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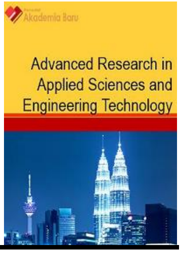

Potential of Underground Hydrogen Storage in Oman

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ABSTRACT

Hydrogen can provide a viable source of energy that can covers the world's energy requirement in the next coming years. One of the major keys to wholly develop hydrogen energy is to provide a safe, cost efficient and compacted type of hydrogen storage. Geological reserves are considered a suitable space for hydrogen storage. In this research, we are trying to examine if there was any technical potential for hydrogen storage based on Oman's geology by Identifying geological deposit in Oman that can be used for hydrogen storage and analyzing salt deposits for hydrogen storage suitability. By overviewing the possible underground hydrogen methods and based on Oman's geology, deep aquifers were not suitable for hydrogen storage; due to the lack of large sedimentary basin, no experience for similar projects and the risks associated with surrounding environment. Depleted reservoir needs more study for deployment; there are no experiences of such projects for UHS. Salt basins are good candidate for underground storage; due to the large salt basin in Oman, salt caverns are known to successfully contain hydrogen and the guaranteed safety of the storage. Analysing the technical potential salt deposits was based on a good depth dome, salt thickness and salt dome size. The main findings illustrate that, two salt domes (Qarn Shamah and Qarn Alam) were offering a good potential of estimated working gas volume of hydrogen around 90 m3 hydrogen (0.2 TWh). Nevertheless, more future work is needed to confirm the geotechnical feasibility of salt domes in terms of internal complex structure, chemical composition and purity of salt.

Keywords:
Energy storage, Salt domes, Oman geology, Hydrogen underground storage, Renewable energy sources

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1. Introduction

Hydrogen energy can provide a viable source of energy that can covers the world's energy requirement in the next coming years. Hydrogen is related to many energy sectors- transportation, utilities and industry. Successful development of hydrogen energy means development in energy security, economy and environment [1]. However, hydrogen energy system is still facing a number of technical and economic barriers that must be first to overcome for hydrogen to become a competitive energy carrier. Producing hydrogen from renewable energy sources can face the difficulty of interment supply of energy, consequently, storing that energy improve the continuity of energy source.

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Natural gas storage in underground storage has been developed for many years. One of the potential methods is to use depleted oil and gas reservoirs for hydrogen storage due to the similarity of construction and operation. For hydrogen case, there are risks associated with hydrogen properties of high diffusivity that can cause leakage and failures on steel components [2]. On the other hand, the cost of drilling new well is eliminated plus most of the well logs on geological data and structures will be available. However, in depleted wells the cushion gas requirement can be approximately 50% [3]. As a result, extra equipment for contamination control will be needed for well cleaning from contaminated hydrocarbon at the bottom, and there are non-preferred type of reactions when hydrogen is microbially catalyzed by bacteria and is converted to H_2S [2].

Salt cavern is the most promising type of storage due to the low investment cost and high sealing potential for energy. utilizing salt deposit for underground hydrogen storage does exit in United Kingdom and the United States [4]. These projects showed it is technically feasible to store hydrogen in salt cavern. Lordache investigated for potential salt sites for hydrogen storage in Romina [5] and it was concluded that there are four potential locations for underground hydrogen storage, the next step for these locations is to identify potential stake holders for further development as seasonal energy storage locations. In HyUnder study [6], the purpose was to assess the potential of hydrogen underground storage in Europe, taking into account the geological and geophysical factors to assess the feasibility of this type of projects. It was concluded that underground storage of hydrogen in salt is technically feasible option for large scale storage of electricity and among the European countries that was included in the study, Germany and the Netherlands offers a good geological condition for this type of storage. While Tarkowski [7] investigated using the salt domes in Poland for hydrogen storage based on geological criteria to identify the best salt deposit for hydrogen storage out of 27 salt domes. It was concluded that seven domes have favorable geological structures for hydrogen storage. Another study in Jiangsu, China [8] showed that salt caverns can be feasible for large scale UHS in the Jiangsu province, with an estimated capacity of 36.9TWh.

The studies cited above focused on potential cavern sites at national level for UHS across different regions in Europe and Asia. There are no studies has been conducted in Oman evaluating potential sites for underground hydrogen storage, which is the aim of this report is to focus on the potential of salt deposits for hydrogen storage. Oman has a unique set of geological structures where salt basins are sealing the hydrocarbon in three large salt basins that extents for more than 400 km. The approach that has been taken in this research was locating suitable cavern sites, which are determined by the technical potential of hydrogen storing requirement. Salt deposits that are suitable for storage are divided into salt domes and bedded salt. The main focus lies on the salt domes since they show more potential to store energy than salt beds, meanwhile the capacity of domal salt structures is higher than bedded salt structures stores [9]. Nevertheless, it must be noted that salt suitability, internal complex structure and purity must be taken in account for future development of these sites.

“There are three colors of hydrogen based on how they are produced and processed. Grey hydrogen is made using fossil fuels like oil and coal, which emit CO_2 into the air as they combust. Blue hydrogen is made in the same way, but carbon capture technologies prevent CO_2 being released, enabling the captured carbon to be safely stored deep underground or utilized in industrial processes.

As its name suggests, green hydrogen is the cleanest variety, producing zero carbon emissions. It is produced using electrolysis powered by renewable energy, like solar and wind energy, to produce a clean and sustainable fuel.”

In this paper the aims are to (1) identify geological deposit in Oman that can be used for hydrogen storage; (2) Analyze and screening salt deposits for hydrogen storage suitability; (3)

Propose salt cavern design for salt leaching; (4) Investigate the risk associated with hydrogen storage underground. Therefore, a broad view on the geological structure in Oman is presented based on the available literature and data, so that it can be used later by researchers to develop suitable designs on the basis of the outcome from this research.

2. Hydrogen storage

2.1 Surface Hydrogen Storage system (SHS)

The goal of storing hydrogen is generally to minimize the cost of delivered hydrogen through balancing the supply and demand or to use it later as requested. These demands of energy have sub sequential impact on the operating of the storage. One of the main difficulties of storing hydrogen is the low density of hydrogen: 1kg of hydrogen gas occupies over 11 m^3 at room temperature and atmospheric pressure [10] while the primary challenge of hydrogen is to release hydrogen under certain conditions and within limited temperature intervals to facilitate it later. There are several technologies for hydrogen storage, the focus will be more in the most developed technologies regarding their technical maturity and feasibility to be used in a large scale.

Figure 1 below demonstrates categorizing hydrogen storage based on the material interaction with the surrounding storage method.

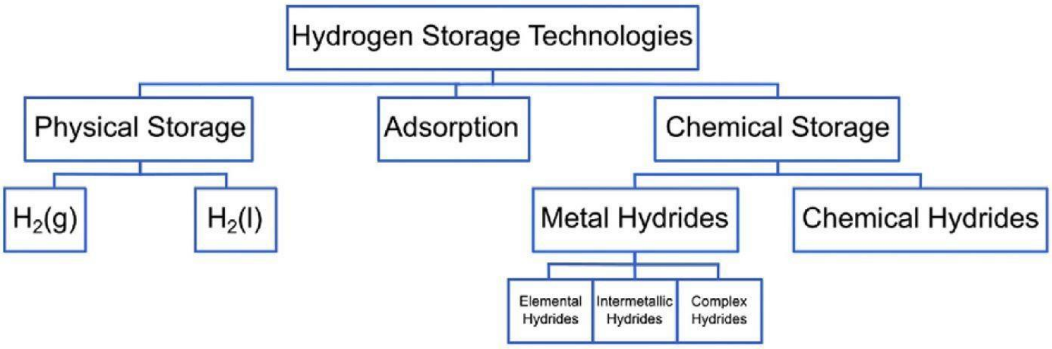


Fig. 1. Hydrogen storage technologies [11] excluding underground

2.2 Chemical Storage

The chemical bond that is formed chemically between hydrogen and metal hydrides are much stronger than the ones that is physically formed by hydrogen adsorption. However, the slow hydrating/dehydriding kinetics, high release temperature, low storage efficiency due to the high enthalpy of formation, and thermal management during the hydrating reaction remain important difficulties. Hydrides were chosen for storage applications due to low reactivity and the ability of storing high densities of hydrogen which it can be achieved in two main ways: heating (thermolysis) or reaction with water (hydrolysis). Thermolysis is endothermic and reversible in some cases while hydrolysis is exothermic and irreversible; thermolysis occurs in the solid phase with elevated temperatures while hydrolysis occurs in solution at normal room temperature [12]. Releasing the stored hydrogen requires high temperature between 120- 200 °C to break the bonds that the metal hydrides is forming with hydrogen [13]. Magnesium hydride (MgH_2) and aluminum hydride (AlH_3) are the most promising metal hydrides for large scale storage of hydrogen. Magnesium hydride (MgH_2) theoretical hydrogen capacity is 7.6% (wt) and it is available at low cost. However, in order to dehydrogenate pure MgH_2 high temperature is required over 300 ^0C, in addition, the kinetics of both hydrogenation and dehydrogenation are sluggish. Whereas aluminum hydride bond is weak and releases of the theoretical 10.1% (wt) of hydrogen at 100 ^0C. despite the fact that energy requirement is lower than MgH_2 this reaction is irreversible and it requires extreme pressure conditions [14].

