THE REGULATORY FRAMEWORK OF GEOLOGICAL STORAGE OF HYDROGEN IN SALT CAVERNS

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ABSTRACT

A growing share of renewable energy production in the energy supply systems is key to reaching the European political goal of zero CO_2 emission in 2050, highlighted in the green deal. Linked to the irregular production of solar and wind energies, which have the highest potential for development in Europe, massive energy storage solutions are needed as energy buffers. The European project HyPSTER [1] (Hydrogen Pilot STorage for large Ecosystem Replication) granted by the Clean Hydrogen Partnership addresses this topic by demonstrating a cyclic test in an experimental salt cavern filled with hydrogen up to 3 tons using hydrogen that is produced onsite by a 1 MW electrolyser. One specific objective of the project is the assessment of the risks and environmental impacts of cyclic hydrogen storage in salt caverns and providing guidelines for safety, regulations, and standards. This paper highlights the first outcome of the task WP5.5 of the HyPSTER project, addressing the regulatory and normative frameworks for the safety of hydrogen storage in salt caverns from some selected European Countries, which is dedicated to defining recommendations for promoting the safe development of this industry within Europe.

1.0 INTRODUCTION

The EU aims to be climate-neutral by 2050 [2] with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal [3] and in line with the EU's commitment to global climate action under the Paris Agreement [4]. Hydrogen underground storage is a solution to tackle the storage problem related to the intermittence of renewable energy necessary to get climate neutral. The concept involves using hydrogen as an energy carrier produced by (excess) renewable electricity which is then stored in underground storage and coupled with the existing natural gas pipe networks. A gas pipe can transport 10-20 times more energy than an electrical cable for the same investment [5]. Moreover, most industrial high-temperature heat demand, currently served by natural gas and other new applications in the steel and concrete industry, can be provided by hydrogen.

A study by D. G. Caglayan et al. [6] estimated a total on- and offshore European hydrogen storage potential at 84.8 petawatts hours (PWh) for salt caverns. Further, the study states that only salt caverns are currently considered to offer the most promising hydrogen underground storage options due to their low cushion gas requirement, the large sealing capacity of rock salt and the inert nature of salt structures, preventing the contamination of the stored hydrogen.

In a detailed model-based analysis of the hydrogen need in Europe, G. S. Seck et al. [7] stated that yearly hydrogen production would increase sharply in the coming decades, exceeding 30 million tons (Mt) by 2030 and more than 100 Mt by 2050, presenting equivalent to between 3,400 TWh and 3,600 TWh in lower heating value. So, the potential storage capacity would be enough to stock over 20 times that of the estimated yearly hydrogen needed in Europe in 2050. The EU-supported project for large-scale green hydrogen underground storage in salt caverns HyPSTER (Hydrogen Pilot STorage for large Ecosystem Replication) located in Etrez, France, addresses the following topics:

- demonstrating large-scale, green hydrogen underground storage in salt caverns,

- studying next stage in energy transition for phasing out fossil energy in favor of renewable, carbon-free energy sources,
- defining relevant cyclic tests to be performed based on the needs of emerging hydrogen regions across Europe,
- assessing the risks and environmental impacts of cyclic hydrogen storage in salt caverns,
- providing guidelines for safety, regulations, and standards.

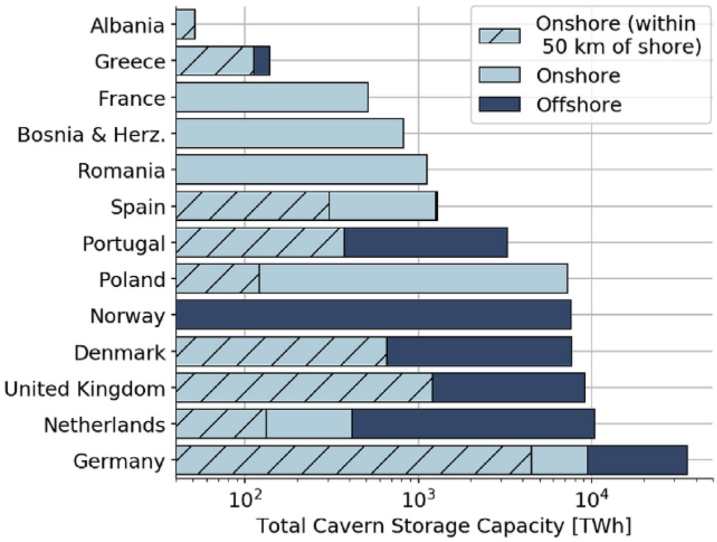

Figure 1. Potential hydrogen storage capacity in Europe according to D. G. Caglayan et al.

Concerning the last point, work aims to establish the current state of the art regarding regulations and standards relevant to the safety of hydrogen salt cavern storage in Europe, both at the Commission and national levels. The purpose is to identify the legal obstacles encountered by operators and competent authorities and the legal and normative adaptations needed to favor a safe and large-scale development of this technology in Europe. In this paper, the attention is focused only on the regulations and standards for managing risks relevant to the cavern and the well (including the wellhead), as shown in Figure 2. The risks associated with surface installations are already accounted for by other regulations.

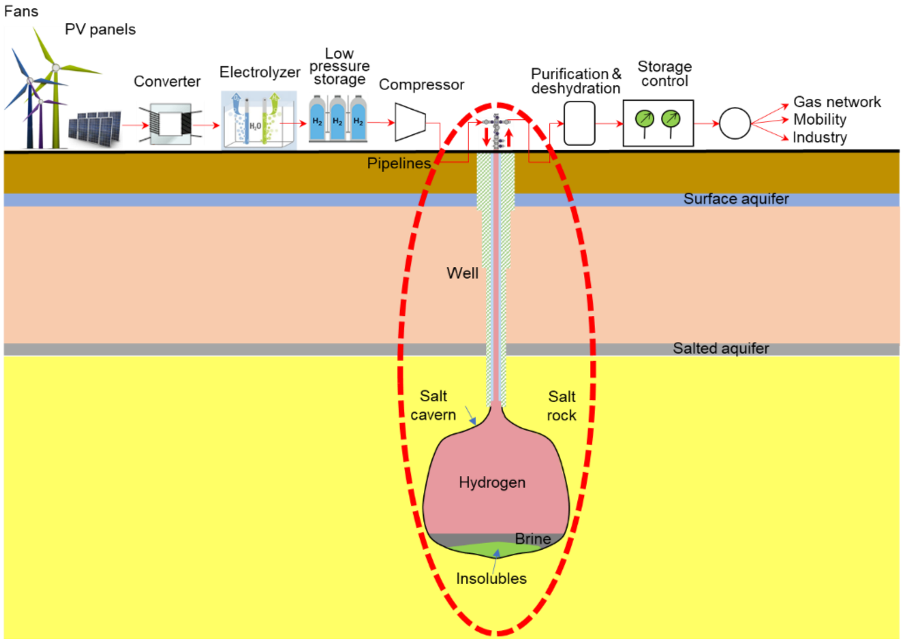

Figure 2. The scope of this regulatory scope is limited to the cavern and the well (including the wellhead) as shown by the red dotted line in this picture.

2.0 EUROPEAN REGULATION AND STANDARDS

Underground hydrogen storage in salt caverns is subject to various European regulations and norms that aim to ensure safety and environmental protection. The most emblematic one is the Directive 2012/18/EU of 4 July 2012, known as the "Seveso III Directive". However, up to now, there is no specific regulation or standard for underground hydrogen storage in salt caverns at European level.

The European standard series EN 1918 covers the storage of natural gas and liquefied petroleum gas in aquifers, oil and gas fields, rock caverns and surface facilities. The European standard EN 1918-3:2016 [8] provides practical recommendations for storage in solution-mined salt caverns for underground gas storage. The standard applies to the solution-mined salt caverns that currently store natural gas or liquefied petroleum gas (LPG), not hydrogen. The working group CEN/TC 234/WG 4 - Gas underground storage is undergoing work to adapt this standard to hydrogen. It gives practical recommendations for such storage facilities for design, construction, operation, maintenance, and abandonment.

Regarding the design of the salt cavern, the standard recommends that the design includes an assessment of the project technical feasibility, economic viability, and environmental impact. It should also comply with local regulations and standards. The design should address the following aspects: geology and geomechanics, well drilling, cavern leaching and shape, well completion, and surface equipment.

Concerning the construction of the salt cavern, it recommends adherence to the design specifications during the construction process, monitoring the environmental impact and ensuring safety. It requires that the construction be carried out by qualified personnel and include the following activities: drilling, casing and cementing wells, cavern leaching, cavern sealing, and provision of surface equipment. The chapter recommends that the storage facility operation should be in accordance with local regulations and standard procedures. It prescribes the following operational requirements: well inspections, well maintenance, pressure monitoring, gas quality monitoring, cavern volume and pressure management, and leak detection systems.

Regarding maintenance, it states that the safe and efficient functioning of the storage facility depends on regular maintenance activities. The standard recommends monitoring the wellbore integrity and surface equipment to detect and correct defects. The frequency of inspections and maintenance should depend on the operational usage of the facility. Finally, the chapter on abandonment recommends a careful and thorough abandonment procedure to avoid any risks to the environment, the safety of facilities, and public safety. It requires a pollution risk assessment, equipment removal, and permanent cavern sealing.

In conclusion, EN 1918-3:2016 provides practical recommendations for managing the design, construction, operation, maintenance, and abandonment of solution-mined salt caverns used for underground gas storage. However, it does not cover the specific characteristics of hydrogen. The recommendations stipulate compliance with local regulations, safety measures, and environmental impact assessments. It guides operators with a best-practice approach to managing risks and ensuring the safety of facilities and the public.

2.1 Regulation in France

2.1.1 Legislation applicable to underground hydrogen storage in a mining title context

Since the publication of Ordinance No. 2021-167 of 17 February 2021 [9] relating to hydrogen, the underground storage of hydrogen is governed by the Mining Code (Book II) [10] regardless of its origin (fossil, renewable or low carbon) or its use (chemical industry, mobility, injection into the gas network, etc.). As such, the research, creation, testing, development, and operation of an underground hydrogen storage facility requires the procurement of a mining title (an exclusive permit for exploration or exploitation concession) according to the procedures defined in the Mining Code (Book II – Titles II to IV) and specified in Decree No. 2006-648 of 2 June 2006 [11] relating to mining titles and underground storage titles. Nevertheless, the ordinance of 17 February 2021 stipulates in its article 6 that “the holder of a combustible or natural gas storage concession is exempt from the obligation to obtain a new mining title for the storage of hydrogen, as long as the geological formations in which the storage of hydrogen is envisaged are included in the perimeter(s) covered by the title already in his/her possession”. Finally, the circular of May 10, 2010, provides a list of mitigation measures which, if they are respected, enables to exclude the scenarios of ground movement and gas rising through the soil in the the detailed risk assessment.

2.1.2 Legislation applying to underground storage sites in the context of environmental authorization

Once the mining title is granted for the underground storage of hydrogen (or in the context of an existing concession if it is exempt according to article 6 No. 2 of the ordinance of 17 February 2021), the project promoter must obtain authorization for the implementation of underground storage works (research, creation, testing, development, or operation). Three scenarios can then arise:

- Exploration works are planned for a new site and will involve a quantity of hydrogen that is less than 100 kg, which is the ICPE (Installation Classified for the Protection of the Environment) classification threshold under section 4715 [12]; this is the case for drilling, creation or development of the caverns, or tests that involve small amounts of hydrogen; these works are governed the Mining Code and must comply with Title VI of Book II of the Mining Code, decree no. 2006-649 of 2 June 2006 [13] relating to mining works, underground storage works and the policing of mines and underground storage, the decree no. 2016-1303 of 4 October 2016 [14] relating to research work by drilling and well exploitation of mining substances (known as the "drilling" decree), and the ministerial order of 14 October 2016 [15] relating to research work by drilling and well exploitation of mining substances (known as the "drilling" order);

- Exploration works are planned for a new site and will involve a quantity of hydrogen that is greater than the ICPE classification threshold under section 4715 (i.e., 100 kg) are undertaken within an existing underground storage; in this case:

- if they are undertaken on a new site, they pertain to the ICPE regulations under the declaration regime (if the quantity of hydrogen is between 100 kg and 1 ton) or the authorization regime (if the quantity of hydrogen is greater than 1 ton, with a low SEVESO threshold of 5 tons and a high SEVESO threshold of 50 tons).

- if they are undertaken within existing an underground storage, they must be treated as a modification of the existing ICPE; the nature of the modifications made, as well as a presentation of the associated stakes, risks, and inconveniences, must be brought to the attention of the Prefect; the Prefect then judges the nature of these modifications, according to the criteria set out in article R.181-46 of the Environment code [16], and decides on the administrative follow-up to be given: if the modifications are deemed to be substantial, it will be necessary to file a new application for environmental authorization. Otherwise, an update of the requirements applicable to the site by a complementary or amending prefectural decree will suffice.

- Underground storage operation works (first filling of the cavern, injection/withdrawal operations, maintenance, and monitoring of the facilities) are planned; according to the provisions of the Seveso III Directive [17], the operation of hydrogen storage is covered by ICPE legislation under section 4715. The Environment code, therefore, governs it (Book V – Title 1).

Given the quantities of hydrogen expected in future underground hydrogen storage sites, these will most likely fall under the SEVESO high-tier authorization regime. In this case, any modification made (creation of a new cavern, drilling of a new well, etc.) as well as the final abandonment of the storage site will be governed by the ICPE regulations and not the mining code.

2.2 Regulation in Germany

The national legislation regarding the use of hydrogen as an energy carrier is the Energy Industry Act or *Energiewirtschaftsgesetz* [18]. The Federal Mining Act or *Bundesberggesetz* [19] is not specific to hydrogen but provides the legal framework for all underground activities, including hydrogen storage and federal state-specific ordinances (e.g., BVOT [20] for Lower Saxony), all not specific to hydrogen.

The need for further development is commonly accepted, and an adaption of the existing hydrocarbon-focused legal framework is expected. The underground storage is already regulated but not concerned with hydrogen.

Regarding the specific permission process for the underground storage of hydrogen, the process is oriented towards existing legal prescriptions, i.e., mining activities such as the building and operation of underground storages require an approved mining operational plan based on the *BBergG* (*Bundesberggesetz*/Federal Mining Act) [21]:

- Above-ground facilities only: Thresholds according to the 12st part of the Federal Immission Control Act *BImSchV* covers the control of Major Accident Hazar (*Störfallverordnung*) [22] for hydrogen are 5 tons and 50 tons:
    - specific operational plans with public involvement and enhanced safety reports are required (thresholds for natural gas: 50 tons and 200 tons)
- Underground storages: At present, there are no specific thresholds for underground hydrogen storages concerning the necessity of a UVP *Umweltverträglichkeitsprüfung* /Environmental Impact Assessment) [23]; (capacity thresholds for natural gas: $\geq$ 1 billion m^3:
    - Requirement of a <u>general</u> preliminary UPV, for over or equal 100 million m^3 a <u>site-specific</u> preliminary UVP, is necessary for less than 100 million m^3 no site-specific UVP is required, (basically lower thresholds are expected for hydrogen).

The existing framework for natural gas is to be applied to H_2 applications (in the analogy). Each environmental impact application must be assessed according to technological standards. The following tests must be carried out before commissioning and during underground hydrogen storage:

- Wellhead tightness test (with N_2 or H_2). According to DIN-EN1918 (N_2 is currently accepted for natural gas storage, but for hydrogen storage test medium (gas/liquid) is not clear yet).
- Casing and cement sheath tightness tests (with N_2 or H_2). According to DIN-EN1918 (N_2 is currently accepted for natural gas storage, but for hydrogen storage test medium is not clear yet).
- Gas completion tightness test (if any) (with N_2 or H_2). According to DIN-EN1918 (N_2 is currently accepted for natural gas storage, but for hydrogen storage test medium is not clear yet)
- Cavern stability and convergence. Rock mechanical assessment is required for the approval process, and regular monitoring with surface levelling and repeated sonar surveys are expected as for natural gas storage.

2.3 Regulation in Great Britain

Great Britain is the only country in this study with an existing underground hydrogen storage cavern(s) in Teesside that has been in operation since the 1970s. From this experience, the use of hydrogen is included mainly in the following three pieces of legislation:

Land use planning and hazardous substance consent legislation

- Planning Act [24]
- Environmental Impact Assessment [25]
- Town and Country Planning Act [26]
- The Planning (Hazardous Substances) Regulations [27]

Control of Major Accident Hazards

- Control of Major Accident Hazards (COMAH) Regulations [28]

Borehole safety

- Borehole Sites and Operations Regulations [29]

Other legislation that must be respected includes:

- 1986 Gas Act [30]
- The Offshore Installations and Wells (Design and Construction, etc.) Regulations (Note this also applies to onshore wells) [31]
- Gas Safety (Management) Regulations [32]
- Pressure Equipment (Safety) Regulations [33]
- The Dangerous Substances and Explosive Atmospheres Regulations [34]

For more information, the following regulations can apply once outside of the cavern and wellhead:

- Pipeline Safety Regulations [35]
- Carriage of Dangerous Goods [36]

There is no specific permission process for underground hydrogen storage, but the existing procedures would be followed. A valuable introduction to Consent and Operational Issues for Natural Gas Storage was made by the Health and Safety Executive (HSE) [37]. The requirements of the following legislation must be met to store hydrogen in underground salt caverns: The Planning (Hazardous Substances) Regulations [38]**.** The threshold for Hazardous Substances for hydrogen is two metric tons.
Establishments wishing to hold stock of certain hazardous substances above a threshold must apply to the Hazardous Substances Authority (HSA) (usually the local planning authority) for the consent of dangerous substances. Information such as the stored inventory (mass and composition), pressure, temperature, and pipe network configuration (length and diameters) are defined. Using this information, the HSA, in consultation with the HSE, determines hazard ranges that occur in the event of hydrogen release. The acceptability of the hazard ranges to occupants and users of the surrounding land informs the planning decision on whether to allow the storage facility to proceed. The principal health and safety legislation covering natural gas storage establishments (which would equally apply to hydrogen) is the Control of Major Accident Hazards (COMAH) Regulations [39]. The threshold for COMAH is five metric tons (lower tier COMAH installation) and 50 tons (upper tier COMAH installation). The operator must demonstrate that the installation risk (including but not limited to underground storage) is 'as low as reasonably practicable' (ALARP). The operator writes pre-construction and pre-operation COMAH Safety Reports for review by the HSE. HSE wells Inspectors will assess information regarding 'downhole' safety included in COMAH safety reports. Where salt caverns for natural gas storage are concerned, the HSE expect that the European Standard BS EN 1918-3:2016, Part 3 (Functional recommendations for storage in solution-mined salt caverns) and Part 5 (Functional recommendations for surface facilities), will be adopted. COMAH would also apply to the underground storage of hydrogen in depleted reservoirs. Guidance to the application of the Control of Major Accident Hazards Regulations 1999 (COMAH) and the Pipelines Safety Regulations 1996 (PSR) for the storage of natural gas at the depleted reservoir and salt cavern site is provided by the HSE [40].

The Borehole Sites and Operations Regulations (BSOR) [41] will apply from the beginning of operations on the site. They will remain in effect during the establishment until the borehole is abandoned. Onshore, BSOR requires an operator to prepare a health and safety document before starting borehole operations. The health and safety document identifies risks associated with operations and details plans for dealing with and managing these risks.

3.0 DISCUSSION

To adapt existing standards and regulations established for the use of natural gas or liquified petroleum gas, it is necessary to highlight the differences between hydrogen and those conventional energies:

Related to the wide flammability range from 4 – 75 vol% at ambient pressure and temperature, hydrogen is classified as an "extremely flammable" gas according to the CLP regulation (EC) No 1272/2008 of 16 December 2008 [42]. Methane (main content in natural gas) is classified "flammable" gas.

Hydrogen ignites very quickly when it is close to stoichiometric conditions where a Minimum Ignition Energy (MIE) in the air of only 17 µJ [43] is found. For comparison, an electrostatic discharge just felt by a person is around 1,000 µJ - the MIE decrease in pure oxygen to 1.2µJ [44]; and 300 µJ [45] for methane.

This characteristic reflects the gas class IIC for equipment used in potentially explosive atmospheres (ATEX) according to the EU legislation Directive 2014/34/EU [46].

The Burning Velocity (BV) of hydrogen in air at stoichiometric ambient conditions is 2.37 m/s [47] and can even increase to 3.5 m/s at a concentration of 40.1% [48]. Related to its fast chemical kinetics and high diffusivity, the BV is higher than that of other hydrocarbon fuel-air mixtures and results in a greater chance for a transition of the combustion mode from deflagration to detonation.

Due to the smallness of its molecule, hydrogen leaks are more likely than with other flammable gases and, related to its low viscosity at the same leak conditions, the volume flow rate is nearly three times higher compared to, for example, natural gas [49].

At ambient conditions, hydrogen is about eight times lighter than natural gas and 14 times lighter than air. Thus, released in an open environment, it will typically rise and disperse rapidly which is a safety advantage in an outside environment, e.g., for a subsonic or vertical-orientated leak. However, for a confined space it must be carefully considered with a pertinent leak detection system and ventilation assuring sufficient air dilution at the leak source.

A jet fire of hydrogen generates a pale blue flame that is almost invisible during daylight. However, its visibility can be increased if the presence of particles entrained in the flame (dust, etc.). In the air, a premixed stoichiometric mixture can rise to a flame temperature of 2,403 K [50] while it is 2,236 K [51] with methane.

The dominant energy emission of hydrogen occurs in the mid-infrared, where the peak irradiance is more than 1,000 times greater than the peak measured in the ultraviolet [52].

According to different experiences with hydrogen at concentrations below 10% vol. in air [53], the explosion resembles a flash fire with nearly no pressure rises. At higher concentrations, deflagration is observed where the flame speed is subsonic, and the maximum pressure peak is reached at 8 bars in air and 10 bars in pure oxygen [54]. Detonation occurs when the flame speed becomes supersonic. Detonation can be observed at ranges over 12.5% vol. of hydrogen where higher explosion pressures are possible depending on concentration and turbulence conditions in the environment. The most violent reaction occurs when hydrogen is near its stoichiometric concentration of 29.5% vol. in air. Although detonation can also happen with methane, the range is limited in volume fraction from 5.3 to about 15.5% [55].

Various embrittlement mechanisms are possible with hydrogen depending on the metal selection (Metal hydride formation, hydrogen-induced cracking, hydrogen-induced blistering…) but also related to the process parameter, like temperature and pressure, so that the choice of the metal for use with hydrogen is a point of vigilance regarding the design. Metal embrittlement does not occur with methane.

Beside all these parameters, that must be considered regarding the risk analysis necessary to establish adapted standards and regulations for hydrogen storage to identify new potential hazards and mitigate these risks, the working group safety and regulation in the HYPSTER project formulized the following recommendations regarding the deployment of geological storage of hydrogen in salt caverns:

1. Conduct thorough risk assessments: Before constructing and operating salt caverns for hydrogen storage, it is essential to conduct thorough risk assessments, including the specific characteristics of hydrogen, to identify new potential hazards and mitigate risks. Risk assessments should include geological surveys, structural assessments of the caverns, and evaluations of potential impacts on the environment and nearby communities.

2. Safety Standards: There should be specific safety standards for underground hydrogen storage facilities. These standards should include guidelines for the design and construction of caverns and the equipment and processes used in storing and extracting hydrogen. The standards should be regularly updated to reflect technological advancements and evolving safety risks.

3. Develop comprehensive safety regulations: To ensure the safety of hydrogen storage in salt caverns, it is essential to develop comprehensive safety regulations. These regulations should include guidelines for constructing, operating, and maintaining salt caverns used for hydrogen storage. The regulations should also cover safety protocols in emergencies such as leaks, explosions, or fires.

4. Monitoring and Emergency Response: The facility should have a monitoring system to detect leaks or other potential hazards. Additionally, an emergency response plan should be in place to address any incidents or accidents that may occur.

5. Establish clear liability and insurance policies: Clear liability and insurance policies should be established to ensure that any damages caused by accidents or incidents are adequately compensated. Liability and insurance policies should cover all aspects of hydrogen storage, including transportation, storage, and distribution.

6. Stakeholder Engagement: Local communities and other stakeholders should be involved in the development of the facility from the early stages of planning. Engagement should include open dialogue, consultation, and transparent communication about potential risks and benefits associated with the facility.

7. Address public concerns: The development of underground hydrogen storage in salt caverns may raise concerns among the public regarding the safety and environmental impacts. It is essential to address these concerns and engage with stakeholders to build trust and support for the development of hydrogen storage.

8. Financial incentives: Governments could provide financial incentives for developing hydrogen storage facilities, including tax credits, grants, and subsidies. The legal framework should address liability and compensation in case of accidents, the rights of local communities and the operator's responsibilities.

9. International Cooperation: Given the potential cross-border impacts of underground hydrogen storage facilities, there should be international cooperation among neighboring countries to ensure a consistent regulatory approach, safety standards, and monitoring protocols.

4.0 CONCLUSION

Regarding the regulatory frameworks in France, Germany, and Great Britain it can be highlighted that:

In France, the regulatory framework for hydrogen storage in salt caverns is governed by the Mining Code and the Environmental Code.

- The process involves obtaining a mining title through the Mining Code, which includes a specific procedure for granting concessions for hydrogen storage projects.
- Environmental authorization is required, emphasizing the need for an environmental impact assessment and measures to mitigate potential risks.
- The French regulations emphasize risk assessment, emergency plans, and monitoring systems to ensure the safe operation of salt cavern storage facilities.

In Germany, the regulatory framework for hydrogen storage in salt caverns is based on the Federal Mining Act and state-specific ordinances.

- The existing legal provisions are adapted for hydrogen storage, as there are no specific thresholds or regulations dedicated solely to hydrogen storage in salt caverns.
- The Federal Mining Authority oversees the process and ensures compliance with safety and technical standards.
- Risk assessments and safety measures are crucial in the planning and operation of salt cavern storage projects.

In Great Britain, the regulatory framework for hydrogen storage in salt caverns involves several existing legislations related to land use planning, hazardous substances, and major accident hazard control.

- Consent for dangerous substances, such as hydrogen, is required under the Control of Major Accident Hazards (COMAH) Regulations.
- The Health and Safety Executive (HSE) oversees safety measures and risk assessments for salt cavern storage projects.
- Borehole safety regulations are also relevant to ensure the integrity of the caverns and prevent any leakage or accidents.

While the French regulations emphasize obtaining mining titles and environmental authorization, Germany adapts its existing legal framework, and Great Britain incorporates multiple legislations to ensure safety and risk management. Each country's regulatory approach reflects its unique legal system and priorities for hydrogen storage in salt caverns.

Underground hydrogen storage in salt caverns has the potential to play a significant role in European energy transition towards a decarbonized energy system. However, as with any new technology, it is essential to carefully assess its potential risks and benefits to ensure that it can be safely and effectively deployed at scale. Although salt caverns have been operating for a long time, little information is available regarding subsurface equipment design and material selection versus the specific issues to be addressed with hydrogen and lessons learned. Currently, there is no specific standard or regulation for underground hydrogen storage in salt caverns in Europe.

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