and socio-economic factors. By means of a structured expert questionnaire and fuzzy logic processing, these were reduced to six primary criteria that were considered most significant for UHS site selection. These criteria - efficiency of sealing, storage capacity, caprock permeability, cavern stability, storage costs (CAPEX/OPEX), and hydrogen withdrawal and injection rates - were the foundation of subsequent studies.

With Fuzzy TOPSIS, three primary underground storage types - salt caverns, depleted gas fields, and aquifers - were compared by the research using the selected criteria. While world best practice recommends the use of salt caverns for hydrogen storage due to their superior sealing and operating properties, Central Asian geological conditions, including low salt formation availability, leave depleted gas fields as the best suitable and most efficient storage option in the region. Such a finding conforms to international practices where geologic conditions of sites determine the optimum arrangements for storage.

Further evaluation of four depleted gas fields under consideration - Tengiz, Kashagan, Karachaganak, and Gazli - was conducted through geological data, expert surveys, and CMG-based models. Kashagan was the most favorable UHS site based on its good sealing characteristics, high storage capacity, tight caprock integrity, and closeness to existing facilities. Preliminary economic evaluation indicated that hydrogen storage at Kashagan would be economically viable compared to constructing entirely new facilities.

6. Conclusion

Despite these promising results, the study identifies some substantial limitations like fewer than expected experts in the sample, reliance on public geologic data, and simplification of CMG simulations. All these impose uncertainties to be dealt with in future studies.

To build upon this study, follow-up studies should expand the numbers and scope of expert contributors, utilize more precise geological and operating data, and conduct large-scale field pilot testing to validate simulation outcomes. Advanced modeling methods and operationally designed strategies for unique regions will be required to guarantee the secure, efficient, and long-term functioning of hydrogen storage systems in Central Asia.

Overall, this project demonstrates the feasibility and value of reusing depleted gas fields as hydrogen storage sites, offering valuable information for the global transition to a decarbonised energy economy and promoting the emergence of Central Asia as a new player in the hydrogen market.

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Appendices

Appendix A. Questionnaires

A.1 First Questionnaire

Geological	Geology	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Depth	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Area	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Thickness	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Caprock thickness	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Caprock permeability	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Reservoir permeability and porosity	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Storage Capacity	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
Technical	Compatibility of materials	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Cavern stability	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Sealing effectiveness	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Energy requirements for operation	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Injection/withdrawal rates	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Monitoring systems	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
Socio-economic	Storage costs	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Initial investment	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Proximity to suppliers & resources	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Job creation	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High
	Legal & social restrictions	Extremely Low	Very Low	Low	Fair	High	Very High	Extremely High

A.2 Second Questionnaire

1. Please evaluate the weight of each criterion							
C1 Sealing effectiveness	Very High	High	Middle High	Middle	Middle Low	Low	Very Low
C2 Storage capacity	Very High	High	Middle High	Middle	Middle Low	Low	Very Low
C3 Caprock permeability	Very High	High	Middle High	Middle	Middle Low	Low	Very Low
C4 Cavern stability	Very High	High	Middle High	Middle	Middle Low	Low	Very Low
C5 Storage costs	Very High	High	Middle High	Middle	Middle Low	Low	Very Low
C6 Injection/withdrawal rates	Very High	High	Middle High	Middle	Middle Low	Low	Very Low

2. Please evaluate following alternatives of these criteria, based on your experience								
C1 Sealing effectiveness	A1 Salt Caverns	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Depleted Gas Fields	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Aquifers	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
C2 Storage capacity	A1 Salt Caverns	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Depleted Gas Fields	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Aquifers	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
C3 Caprock permeability	A1 Salt Caverns	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Depleted Gas Fields	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Aquifers	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
C4 Cavern stability	A1 Salt Caverns	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Depleted Gas Fields	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Aquifers	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
C5 Storage costs	A1 Salt Caverns	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Depleted Gas Fields	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Aquifers	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
C6 Injection/withdrawal rates	A1 Salt Caverns	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Depleted Gas Fields	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Aquifers	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor

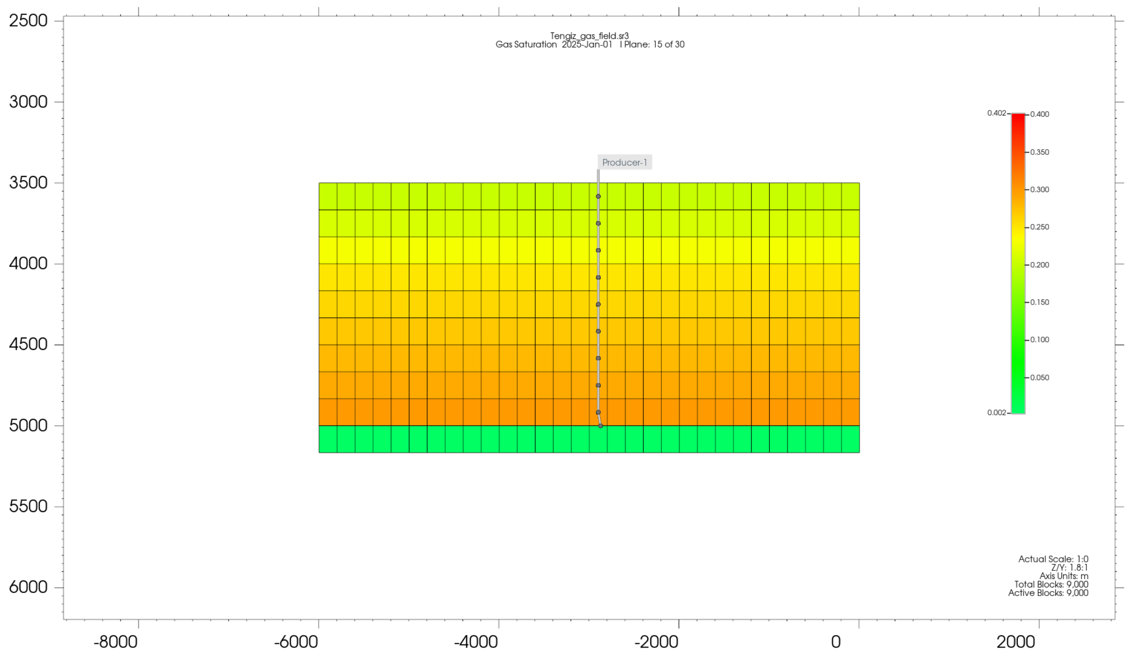
A.3 Third Questionnaire

C1 Sealing effectiveness	A1 Tengiz	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Kashagan	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Karachaganak	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A4 Gazli	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
C2 Storage capacity	A1 Tengiz	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Kashagan	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Karachaganak	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A4 Gazli	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
C3 Caprock permeability	A1 Tengiz	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Kashagan	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Karachaganak	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A4 Gazli	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
C4 Cavern stability	A1 Tengiz	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Kashagan	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Karachaganak	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A4 Gazli	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
C5 Storage costs	A1 Tengiz	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Kashagan	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Karachaganak	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A4 Gazli	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
C6 Injection/withdrawal rates	A1 Tengiz	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A2 Kashagan	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A3 Karachaganak	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor
	A4 Gazli	Very Good	Good	Middle Good	Fair	Middle Poor	Poor	Very Poor