The number of intermetallic hydrides that are used to store hydrogen are quite few and it is known with low storage capacity less than 2% (wt), which maybe applicable for some applications. These types of hydrides are commonly expensive, like (TiFe), that is considered one of the low-cost intermetallic hydrides that can be estimated around $6.9/kg [15]. However, the stability of intermetallic hydrides has been proven to be excellent despite their high cost but there are technical barriers of implementing intermetallic hydrides for large scale storage [16].

In complex hydrides alanates, boron hydrides and the amids are the most used ones for hydrogen storage. They are mostly consisting of light elements with high gravimetric hydrogen storage, nevertheless, most of them requires high temperature for their dehydrogenation via thermolysis [17].

The last type of chemical storage is chemical hydrides, such as methanol, ammonia, and formic acid. Methanol (CH_3OH) with hydrogen capacity of 12.5% (wt) is producing hydrogen through hydrogenation of carbon dioxide (CO_2). Also, hydrogen can be released from methanol by reaction with water in steam reforming and through methanol thermolysis (decomposition) [18]. For ammonia (NH_3) hydrogen storage density is quite high 17.7% (wt). However, storing large scale hydrogen is challenging due to the dehydrogenation process that requires high energy demand. Ammonia requires a temperature over 650 ^0C, in order to achieve a complete conversion of decomposition [19]. Formic acid has the lowest hydrogen storage capacity 4.4% (wt) with the privilege that dehydrogenation can be performed in normal temperature conditions, close to room temperature in some cases [20].

2.3 Physical Storage

Storing pure hydrogen can be done in liquid phase and in gaseous phases. For the gaseous phase it is divided into two types: above the ground and underground hydrogen storage, underground storage will be covered in details in the next Chapter. Storing hydrogen above the ground requires pressure more than 100 bar to compress the hydrogen at 20 ^0C with density of 7.8 kg/m^3. Investing in hydrogen storage above the ground requires high capital due to the high compression work that is needed for hydrogen. On the other hand, lowering storage pressure means lower compression work, thus, lower operating cost [21]. Storing hydrogen in liquid state can have the advantage of high hydrogen density storage; the density of saturated liquid hydrogen at 1 bar is 70 kg/m^3 [22]. However, this form of storage is not always favoured because of the energy- intensive liquefication process which needs extremely low boiling point of hydrogen (-253 ^0C at 1 bar) in liquification process.

2.4 Adsorption

Storing hydrogen by adsorption requires low temperature and high pressure to exploits physical van der Waals bonding between molecular hydrogen and the material. The most common refringent used for hydrogen adsorption is liquid nitrogen [23]. The needed pressure for hydrogen adsorption can vary between 10-100 bar according to the intended application. There are many materials that were used for hydrogen storage such as metal-organic frame works, zeolite, porous polymeric materials and carbon-based material [23]. Veenstra [24] suggested that using the current available adsorbents to achieve a vessel level deliverable hydrogen at higher capacity than 40-50 kg/m^3 at

-196 ⁰C is quite challenging due to the low density of most applied adsorbents and the need for additives to improve the effective heat conductivity.

Table 1
Comparing different storing methods

Storage type	Storage Method	Advantages	Disadvantage
Physical	Compressed H2	Available commercially	High compression energy, low volumetric capacity
Physical	Liquid H2	High hydrogen density storage	High liquification energy, safety issues
Chemical	Metal hydrides	Reversible reaction	High operating temperature to release H2
Chemical	Chemical hydrides	High storage density (17.7 %wt)	High energy for dehydrogenation
Chemical	Complex hydrides	high gravimetric hydrogen storage	high temperature for dehydrogenation

3. Underground H_2 Storage (UHS) Systems

3.1 Technical Background

Geological reserves are considered a suitable space for hydrogen storage which may then be used as energy source that can release the surplus energy that was produced from different location to meet the energy demand when it is needed. The known technology of storing hydrogen underground until now is in porous rock (depleted oil and gas reservoir, deep aquifers) and in artificial spaces (salt cavern, used mine cavern) (Figure 2). These types of technologies in terms of storing hydrogen gas are still lacking hands -on experiences for development, also hydrogen production in the middle east is not well known across the region.

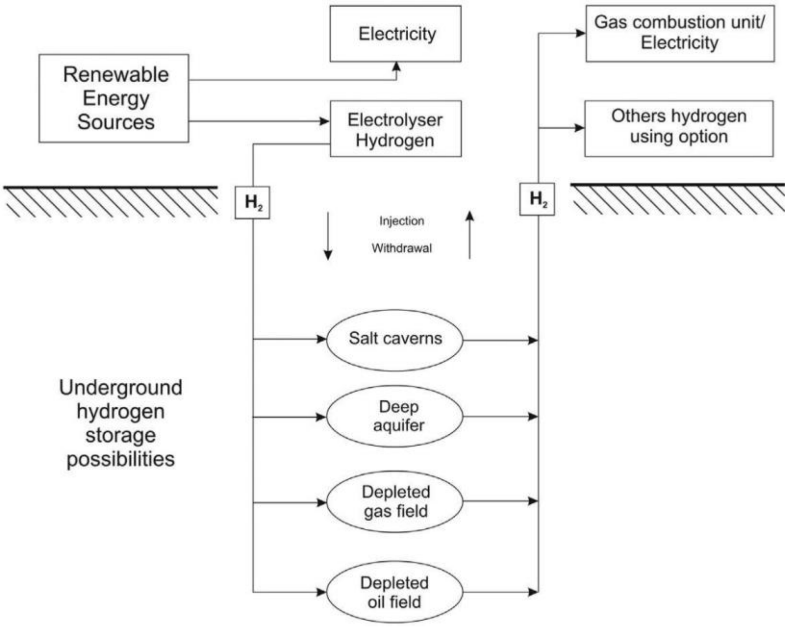


Fig. 2. underground hydrogen storage facility [25]

The concept of storing gas underground in geological formations is worldwide known in with petroleum companies for hundreds of years, even for underground storage of carbon dioxide (Carbon Capture and Storage – CCS). There are two main important characteristics for underground storage which are the capacity to hold the gas and the rate at which has can be injected and withdrawal. Cushion gas is defined as the volume of gas required in a storage field for reservoir management purpose to maintain minimum storage pressure to meet working gas volume delivery [26]. Underground storage has several advantages such as:

1-Guaranteed safety of storage - Underground store has a less risk to explosion risk

2-Less surface area for storage – if a similar space was to be built on the surface it will take a large surface area to store the hydrogen, which means the ability to build based on the required energy.

3-Cost – the cost of building underground reservoir is much lower than the cost of building traditional reservoirs of comparable capacity on the ground

4-Possible use for storage more frequent than usual

5-Positive experience with storage of hydrogen in other countries Underground hydrogen storage energetic hydrogen cycle:

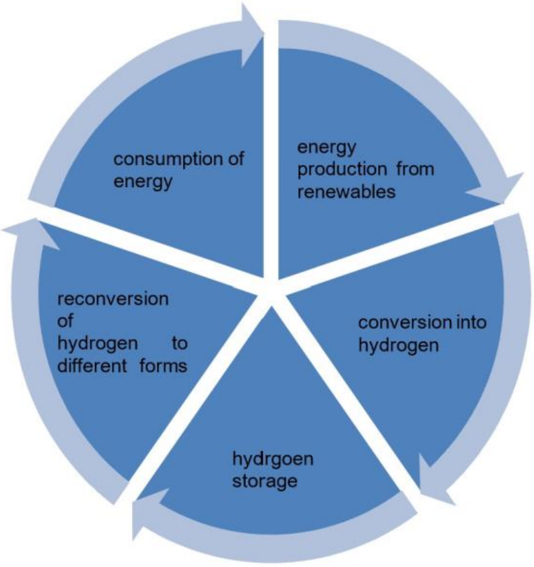


Fig. 3. Hydrogen energy cycle

For underground hydrogen storage facility, it includes the transportation from site where it is produced (electrolysis) via dedicated pipelines to the site of injection. The surface installation at the facility includes four parts: compression, decompression, purification and dehydration. The underground section consists of an injection and extraction well with surface installation equipment. Determination of the amount of injection and withdrawal can be concluded using software modelling, based on the geological parameters of the storage conditions [27].

3.1 Hydrogen Storage in geological structures

There are three favorable geological structures for gas storage that are; deep aquifers, depleted oil and gas fields and cavern storage that are widely known. Each one of these requires specific geological conditions to build underground storage for hydrogen. Despite the fact that underground storage has been used since the beginning of the last century, there are few publications presenting the criteria used when selecting sites for gas storage. However, Smierzchalska developed a criterion for selecting potential underground hydrogen storage sites using Analytic Hierarchy Process (AHP) as a multi-criteria decision-making process. The results showed that AHP- based approach can be useful for preliminary selection of potential underground hydrogen storage sites [7].

Most deep aquifers occur in sedimentary basins at various depths, optimally up to 2000 m while, salt basins are the most abundant basins in Oman. These aquifers are underground layers of rock that are saturated with water and characterized with high porosity and permeability reservoir. Two basic geological conditions are important to meet for these aquifers which are: good sealing rocks properties that prevents hydrogen from leaking upward and good reservoir conditions in terms of natural fractures and fissures. The process of filling the reservoir with hydrogen include filling the pore space with water, then displacing water with injected gas to increase the pressure inside the storage space. Water will act as seal for storage space also, at the bottom. The maintained pressure depended on the injection and withdrawal rates of the stored gas. Drilling wells next to the aquifer are important to gather all the necessary details about the reservoir suitability and for core samples to analyse rock samples. Deep aquifers can be used for enormous capacity volume for seasonal storage but there are high risks of leakage paths in the surrounding environment leading to chemical, mineralogical and biological reactions between hydrogen and the other rocks. There are no prior experiences with storage of hydrogen in deep aquifers, also the cost of operation for this type of storage is higher than salt caverns and depleted oil and gas reservoir [25].

In general, the most common type of underground storage sites are depleted gas fields since the geological conditions of the well is known and studied previously for example; petroleum products, natural gas and hydrogen. In depleted oil and gas fields the reservoir conditions are usually suitable for storage since most of the surface facilities and subsurface data are available for further development. However, the adaptability for hydrogen storage needs more technical development for casing material that used for the well, cement type that is used to install the casing and extra surface equipment for hydrogen compression. The main benefit of using such wells is that lowering the cost of exploration data and exploitation. Also, the seal integrity of the well is confirmed since it is already used to seal the hydrocarbon from migration. On the other hand, the residual gases from the well itself can effect on the extracted hydrogen purity and may react with hydrogen and become irreversible from the well. The amount of gas that can be stored in such wells is close enough to the amount of extract gas from depleted gas wells, which will be suitable for seasonal storage. Though, there are no projects has been done yet in depleted oil/gas reservoir for hydrogen storage.

Salt caverns are artificial chambers that are created by leaching for storing gas purposes. The gas is stored inside the salt because of the salt low permeability, self-healing properties and its resistivity for chemical reactions with the stored gas. Salt deposits that are suitable for cavern can be found in two types of salts which are: bedded salt and salt domes (Figure 4). This type of storage has been done before in UK and USA for hydrogen storage. The process of injection and withdrawal of hydrogen from salt caverns is more flexible in operation; gas may be injected and extracted ten times a year [28]. Nevertheless, salt tightness might be not suitable if there were interlayers within the cap rock which can decrease the sealing integrity for hydrogen storage. Adding to that, if salt depths was not sufficient for cavern proper designing, the operating pressure will be lower and lesser amount of gas is going to be injected in the cavern.

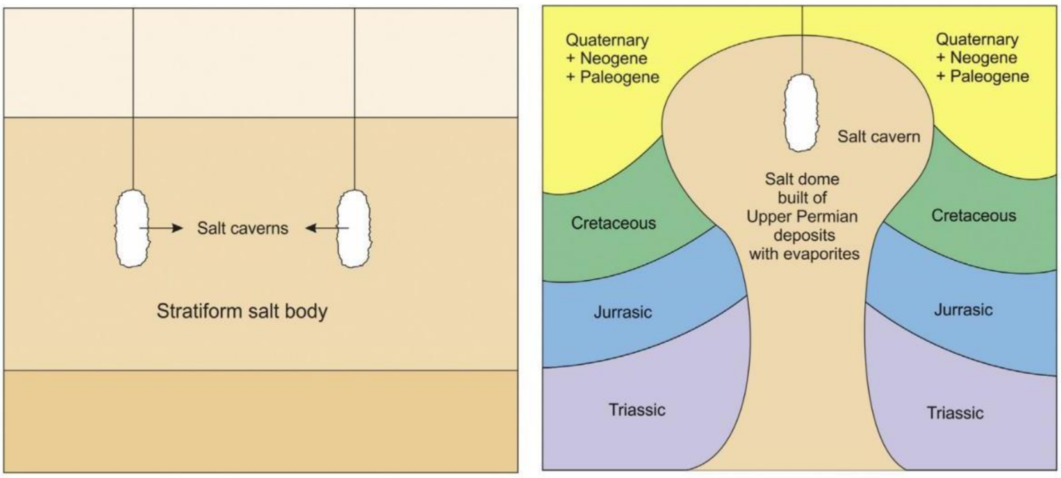


Fig. 4. Salt beds (a) and salt domes (b) [15]

Hydrogen was previously stored in salt caverns stored at UK, Teesside and two at USA, Texas. The fourth salt cavern was in USA, Texas by Air Liquide in 2014, the estimated volume was 580,000 m^3, which can provide energy more than 120 GWh [29]. It has been proven that hydrogen that can be stored safely for a long time period. In UK, 1 million m^3 of pure hydrogen was stored in three salt caverns at a depth about 400 m. Hydrogen was consumed by nearby industrial plants for the production of ammonia and methanol. In 1980, Chevron Philips stored 95% hydrogen in a cylindrical cavern at the depth of 850m for cavern roof top. The cavern diameter of 49m, a height of 300 m, and hydrogen capacity of 30.2 million m^3 [25].

The volume of a single salt cavern can vary from 150,000 to 800,000 m^3 depending on the depth, pressure, geological features and salt thickness. Scientists at Germany's Julich institute for Energy and Climate research believe that salt caverns are feasible, flexible and efficient solution for hydrogen storage. The energy density of salt caverns can vary between 214 kWh and 458 kWh/m^3. If we have the energy density of hydrogen at certain depth, pressure and temperature, we can estimate the capacity at domal salt structures is the highest at 210 GWh, while bedded salt caverns can range between 65GWh to 160 GWh. Deeper salt structures can increase the amount of storage capacity [30].

Focusing on the technical specifications for UHS on (Table 2) shows that storing hydrogen is more complex than natural gas, that requires detailed studies to confirm the viability for using such techniques to store hydrogen.

3.2 Omans's Geological Data

An understanding of the basic geology of Oman is mandatory discussion in order to analyse the feasibility and the potential of geological hydrogen storage. The sultanate of Oman is located at the south eastern margin of the Arabian plate. Oman mountains are covering an area of 700 km long and reaching an elevation of 3 km above sea level. Tertiary sediments in Oman are mainly deposited in the central part of the country, with Pre-Cambrian to tertiary accumulates towards the eastern flank. Most of the hydrocarbon deposits are onshore fields located on the southern and north-east region in Oman's desert. As seen in (Figure 6) the plate movement have resulted in complex structure, sedimentation and burial history in the country. The south side of Oman is bounded by Gulf of Aden spreading zone, and the northern side by Zagros- Makran collision zone between the Arabian plate and Eurasian plates. Most of the Middle East petroleum system deposits are ranging from Silurian to

Jurassic expect Oman hydrocarbons. Nearly, of all of its hydrocarbons are from Pre-Cambrian source rock which is compared to other countries are considered phenomenal since, the middle east oil and gas is generally sourced in much younger age [31].

Table 2
Technical specification for UHS

Technical specification	Deep aquifers	Depleted Oil/Gas	Salt caverns
Abundance	Appears mostly in sedimentary basins	Hydrocarbon accumulations zones	Salt basins in Oman
Estimated capacity	Very high	Very high to high	High. It can increase if more than one cavern were built
Experience	No prior experience	No prior experience	Good experience in USA and UK
Injection and production intervals	One, maximum	One, maximum	Up to 10 cycles per year
Bore holes per cavern	Few boreholes	two cycle per year	One bore hole
Storage use	Seasonal storage	Few boreholes Seasonal storage	Possible use for more than seasonal
Research fields	Leakage, reacting with the surrounding environment	Reservoir pressure, biological and chemical	Cavern convergence, periodic monitoring for salt shaping

The age of Oman's source rock is ranging from Pre-Cambrian to Cretaceous that are deposited in different set of tectonic environments. There are five suggested oil types and they are distinguished based on the origin of the source rock, two derived from Pre-Cambrian to Early Cambrian. Two from Mesozoic and the Type "B" oil family.

The Huqf Oils are derived from early Cambrian intra-salt shale and siliceous source rock of the Ara group [32]. Huqf and Ara are sourced oil from the eastern flank of the South Oman Salt Basin occurring at shallow depths and sealed by Nahr Umar Shales. Such oils need tertiary recovery methods like EOR to produce the oil efficiently. Second, the "Q" oils are mainly found in central and northern Oman in Gharif reservoirs, hydrocarbon generation of this type of oil is thought to occur during Mesozoic. Next, the "B" oil family that occur in Ghaba Salt basin and in the western-central Oman. The "B" type is thought to be originated from Pre-Cambrian oils, and the possibility that it might be came from another source is still possible. The Shu'aiba oil may have been sourced from bab basin, which is developed in Abu Dhabi and extended over a small area in the north west of Oman [33]. Finally, Natih Oils that appears in late cretaceous foreland basin in south Oman Mountains and sealed by overlying Fiqa Shales as seen in (Figure 6).

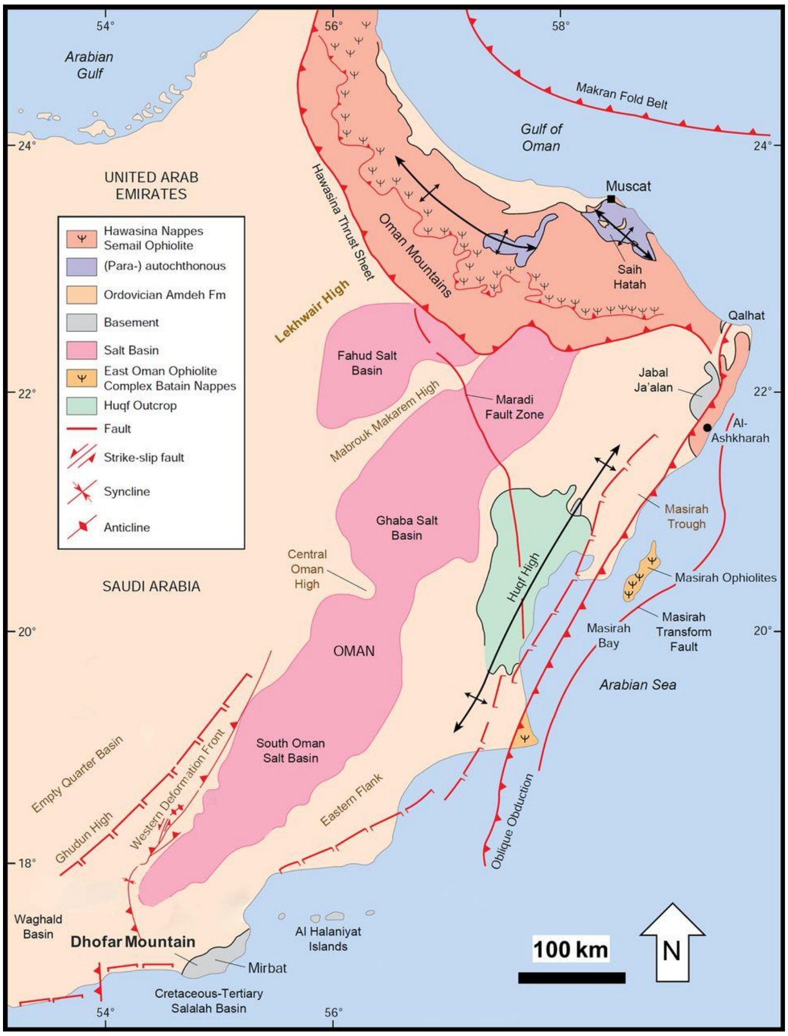


Fig. 5. Oman's Map [31]

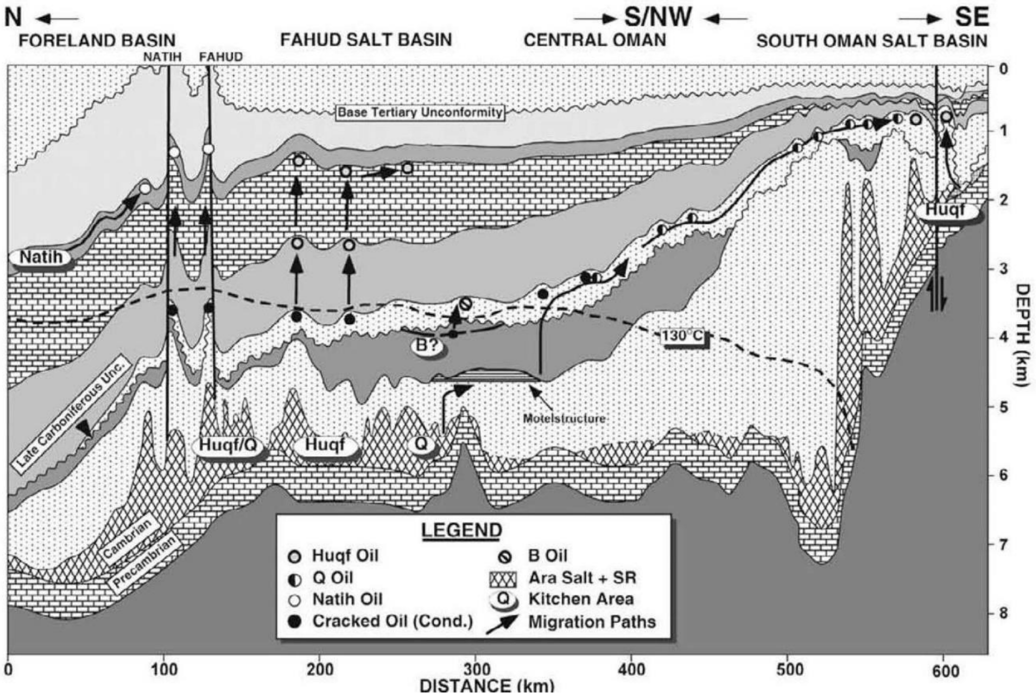


Fig. 6. Cross section through Oman showing the different petroleum systems [31]

In North Oman most of the entrapment system for hydrocarbon are faults that were aided by salt uplifting. Many of those faults were initiated in Paleozoic, resulting in downbuilding of salt. Younger entrapment system on the northern part is a result of later Cretaceous and Tertiary compression related to the foreland basin development. In central Oman, most structures are located along plunging structural highs combined with stratigraphic structural traps. While, trapping in the south Oman Salt Basin is strongly controlled by Cambrian Ara salt [34].

3.2 Salt Basin

There are three evaporitic basins in Oman that are Fahud Salt Basin on the North East side, Ghaba Salt Basin in the middle and South Oman Salt Basin in the South East part of Oman as seen in (Figure 7).

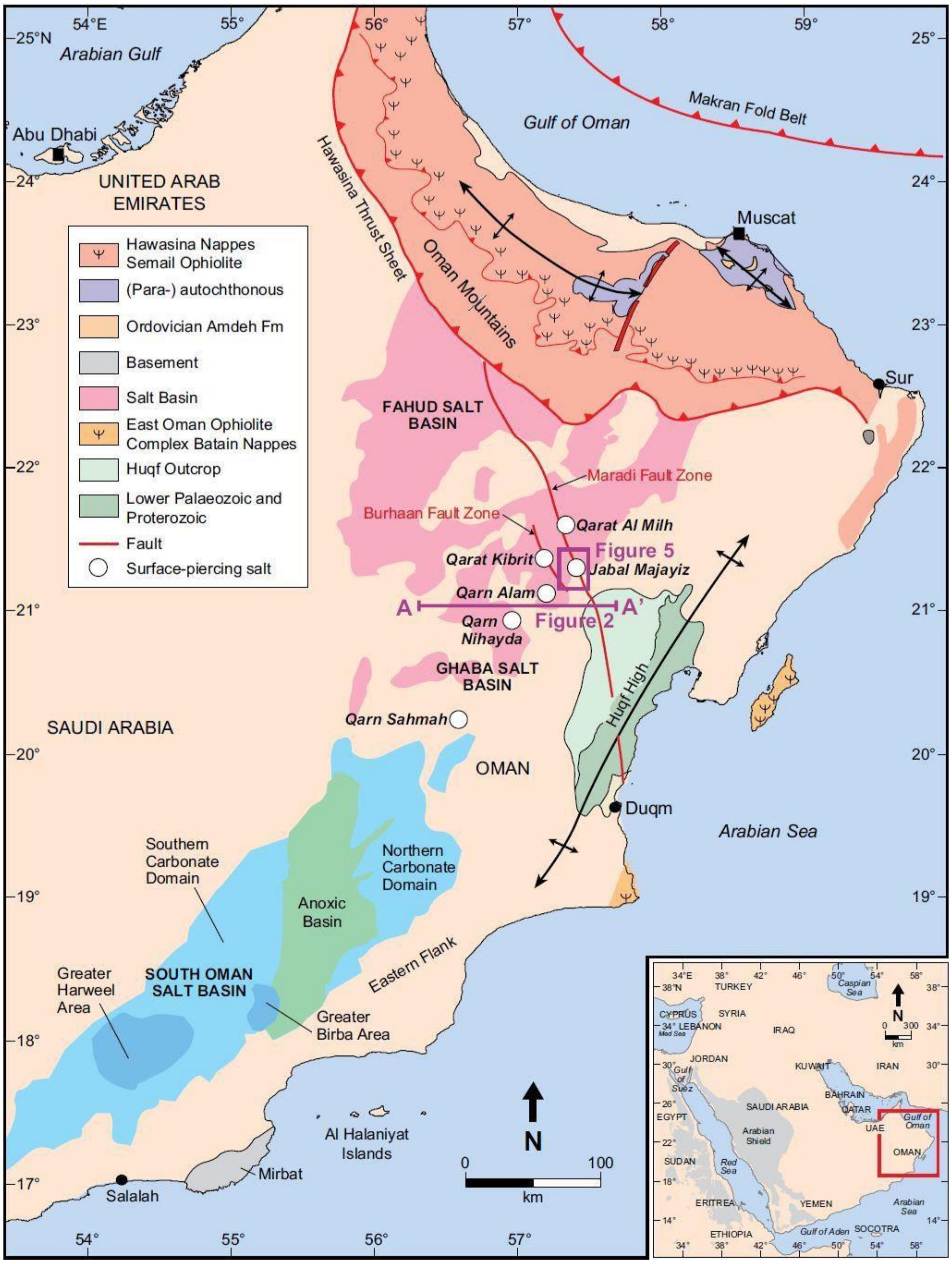


Fig. 7. Oman Salt Basins distribution [35]

The carbonates and evaporates outcrops do appear as six surface piercing salt domes of Ghaba Salt Basin. Major tectonic activities played a major role in the configuration of intra and post salts traps like the three diaprisim salt tectonics, i.e., passive (down building), reactive (normal faults) and active (forceful intrusion), and other factors of salt dissolution, salt doming.

In Ghaba Salt Basin (GSB) the development of salt diapers is a result post depositional salt movement that was followed by rapid deposition variations of the Haima sediments. The dominant mechanism formed GSB was fault-initiated downbuilding [36]. In South Oman Salt Basin (SOSB) passive diapirism i.e. (downbuilding the accumulation of sediments around a salt dome) is the dominant mechanism formed the basin followed later by sedimentation that resulted in elongated domes and salt walls in the central SOSB.

In GSB there are six surface-piercing salt domes. These salt diapers are extremely high relief features (as much as 9 km deep) that pierces the entire stratigraphic succession in GSB. The diapers have an elevation of 100m or less above the surrounding area (Figure 9) and roughly circular to irregular oval in shape, with the largest (Qarn Shamah) being over 8 km circumference at the surface [35].

Qarn Sahmah is the largest salt dome of the six, with numerous ridges and forms circular outcrop with a depth of 3km. The nearest drilled well from the dome are exploration wells Qarn Sahmh-1 (1979) and Qarn Shamah North-1 (1983) 7km and 16km, respectively, from the diapir [35]. Qarn Nihadya salt dome forms a sharply defined topographic feature in the desert, in 1997 unsuccessful attempt (Qarn-Nihayda-1) exploration well was drilled just to the east of the diaper to test for hydrocarbon potential. Qarat Kibrit salt diapir can reach the depth of 15 km with top surface piercing that is characterized by discontinuous outcrops of salt, gypsum, minor amounts of clastics. In Jebel Majayiz salt dome, the dome is large and not yet fully explored. Qarat Al Milh salt dome is considered small salt diapir compared to the other salt domes. The depth can reach up to 2.5 km with poorly exposed surface piercing and minor topographic expression. In Qarn Alam the depth of the salt diapir is about 10 Km (Figure 8) with relatively small outcrop on the surface that indicate the carbonate facies development [35].

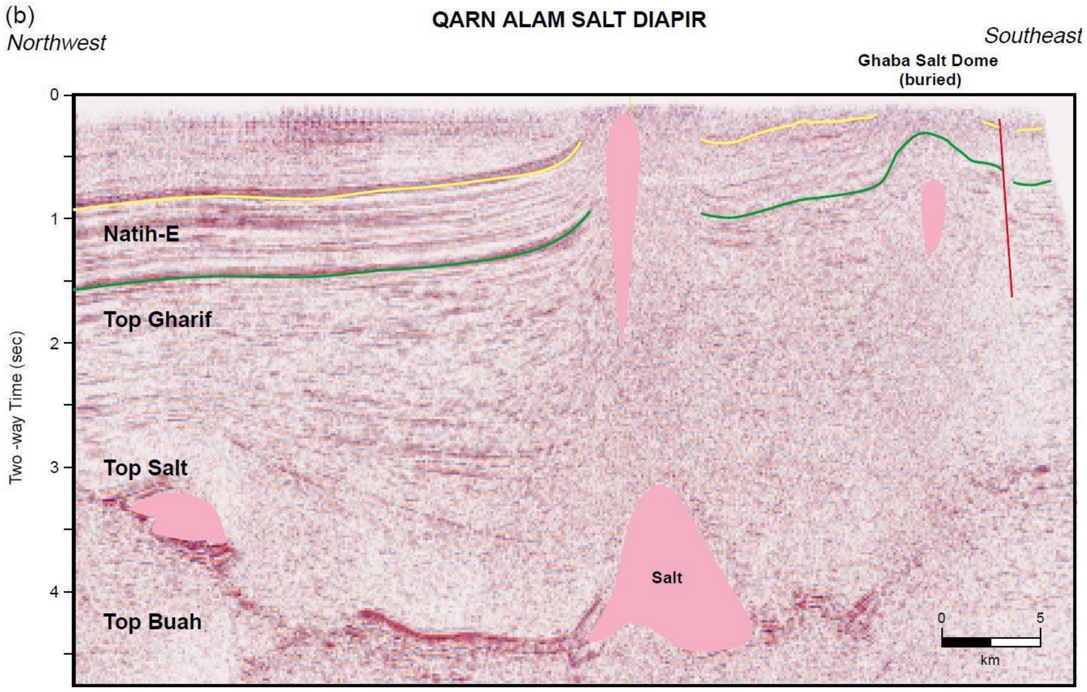


Fig. 8. Qarn Alam surface-piercing [38]

4. Methodology and Screening Analysis

A preliminary analysis for Oman salt basins has been performed to identify salt domes suitability for hydrogen storage. The data assembly involved gathering available geological reports. The methodology involves estimation of the salt structures area size, the depth of salt dome, cavern design, placement of single salt cavern and calculation of the potential storage of hydrogen. The results of potential cavern design and capacity estimation is presented in discussion section. Finally, the main findings and suggestions for future work are discussed on the end of this research.

Based on [39] method of selecting salt domes for hydrogen storage in Poland. Two basic criteria were used to filter the domes: the maximum accepted depth of the salt diaper location must be less than 1km. the other one is the salt depth, which needs to be more than 1000 m. Most of the surface piercing salt domes that are within GSB depth is more than 1000m, except Qarn Majayiz depth which is unknown. The selected domes, needs to be examined for practicality which relays on five main factors:

- Size/area of salt dome: the larger the dome size, the more caverns can be leached out. Each cavern must be spaced out for at least 200 m [9] to maintain a safe distance for salt caverns design.
- Depth of the salt level: salt level depth is depending heavily on the depth of the salt dome itself. Salt tectonics like convergence of the salt dome, where the layers are thinning over the salt body, might be affected by the salt level depth. Also, the lithology and thickness of the salt cap rock can be affected by the placement depth of the salt cavern.
- Detailed study on salt dome subsurface data: this type of study includes, boreholes, seismic data, salt quality in terms of sealing integrity, geomechanical properties, degree of the salt purity. Availability of the data is a key factor to recognize the salt consistency and suitability for cavern storage
- Complexity of internal structure: the salt structure can be found in different forms and variety internal structures. The shape can change according to the depth and pressure zones, knowing the salt structure style can help to model quite good design for leaching.
- Geological Reports: the existence of detailed geological reports that covers intensive research, borehole data, seismic imaging, will be necessary to decide whether to build a cavern storage or not [39].

Table 3
Salt domes size and depth

Salt dome	Size (Surface Area)	Depth (Centroid)
Qarn Alam	1 x 6 km	10 km
Qarat Al Milh	0.5 X0.4 km	2.5 km
Qarn Shamah	2.8 X 2.5 km	3 km
Qarat Al Kibrit	0.7 X 0.5 km	15 km
Qarn Majayiz	3 X 1.4 km	Unknown
Qarn Nihidya	2.8 X 1.6 km	3 km
Qarat Al Milh	0.5 X0.4 km	10 km

According to Tarkowski [25] the potential salt domes needs to have a good depth, salt thickness and salt dome size. The great thickness of the salt deposits enables the construction of underground with sufficient capacity and the good size salt can help to build more than one salt cavern at the same dome. These were applied to Oman salt domes to filter out the best candidates for cavern storage. The dome depth and size were from seismic data and the field investigation in Peters [35]. Qarn

Majayiz salt depth is unknown so it won’t be considered as a potential site. Qarn Nihidya, Qarat al Kibrit, Qarat Al Milh salt domes sizes are less than 4 km, that is categorized as relatively small dome compared to the others. However, Qarn Shamah has an average dome size and a good salt depth which making this salt dome as a good candidate for underground storage. The second potential salt dome is Qarn Alam with smaller dome size than Qarn Shamah and deeper depth. Assuming that these salt domes have a lithostatic gradient of 1 psi/ft, and potential salt thickness of 400 m. if Qarn Shamah useable salt thickness for hydrogen storage was 400 m, the maximum potential hydrogen gas storage capacity for a hold up to 6.4 million m3[40].

4.2 Salt cavern leaching process and calculation

The main parameters to be considered in the design are; the cavern depth, in- situ stresses, the maximum and minimum internal gas pressure levels, various mechanical conditions for the rock salt. For salt construction process it is carried as follows:

- A hole is drilled from the surface all the way to the bottom reaching to desired depth for cavern shaping. Then, two pipes are seated next to each other into each other are run into the bore hole. After the drilling, the bore hole is cemented on the ground surface to the casing shoe which indicate the top of the cavern.
- Next, fresh water is used that will dissolve the rock and to create brine water which is transferred to the surface. There are two types are used to control the cavern shape. The first type is direct leaching process in which leaching pipe will be transferring the water and the brine will go via the outer pipe. The indirect leaching process where the brine is transferred using inner pipe and the fresh water will be pumped via outer pipe (Figure 9). This process is takes long time that could reach up to years, based on the required volume and shape of the cavern [41].

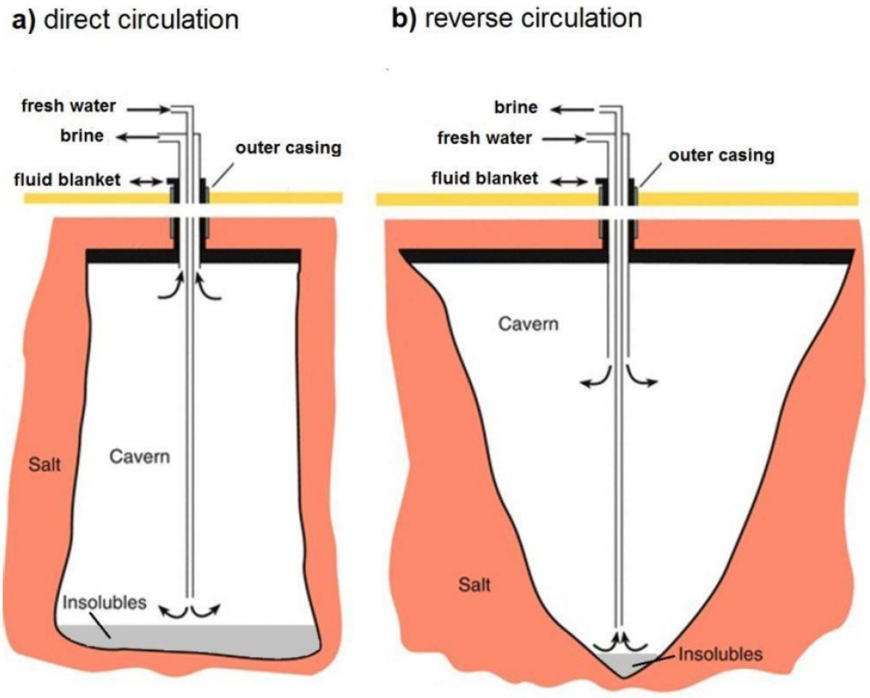


Fig. 9. Direct and indirect leaching [4]

- In this phase the remaining brine is will be replaced by hydrogen into the cavern. Hydrogen will go through the outer pipe while the brine is extracted via the inner leaching pipe. Then, first filling stage come where the pressure inside the cavern will reach to the minimum required pressure to prepare the cavern for next stage (cyclic loading phase). In cyclic loading phase the internal pressure of the cavern will not be stable within a fixed range due to injection and withdrawal at this level [42].

Building salt cavern can be stable when it is built between a few hundred meters and in the range up to 2000 meters depth depending on pressure conditions around the cavern, composition of the salt, geothermal gradient and the hydrostatic pressure. The elastic plastic transition zone occurs at the depth ~1000 m to ~ 2000 m. Caverns that goes below this zone are usually unstable where, large volumes decreases has been seen in previous projects, like the case of Eminence cavern in USA, that was built at depths from 1700-2000 m, closure was at 40 percent of the initial volume in just two years [43]

Measuring the accurate volume of cavern can be difficult, so in cavern leaching process the "mining volume" is used to calculate the effective cavern volume. Assuming that the salt cavern is a cylindrical shape and the total volume is "1" and the volume of interlayers is "w" then, the salt rock volume layers is "1-w", for the mined mass (m_s), the "mining volume" (V_s), Eq. (1) can be equal to:

$$V_s=m_s/\rho_s \tag{1}$$

where ρ_s is the salt density.

The volume of impurity in the salt rock layers is "n", where "k" is the expansion factor. The volume of pure salt is "(1- w).(1- n)", the volume of sediments is "(w+ n.(1- w)",including inter layers and salt rock impurity . the volume of sediments after expansion is "k.[w + n.(1- w)]". considering these conditions, the effective cavern volume (V_e) [8]:

$$V_e=(1-k\cdot[w+n\cdot(1-w)])/((1-w)\cdot(1-n)).V_s \tag{2}$$

By combining Eq. (1) and Eq. (2), V_e will be:

$$V_e=[1-(k-1)\cdot 1/(1-n)\cdot(n+w/(1-w))]\cdot m_s/\rho_s \tag{3}$$

Measuring the storage capacity under the ground can be done by "working gas volume", where, R is constant; z is the compression factor; T is the temperature; and P is the gas pressure [8]

$$V_{NG}=(M\cdot V)/(\rho_{ng}\cdot R)(P_{max}/(Z_1.T_1)-P_{min}/(Z_2.T_2)) \tag{4}$$

4.3 Risk Factors

Storing hydrogen underground could lead to potential risks that are associated with the gas itself and the surrounding environment. The risks can be divided into two major risks that are environmental and technical risks. Environmental risks can be related to hydrogen storage in depleted oil and gas reservoirs. The first environmental risk arises is the microbial activities underground, which is; bacterial sulfate reduction, where hydrogen is microbially catalyzed by bacteria and is converted to H_2S [2]. H_2S is toxic if inhaled and can be corrosive towards storage facility. Another risk is the reaction of hydrogen with surrounding minerals at the cap rock. The high diffusivity of hydrogen could lead the loss of the cap rock integrity, knowing that the diffusion ability of hydrogen can reach up to 5X10^{-5} cm^2/s. plus, the low viscosity and low density of hydrogen increases the probability of storage leakage. Technical risks in salt caverns it can subcategorize into three main risks: (1) salt properties, (2) geological features and (3) storage cavern design. salt creeping phenomena is when the salt deforms continuously according to the surrounding pressure, which helps the salt to contain the hydrogen in different pressure conditions. However, this can result in cavern shrinkage and losing hydrogen volume during underbalanced stress state. Second, if the operating pressure went above the maximum pressure, it can create tensile stress around the cavern, which can crack the cavern walls and decrease the tightness of the cavern. Third, salt rock is a highly corrosive material. It can corrode the casing steel and results in gas leakage through the cracks of casing. Moving to the geological features' risks; the salt cavern is not allowed to be built around any nearby faults and fissures. Building a slat cavern around faults can create a natural channel for oil and gas leakage. Joints or fissures can decrease the tightness of the salt cavern specially if there were many joints or connected fissures. Cap rock lithology, thickness and break through pressure can determine the quality of the salt cavern. Having a large void in the cap rock can easily become connected with the caverns which can result in cavern tightness failure. Similarly, the presence of ground water in the cap rock can loosen the integrity of the cap rock. In storage cavern design, storing hydrogen at shallow depths is unfavorable for cavern constancy and volume quantity. While designing for salt cavern, thermal expansion of brine is common in salt at great depth. The difference between the temperature of injected water and the temperature of the rock cause increase on the internal pressure inside the sealed cavern [45].

4.4 Economic factors

The capital expenditures for hydrogen storage in salt cavern is divided into two parts: (1) cavern construction cost and (2) surface installation cost. In cavern construction, gas cushion cost and dissolution are the main costs. The length of the pipe line cost, geological survey methods and the cost of cavern construction in terms of size must be considered. The material the is used for hydrogen transportation needs to be resistant to hydrogen brittleness which means extra cost for material used. In surface installation cost, it includes gas compressors required according to the given cavern design. Presenting with Lord [46] cost analysis for hydrogen storage in USA, it appeared that depleted oil and gas reservoirs (1.23 USD/kg of stored hydrogen) or aquifers (1.29 USD/kg) would be the economically-attractive options. While, there are substantial costs related to controlling H2 from migrating within the formation and potentially escaping out. Therefore, salt caverns (1.61 USD/kg) might be appropriate solution due to their low permeability. The HyUnder project [29] presented several studied cases with respect to CAPEX (cost of cavern, electrolyzers, surface installations) in Europe. The results showed that the cost of electrolysis is the highest cost in production stages and underground hydrogen storage (more than 80% of investment cost), and electric power relatively high cost. Which means in order to have a profitable UHS, high utilization rates of electrolyzers are needed to be done. Using hydrogen as an energy source and storing the produced hydrogen to cover the demand will depend heavily on the development of future related industries: power industry and hydrogen consuming industrial products.

5. Analysis, Results, and Discussion

Based on the geological structures that is available in Oman, deep aquifers are not suitable for hydrogen storage since sedimentary basins are not very common and there are no experiences of doing such projects. Oman is the largest non- OPEC oil producer in the middle east with a total of liquid reserves 4.90 billion barrels and 23.2 tcf of gas reserves [47], using the depleted oil and gas reservoir for hydrogen storage will be cost effective solution since the pipelines network and well construction is already established. However, there are no experiences of using this method for hydrogen storage, extensive research needs to be done for hydrogen adaptability for each well including geochemical analysis, material requirement and safety standard procedures. There are three salt basins in Oman, one of them is South Oman Salt Basin (SOSB) which covers approximately 400 by 150 km in extent [48]. Utilizing such deposits for surplus energy storage can support the storage of renewable energy resources to cover the energy demand if there was shortage.

Summarizing the above, deep geological formations can be the safest and most promising locations for the storage of large volumes of electrical energy if it will be converted to hydrogen later [49]. Salt caverns are the technically preferred option in Oman's case , not least since there are similar projects were done and the salt basin size can have a great potential for energy storage.

Thick salt deposits probably provide the best environment for cavern construction and containment. This is because of the unique salt rheology, plasticity and self-healing over long period of time. The cavern working principle is by compression and decompression of the minimum and maximum pressure. Assuming we have a perfect salt thickness with efficient salt integrity as a cap rock in Qarn Alam salt dome, with outstanding results from doing a numerical simulation on the dome for hydrogen storage. Based on the values that is used for Zuid- wending underground gas storage [50] similar design can be illustrated (Figure 13) of a cylindrical shape storage at 1000 m, that guarantees low rate of convergence for the cavern, which is permitting the pressure to reach to 180 bar to maximize the storage volume at this depth. Assuming the temperature gradient is 19°C/km [51], then it will be approximately 48 °C around the cavern.

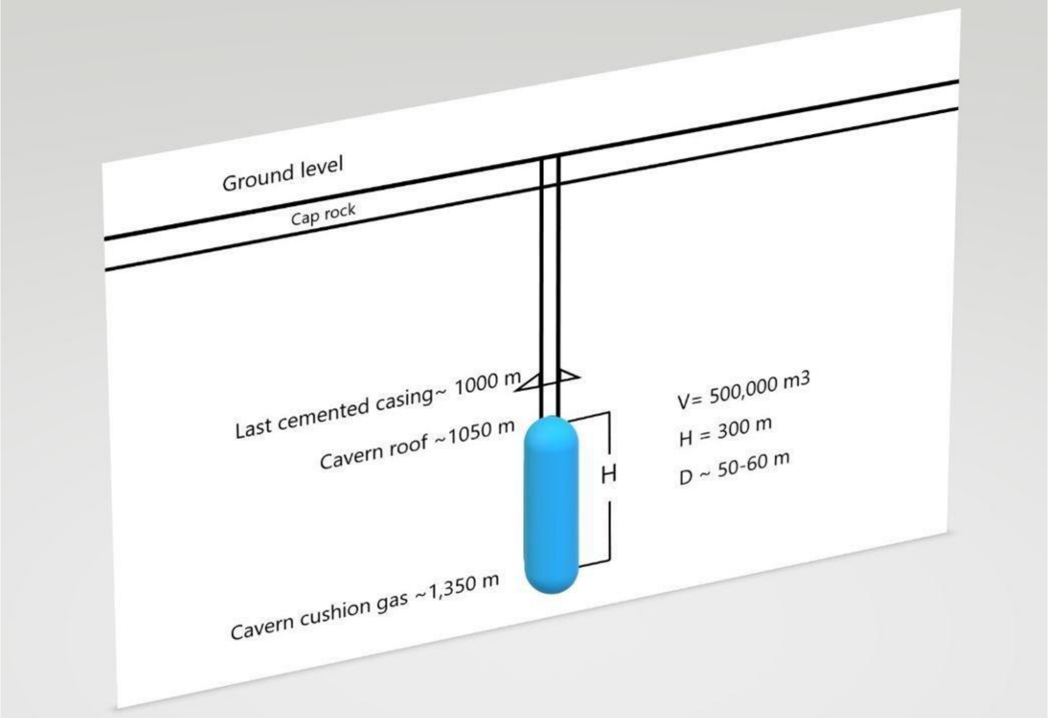


Fig. 10. Cavern shape design for Qarn Alam

The proposed cavern volume is 500,000 m^3, height of 300m and diameter ~54m with 30% of total cavern volume is used a cushion gas, in order to maintain the pressure inside the cavern. Multiplying the value of working gas for natural gas with average expansion factor of 0.85 to gives us the amount of working gas for hydrogen, which is valid for the range of pressures (100-300 bar) and temperatures

(80-140°C) [52], which is equal to 40.8× 106 Kg of hydrogen. Estimating the stored energy in the cavern can be done using Eq8.1. The cavern capacity is in $GWhH^2$, while the lower heating value of the gas is (LHV) is in $GWhH_2$ Kg^{-1} [9].

$$CavernCapacity = mworkingGass.LHVgas \quad (5)$$

So, it is estimated that Qarn Alam can store up to 0.1TWh of energy. Assuming that on each cycle only 10% of the working volume can be produced, which is almost 12 GWh. According to Oman Power and Water Procurement 7 years plan, the peak demand for electricity by 2025 will reach to 8.6 GW (Figure 11). Qarn Alam and Qarn Shamah can both stores up to 0.2 TWh.

Based on these salt domes location, producing green hydrogen will need a good source of renewable energy. As seen in (Figure 13) that solar irradiation levels are high throughout the country in Oman and it is increasing toward the south region. Sky clearness, at about 342 days in a year. Downward price of solar energy production is encouraging businesses to make the transition to solar on a purely economic basis. For wind energy potential in Oman, it has an excellent potential. According to Wind Resources Atlas (Figure 14), there are four suitable locations for wind farm two locations are in the south, one location in Duqm, and one in Sharqiyah region. Fortunately, Duqm area have a good potential for solar and wind energy, using that energy to produce hydrogen and store it in salt domes can manage the intermittency of hydrogen production from renewable energy. Knowing that Qarn Shamah salt dome is only 150 km from Duqm area.

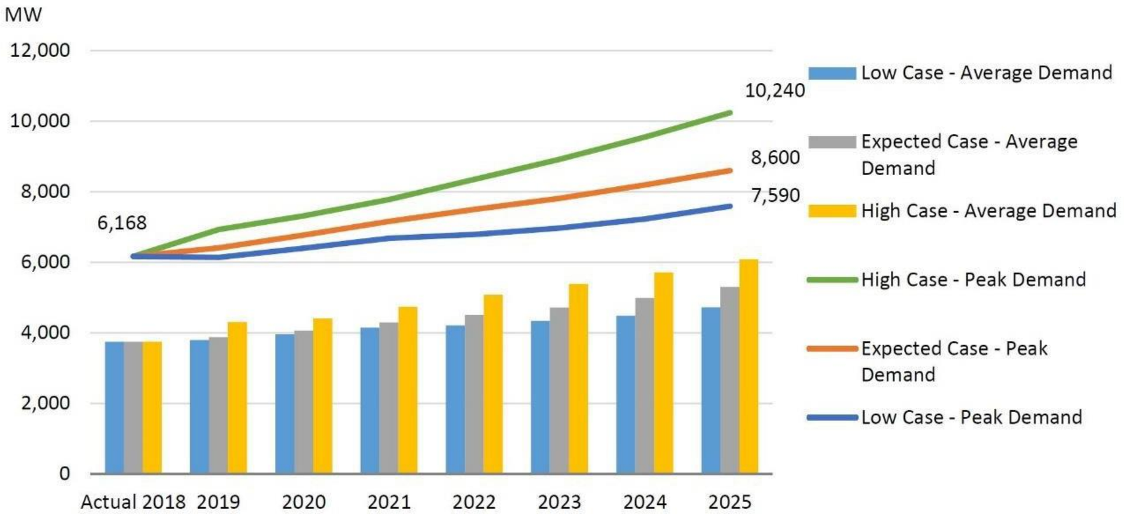
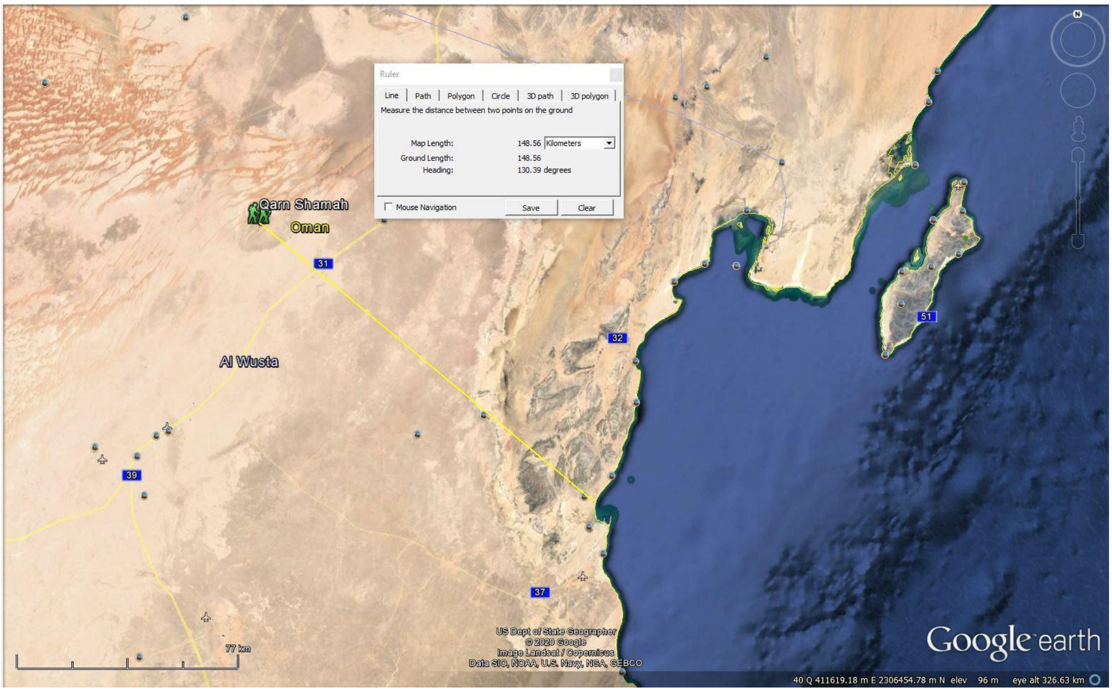


Fig. 11. Projected Oman's electricity demand [53]



Ruler

Line | Path | Polygon | Circle | 3D path | 3D polygon

Measure the distance between two points on the ground

Map Length: 148.56 Kilometers
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Heading: 130.39 degrees

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Fig. 12. Qarn Shamah salt dome from Duqm Area

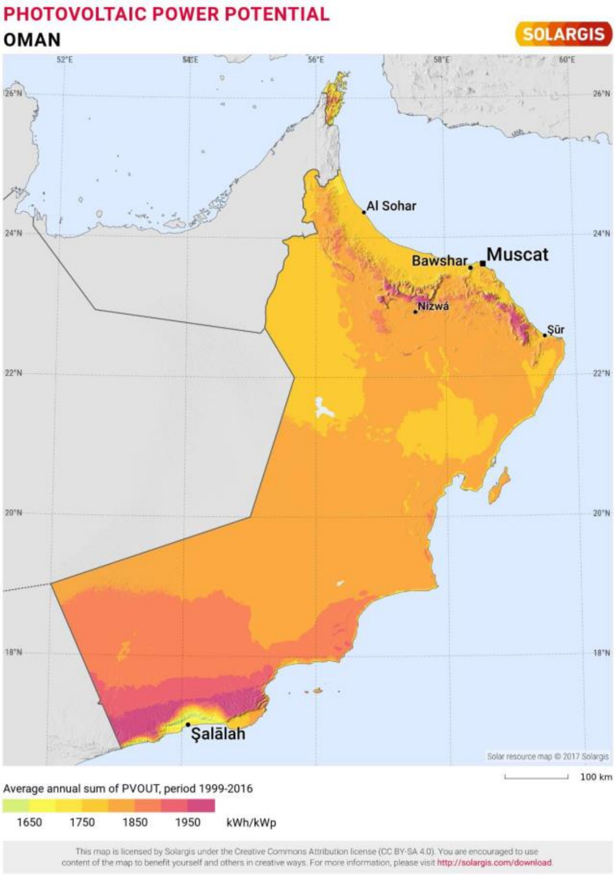

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Fig. 13. Solar energy in Oman[55]

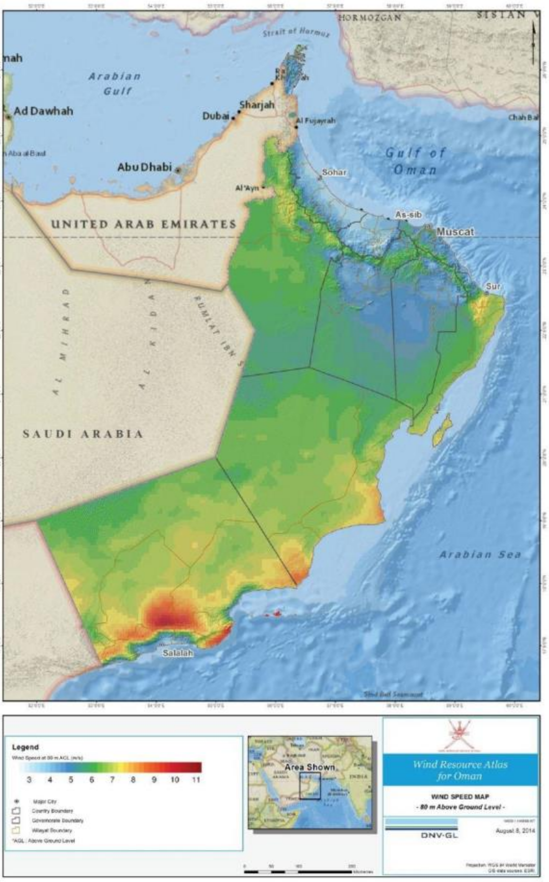

Fig. 14. Wind energy in Oman [54]

5. Conclusions

Oman has a good potential of salt basin deposits, which includes six surface piercing salt domes that appears at the surface. The methodology that was used to filter the technical potential salt deposits was these salt domes needed to have a good depth, salt thickness and salt dome size. out of the six, two salt domes (Qarn Shamah and Qarn Alam) were offering a good potential of estimated working gas volume of hydrogen around 90 m3 hydrogen (0.2 TWh). Storing hydrogen underground could lead to potential risks that are associated with the gas itself and the surrounding environment. The technical risks in salt caverns can be subcategorize into three main risks: (1) salt properties, (2) geological features and (3) storage cavern design. However, using salt cavern for UHS guarantees safety of storage with less risk to explosion risk, less surface area for storage, the cost of building underground reservoir is much lower than the cost of building traditional reservoirs of comparable capacity on the ground and possible use for storage more frequent times up to 10 times per year. producing green hydrogen needs a good source of renewable energy, fortunately, the southern region in Oman shows a good potential of renewable energy. Utilizing that energy for hydrogen production and storing surplus energy in underground salt will cover the energy intermittency from renewable energy. Despite the good potential for underground energy storage, the future of the type and size of energy storages will depend to large extent on the country vision on which energy system it will be used for (production, conversion, transport and consumption).

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