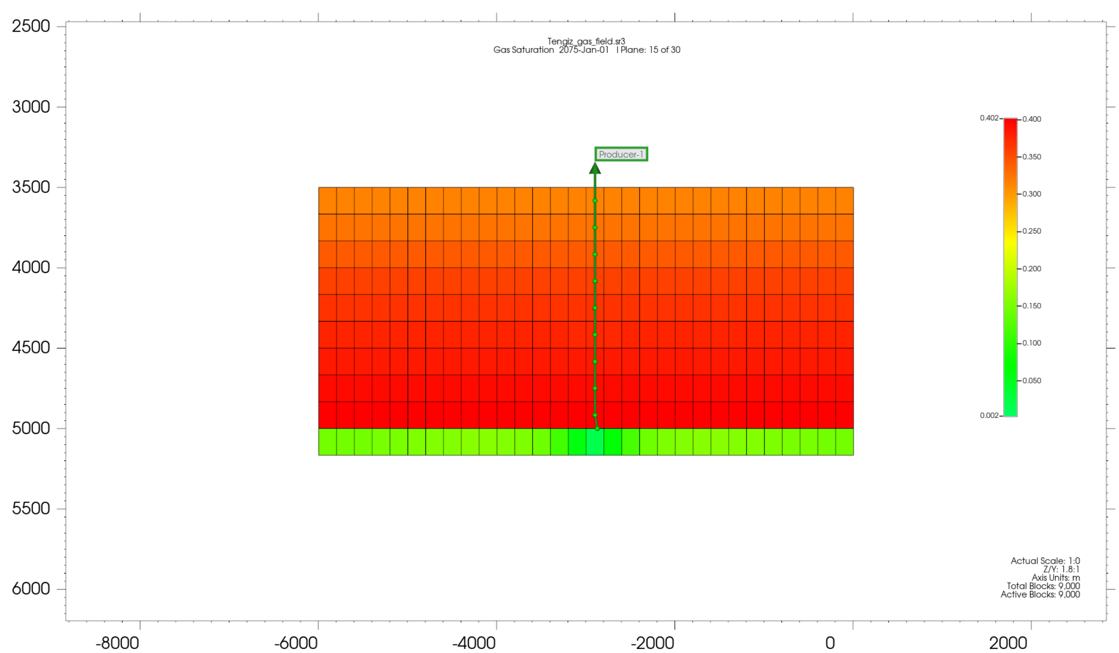
Appendix B. CMG Simulation Screens

B.1 Tengiz gas field simulation

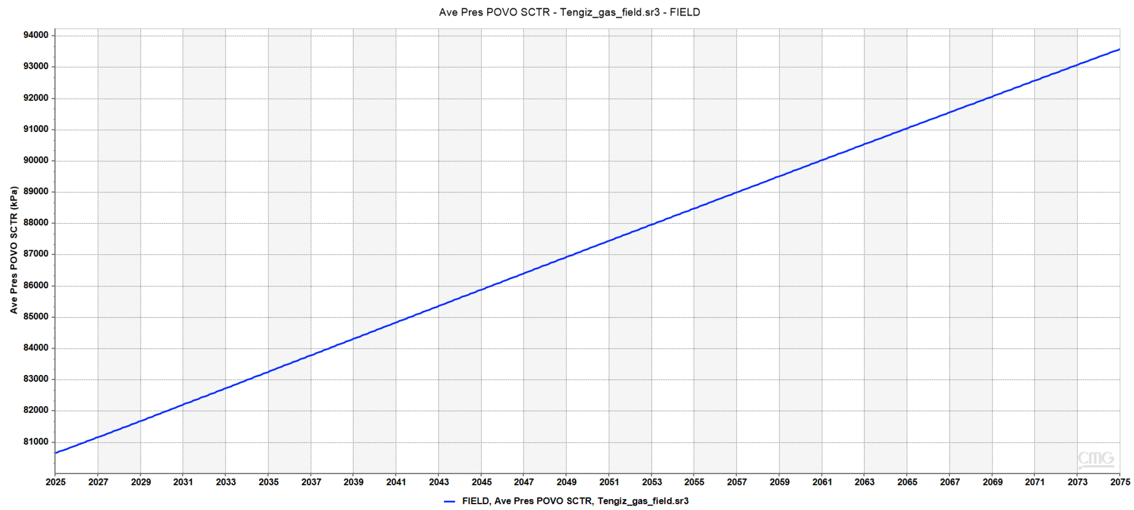
Gas saturation at the beginning:



Gas saturation after 50 years:

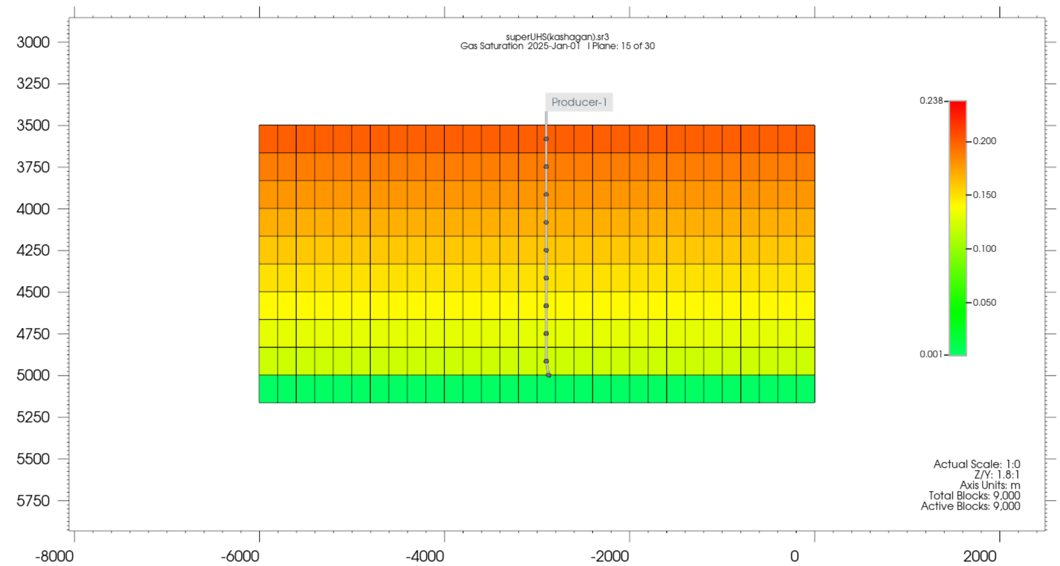


Pressure profile graph:

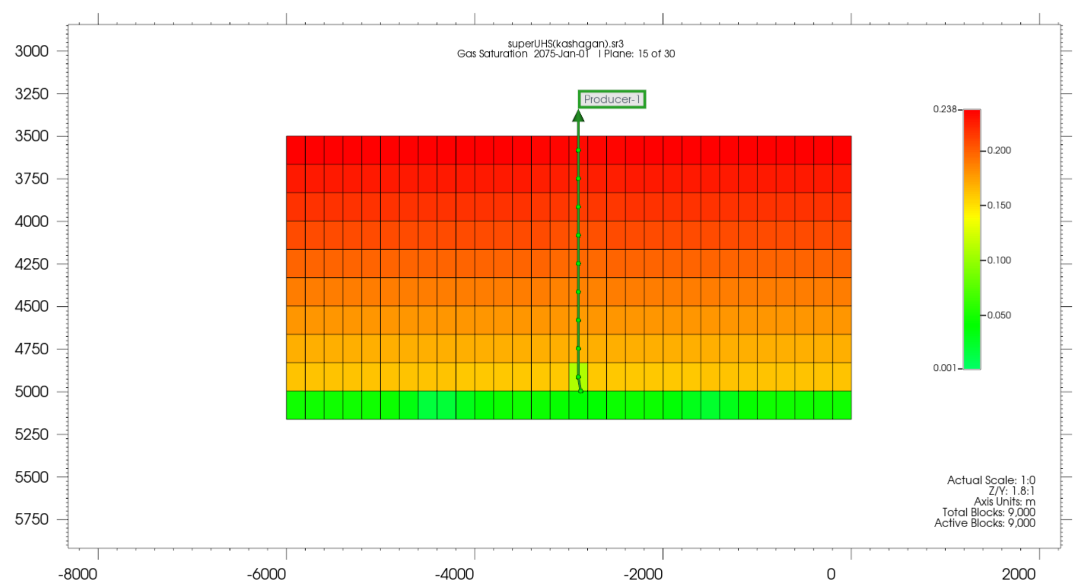


B.2 Kashagan gas field simulation

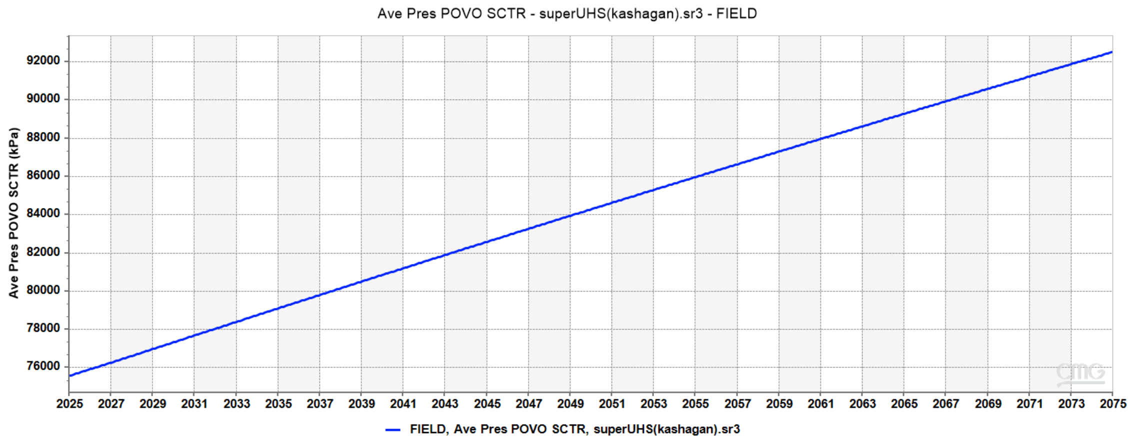
Gas saturation at the beginning:



Gas saturation after 50 years:

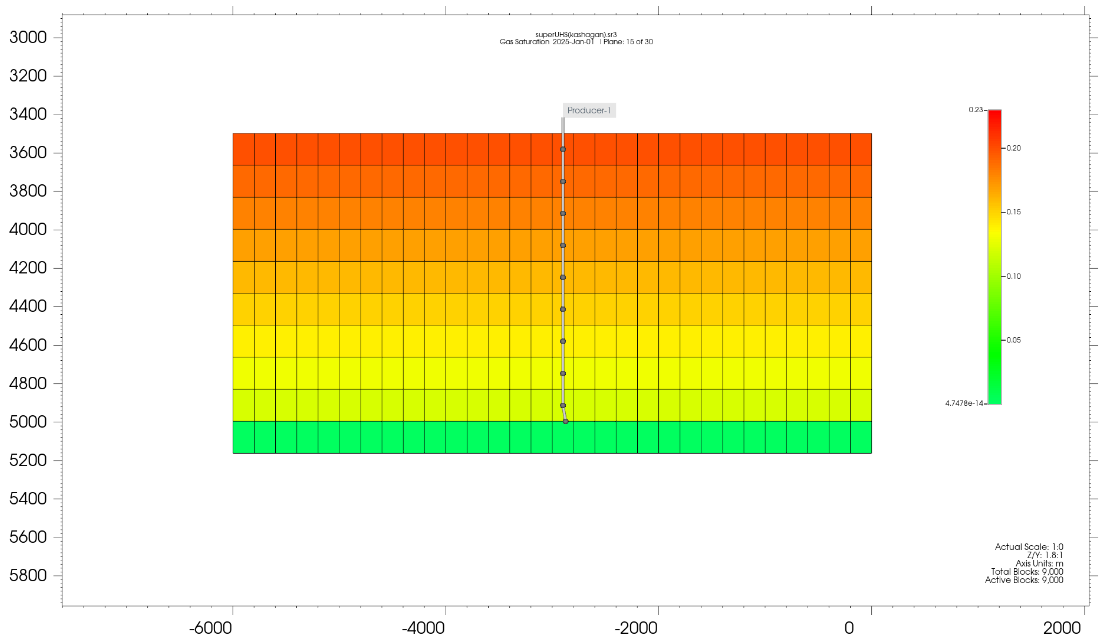


Pressure profile graph:

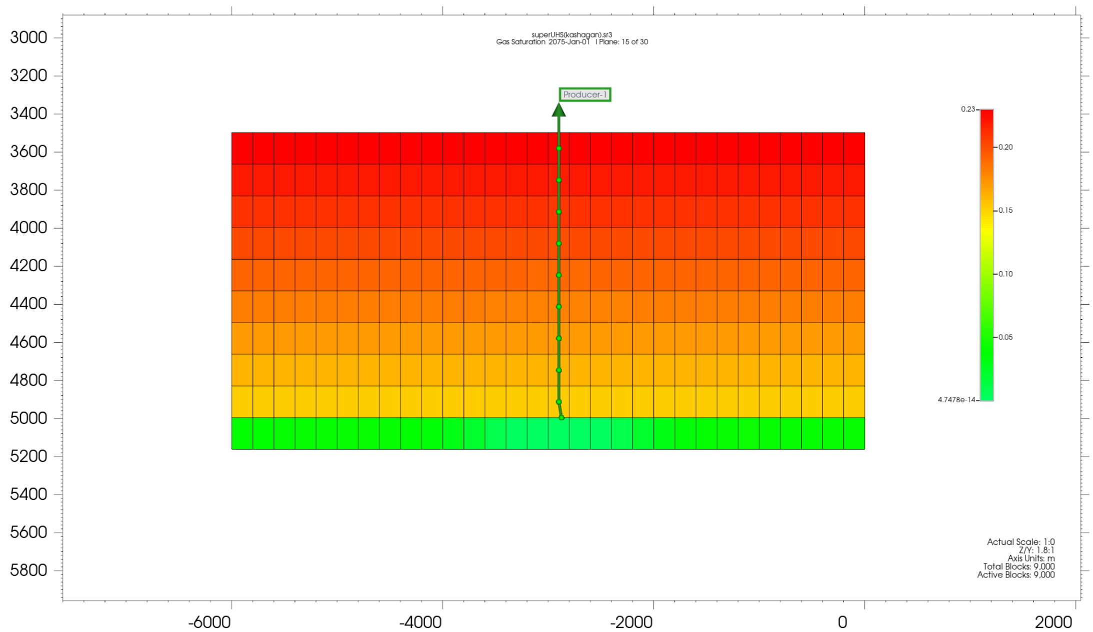


B.3 Karachaganak gas field simulation

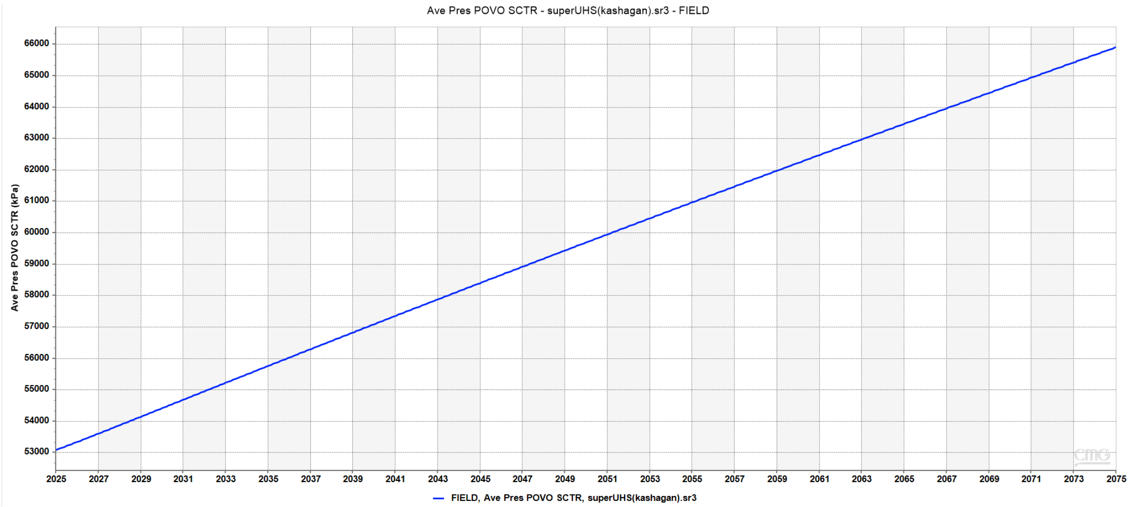
Gas saturation at the beginning:



Gas saturation after 50 years:

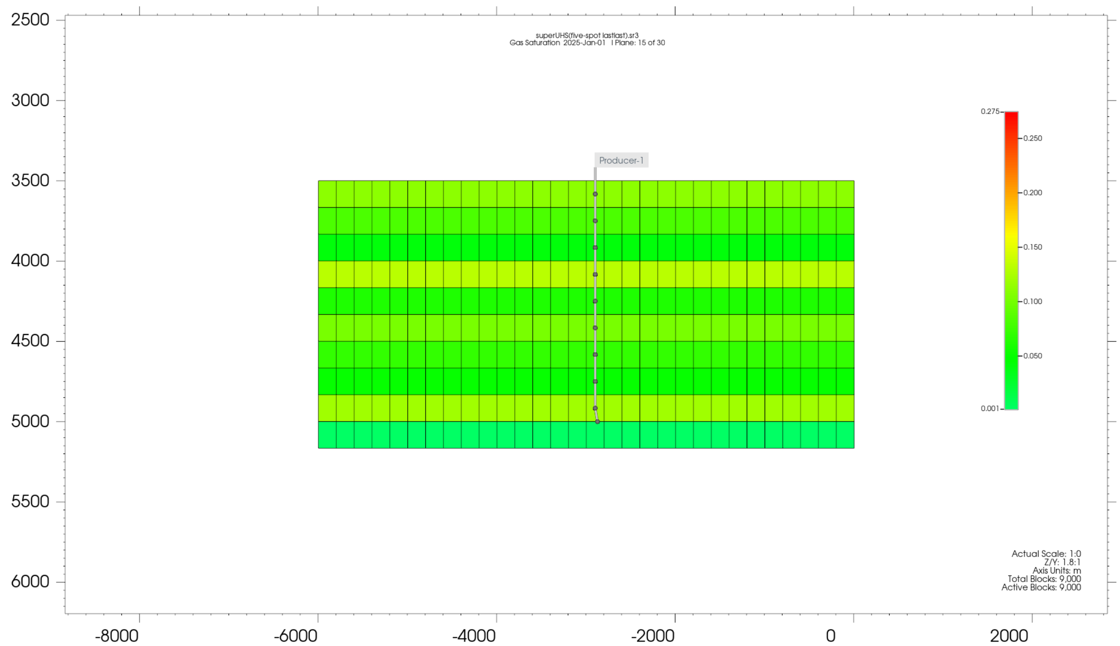


Pressure profile graph:

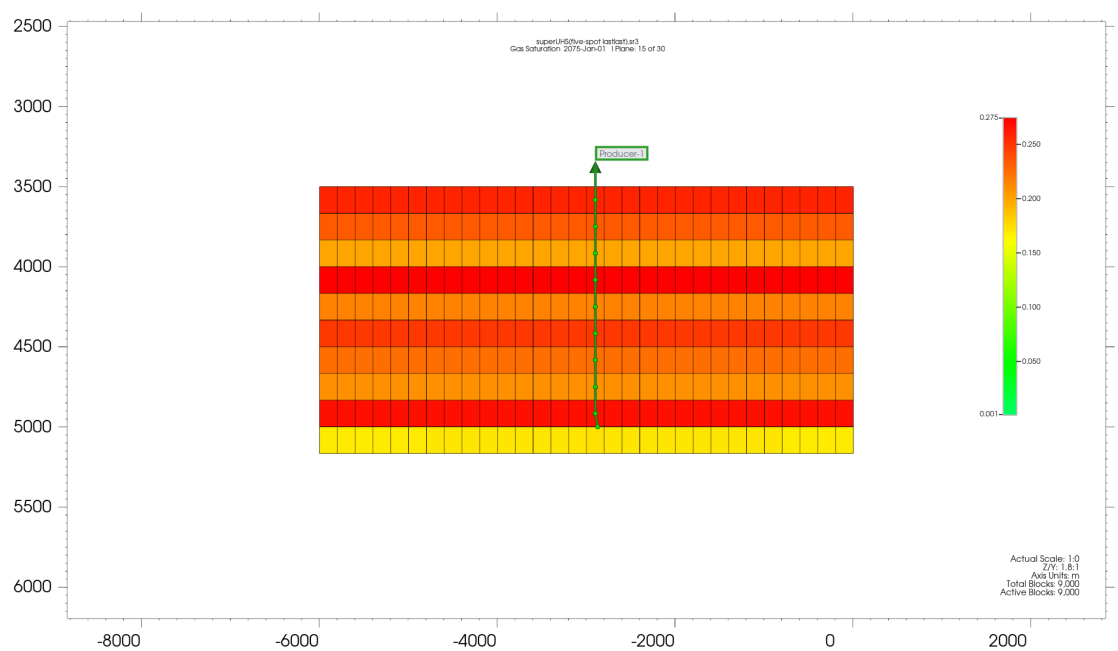


B.4 Gazli gas field simulation

Gas saturation at the beginning:



Gas saturation after 50 years:



Pressure profile graph: