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TNO report

TNO2020 R12005

Inventory of risks associated with underground storage of compressed air (CAES) and hydrogen (UHS), and qualitative comparison of risks of UHS vs. underground storage of natural gas (UGS)

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Copy no	
No. of copies	
Number of pages	47 (incl. appendices)
Number of appendices	2
Sponsor	NAM, Gasunie, Gasterra, Nouryon, EBN, Rijksdienst voor Ondernemend Nederland (RVO)
Project name	Large-Scale Energy Storage in Salt Caverns and Depleted Gas Fields (Acronym: LSES)
Project number	060.36821, subsidy reference: TGEO118002

Preface

This report details the results of the activities performed in work package 4 of the research project "Large-Scale Energy Storage in Salt Caverns and Depleted Gas Fields", abbreviated as LSES. The project, which was given subsidy by RVO, had two main goals:

1. Improve insights into the role that large-scale subsurface energy storage options can play in providing flexibility to the current and future transitioning energy system;
2. Address techno-economic challenges, identify societal and regulatory barriers to deployment, and assess risks associated with selected large-scale subsurface energy storage technologies, in particular compressed-air energy storage (CAES) and Underground Hydrogen Storage (UHS).

The research was carried out by TNO in close collaboration with project partners EBN, Gasunie, Gasterra, NAM and Nouryon. Activities were divided over 4 work packages that ran in parallel:

1. Analysis of the role of large-scale storage in the future energy system: what will be the demand for large-scale storage, when in time will it arise, and where geographically in our energy system will it be needed?
2. Techno-economic modelling (performance, cost, economics) of large-scale energy storage systems, focusing in CAES and UHS in salt caverns, and UHS in depleted gasfields - analogous to UGS (Underground natural Gas Storage).
3. Assessment of the current policy and regulatory frameworks and how they limit or support the deployment of large-scale energy storage, and stakeholder perception regarding energy storage.
4. Risk identification and screening for the selected large-scale subsurface energy storage technologies.

In this report, the results of the activities performed in work package 4 on risks associated with CAES and UHS are detailed.
The results of the other work packages are detailed in three other reports.

Project details

Subsidy reference:	TGEO118002
Project name:	Large-Scale Energy Storage in Salt Caverns and Depleted Gas Fields
Project period:	April 16, 2019 until August 30, 2020
Project participants:	TNO (executive organization), EBN, Gasunie, Gasterra, NAM and Nouryon

Acknowledgements

All project partners (EBN, NAM, Gasunie, GasTerra, and Nouryon) are thanked for their reviews of the final draft of this report.

Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken en Klimaat, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.

Summary

Energy storage can play a pivotal role in the energy transition by adding flexibility to the sustainable energy system. Large-scale storage of energy underground, in salt caverns, depleted gas fields and (potentially) aquifers, is an attractive option to store large amounts of energy, and can help to secure supply in prolonged periods of several days to more than a week with calm winds and no or little sunshine.

However, the use of the subsurface for energy storage may introduce risks that can negatively impact health, safety and environment, system integrity, economics and the public perception towards this technology. The risks associated with Underground natural Gas Storage (UGS) in the subsurface are well-known from decades of experience. However, the risks associated with Underground Hydrogen Storage (UHS) and Compressed Air Energy Storage (CAES) are relatively underexplored.

In this study the potential risks associated with UHS and CAES in salt caverns, and UHS in depleted gas fields (porous reservoirs) were inventoried, and possible mitigation measures were explored. Risks were inventoried by conducting a literature review, and supplemented with expert knowledge. All risks were included in a risk inventory that categorizes the risks into their relevant project phase, system component, reservoir storage type and TEECOPS[1] category. In total, 159 risks were derived from 40 references, of which about half (75) pertain to operating the storage facility. The purpose of the risk inventory is to serve as a starting point and checklist to identify and manage risks in development projects, and to provide guidance on potential mitigation measures to reduce the risks.

In order to improve our understanding of the significance of the risks associated with underground hydrogen storage (UHS), a selection of six key risk themes associated with storage of hydrogen was made: material integrity/durability, leakage of hydrogen, blow-out, diffusion and dissolution, loss and/or contamination of hydrogen, and ground motion (subsidence, induced seismicity). A qualitative non site-specific comparison was made for these risk themes between UHS and underground storage of natural gas (UGS, with methane as a proxy for natural gas), primarily based on differences in gas properties. Overall aim of this comparison was to leverage the experience from UGS to provide useful information to better understand and reduce risks and consequences, increase control and inform stakeholders. Although in general, UGS and UHS have a similar risk profile, there are also differences that were highlighted in this study:

- Hydrogen has a much wider flammability range and a much lower ignition energy compared to methane, and is therefore more prone to ignite when released in air. Hydrogen is therefore classified as a high reactive[2] gas, while methane is classified as a low reactive gas. On ignition methane radiates heat and creates a flame that is clearly visible. Ignited hydrogen on the other hand radiates little (infrared) heat (IR), but emits substantial UV (ultraviolet) radiation. The lack of IR gives little sensation of heat but the exposure to a hydrogen flame still causes severe burns because of the UV radiation. Because a burning hydrogen flame is

[1] TEECOPS: technical, economic, environmental, commercial, organisational, political and societal
[2] “Reactive” here refers to the ability to ignite

also not easily detectable (contrary to methane), it increases the risks associated with hydrogen when it ignites to form a flame. Detection sensors validated for hydrogen should be used to detect possible hydrogen releases.

- In case of leakage of hydrogen or methane in confined spaces, where leakages can remain undetected, or in case of large volume releases (e.g. a blow-out, see below) there is an elevated risk of explosion for both hydrogen and methane, however, the effects of a hydrogen explosion are different compared to methane. When a mixture of hydrogen and air explodes, the higher flame propagation speed potentially generates high pressures that could result in an explosion (a pressure shock wave) with massive burst damage, i.e., damage to buildings or even collapse. In contrast, when a mixture of methane and air explodes, the potential for burst damage is lower, but the longer duration of the flame, in combination with the heat that it radiates, can potentially lead to lasting harm. In the absence of confinement and congestion though, no overpressures are generated, and the consequence of an explosion is limited to a flash fire.

- A catastrophic event on the wellpad (e.g. an accident with a heavy truck, or a dropped object) could lead to complete or partial removal of the wellhead and/or Xmas tree with all valves, which could lead to uncontrolled outflow of gas (also referred to as a blow-out). When ignited, both hydrogen and methane will form a jet flame (flare), but the hydrogen flame is expected to be narrower and reach higher, which together with the lower energy content, likely reduces the effect of heat radiation. A properly installed and operationally tested SSSV[3], which is mandatory for gas (production and) storage wells, must prevent significant outflow in case of such catastrophic event. Although SSSV's are extensively used in oil and gas industry, their effectiveness in shutting in a flowing hydrogen storage well is yet to be confirmed.

- Contrary to methane, which is an inert gas, hydrogen is a reactive gas[4]. It can potentially react with rocks and reservoir fluids and may interact with microbes in the reservoir. This might affect reservoir performance (e.g. by pore clogging due to precipitation of minerals or rapid bacterial growth in the near-wellbore region) and/or could result in loss of hydrogen and/or contamination of the production stream due to the formation of H_2S, a toxic, corrosive gas that degrades wellbore materials and poses a threat to human health when released to the atmosphere.

Although the risks associated with UHS are generally known, further research is required in particular on a) the long-term durability of rocks and (well) materials (steel alloys, cement, elastomers, etc.) when subjected to hydrogen under an alternating pressure regime that causes mechanical and thermal stresses, and b) interactions of hydrogen with rocks, fluids and microbes in reservoirs and their effects on reservoir performance, quality and retrievability of the stored hydrogen, and integrity and durability of materials subjected to products of such interactions (e.g. H_2S).

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[3] SSSV: subsurface safety valve
[4] "Reactive" here refers to the ability to react with other chemicals (in the reservoir and/or casing)

Contents

1 Introduction

Energy storage can play a pivotal role in the energy transition by adding flexibility to the sustainable energy system. Storage of energy needs to be deployed at both small-scale (low power and fast response solutions) and large-scale (longer-term balancing for grids). While batteries are ideally suited to store and deliver energy with fast response for a short period, they are not capable of storing the large amounts of energy that must be supplemented to secure supply in prolonged periods of several days to more than a week with calm winds and no or little sunshine. At this timescale, large-scale storage of energy underground, in salt caverns, depleted gas fields and aquifers, is an attractive option. Underground energy storage provides flexible bulk power and energy management and offers essential services to society in the form of strategic energy reserves and balancing solutions for unavoidable seasonal variations.

The use of the subsurface for energy storage however may introduce risks that can negatively impact health, safety and environment, system integrity, economics and the public perception towards this technology (Evans, 2008). Risks associated with natural gas storage are well-known from decades of operational experience (CMEO, 1993; Pudlo et al., 2013). In contrast, the risks associated with Underground Hydrogen Storage (UHS) and Compressed Air Energy Storage (CAES) are relatively underexplored. In this study we identified potential risks and mitigation measures associated with CAES in salt caverns, and UHS in salt caverns and depleted gas fields (phase 1), and qualitatively compared selected key technical risks of UHS with Underground (natural) Gas Storage (UGS; phase 2).

In the first phase a literature review was conducted to inventory risks associated with hydrogen storage and CAES, and identify potential mitigations to reduce risks. Risks were included in an Excel-based risk inventory, categorized by project phase, system component, reservoir type, and classified according to the TEECOPS criteria (i.e. technical, economic, environmental, commercial, organisational, political and societal). The purpose of the risk register is to serve as a starting point and/or checklist to identify and manage risks in underground energy storage projects, and to provide guidance on potential mitigation measures to reduce the risks.

In the second phase, a qualitative non site-specific comparison between natural gas storage and hydrogen storage was performed for a selection of key risks. The selection was made by careful evaluation of the risks and mitigation measures in the risk inventory, supplemented with expert judgement. This comparison is deemed valid because UHS essentially uses the same technology as UGS. UGS has been done for many decades and the risks are well-understood. As such, it can serve as a point of reference for assessing the risk associated with UHS.

2 Risk Inventory

A risk inventory was created in Excel, which lists the risks and ways to mitigate them. The aim of the Risk Inventory (RI) is to serve as an instrument to: 1) visualize and increase awareness of important risks, and 2) indicate the impact of mitigations relevant for communication and/or permitting. It is a structured template, which is self-explanatory, has a clear scope and boundaries, and has the possibility to filter risks on relevance. Each risk is categorized by system component it pertains to, and project phase where the risk is present, and to classified into the TEECOPS[1] criteria. The Risk Inventory can be found in Appendix 1 – Risk Inventory and can be shared on request.

Literature survey

The RI was compiled from risks found in literature, and supplemented by internal TNO expertise and expertise from partners in the LSES consortium. Risks were ordered by system component to which the risk pertains, project phase during which the risk is present, classified according to the TEECOPS criteria and incorporated in the RI template. An important step was cleaning up the inventory by regrouping, merging and deleting risks. Ultimately, this resulted in an RI with 159 risks associated with UHS and/or CAES. Furthermore, the RI template also allows for a first qualitative ranking of the risks, based on their consequence and probability rating.

Inventory structure

The RI template allows to filter by project phase, system component and TEECOPS criteria, which makes it an efficient template for the determination of specific risks within different fields of interest.

The risks in the RI are categorized in five project phases (Figure 1) and one general category for risks that apply to all (or the majority of the) phases:

- Pre-execution phase: the phase during which all work is done in preparation for the execution phase, including analysis, design, permitting, stakeholder engagement and contracting;
- Execution phase: the phase during which the facility is constructed /adapted;
- Operational phase: the phase during which the storage operations take place, i.e., the charging and discharging of energy in the form of compressed air or hydrogen;
- Decommissioning phase: this phase includes all activities required to abandon wells, remove surface facilities and clear the site for future use;
- Post-abandonment phase: the phase after decommissioning, during which the abandoned site is monitored for early detection of failure of barriers that might lead to the occurrence of a potentially harmful event with negative consequences;
- All phases: risks that apply to all (or most) of the above defined project phases.

Of the 159 risks, 17 are categorized as being relevant during the pre-execution phase, 32 as relevant during the execute phase, 75 as relevant during the operational phase, 21 as relevant during the decommissioning phase, and 12 as relevant during the post-abandonment phase

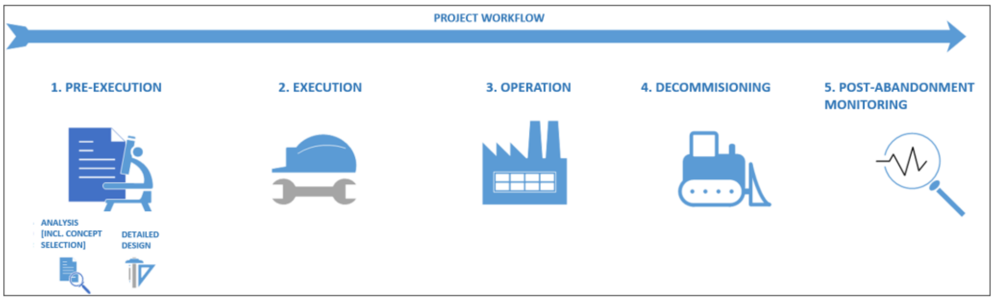

Figure 1 The structure of the Risk Inventory in Appendix 1 is composed of five project phases, which are consistent with the typical project workflow.

Additionally, the risks are categorized into the three main (groups of) components of an underground energy storage system they can pertain to:

1) “Surface Facilities” group: includes compressors, piping, instrumentation, process facilities;
2) “Well” group: includes the X-mas tree, wellhead, well (completion and cemented casings), sand-face completion;
3) “Subsurface” group (storage reservoir): includes the target storage reservoir, the caprock and overburden.

A “General” component group is included, for risks that pertain to all (or multiple) of the system components. An unfilled section for project specific risks is also present in the template. In this section risks that are project specific and probably not relevant for (most) other projects can be noted.

Finally, individual risks have been classified into the TEECOPS criteria (based on the Peterhead CCS project, 2016):

- Technical: (Sub)surface, Infrastructure, Technology, Operability, Availability, Integrity, Sustainability, Maintenance
- Economical: Life-Cycle Cost, Phasing, Valuation method, Capacity, Economic model, Regret costs
- Environmental: Surface exposure, Subsurface environment
- Commercial: Contracting & Procurement, Financing, Business controls, Legal, Terms & Conditions, Competition, Marketing, Liabilities, Collaboration Agreement
- Organizational: Structure, Resources, Procedures, Project Controls, Knowledge Management, Systems & IT, Interfaces, Partners, Governance
- Political: Government, Stakeholders, Employment, Regulation, Security, Reputation, NGOs, Export Control, Localization
- Societal: Community, Public opinion, Social License to Operate

Application
A similar RI was made for the purpose of High Temperature - Aquifer Thermal Energy Storage (HT-ATES) in the context of the HEATSTORE[5] project (Van Unen et al., 2020). In order to test the robustness and added value of the RI the template was used in the preparatory study of the HT-ATES demonstration in Middenmeer in The Netherlands. Prior to the workshop experts were asked to select (but not rank) the most important risks for each system component from the RI. The participants could

[5] https://www.heatstore.eu/

provide their input through a questionnaire (Mentimeter). TNO assessed the expert input and selected the 10 most relevant risks (or risk themes), which were then discussed in more detail and ranked in a dedicated workshop. For the ranking of the risks the consequence – probability matrices from DAGO (DAGO, 2019) were used (Appendix 2). For a full explanation of this workflow, the reader is referred to van Unen et al., 2020. The application of the RI in the Middenmeer study was received very positively by the participants. A similar application process is suggested here to select the most relevant risks for CAES and UHS and rank them in a risk matrix, as a precursor to e.g. a more detailed bowtie analysis of causes and consequences of specific undesired events.

3 Qualitative risk comparison - UHS vs. UGS

The qualitative risk assessment presented in this section focuses on hydrogen storage in salt caverns and depleted fields. This is done by taking Underground Gas Storage (UGS) as reference and extrapolating selected risks or risk themes from UGS to Underground Hydrogen Storage (UHS). In the Netherlands, there are four UGS facilities where natural gas is stored in depleted fields (Grijpskerk, Norg, Alkmaar and Bergermeer) and one facility that stores natural gas in salt caverns (Zuidwending). From the literature study and with the help of relevant experts and the consortium partners, six high-level risk themes were selected for which to analyze the risks and compare them to natural gas:

1. Material integrity/durability
2. Leakage (above ground and below ground)
3. Blow-out (uncontrolled flee outflow at the wellhead)
4. Diffusion and dissolution
5. Loss/contamination of production stream
6. Ground motion: subsidence and induced seismicity

3.1 Gas properties

The difference in gas properties between methane and hydrogen forms the basis of the comparison. Natural gas can be produced in many qualities and the composition varies per field. The main constituent of natural gas is methane (70-90%). To reduce complexity pure methane was assumed as representative gas for natural gas. Table 1 (next page) highlights the main properties of methane and hydrogen.

3.2 Qualitative comparison of selected risks for H_2-storage vs. CH_4-storage

Risks associated with natural gas storage are well understood from decades of (industrial) experience with natural gas production and storage. This knowledge and expertise will serve as a point of reference for assessing the risks associated with underground hydrogen storage, which will be presented in the following sub-sections for the six risk themes. Evans (2008) suggests that it is important to determine potential points of failure in an underground gas storage system as these could harm health, environmental, and economic aspects. By identifying potential points of failure, putting in place barriers and measures to monitor them, and mitigating the consequences when failure occurs, the impact to health, safety and environment can be minimized.

3.2.1 Risk theme 1: Material integrity and durability

The chemical properties of methane and hydrogen are different (see Table 1) and this could affect the integrity and durability of the materials that are commonly used for underground storage. In the next subsections, the comparison of the effects of hydrogen on materials vs. natural gas is split into materials used in pipelines and surface facilities and well materials because of their difference in characteristics and technological readiness.

Table 1: Gas properties of methane and gaseous hydrogen (H2Tools, 2020; Hyde & Ellis, 2019; Klebanoff et al., 2016; Uehera, 2013; Maytal & Pfotenhauer J.M., 2013).

Property	**Methane (CH_4)**	**Hydrogen (H_2)**
Molecular weight [g/mol]	16.0	2.02
Kinetic Diameter (Å)	3.8	2.89
Diffusion coefficient in air at (NTP[6]) [cm^2/s]	0.16	0.61
Normal boiling point[7] (NBP) [°C], 1 atm	-162	-253
Solubility in water [mg/ml]	0.022	0.0016
Viscosity at NTP [g/(cm·s)]	1.10 E-4	8.81 E-5
Physical state at NTP	Gas	Gas
Normal density at NTP [kg/m^3]	0.668	0.0838
Explosive limits in air [vol%]	6.3 – 13.5	18.3 – 59.0
Minimum spontaneous ignition pressure [bar]	100	41
Heating Values (energy density)[8] at 0 °C, 1 bar LHV - HHV [kJ/g]	50 - 55.5	120 - 142
Flammability range in air [vol%] (LEL & UEL)	5.3 - 15	4.0 - 75
Burning velocity at NTP in air [m/s]	0.37 – 0.45	2.6 – 3.2
Flame temperature in air[9] [°C]	1875	2045
Max. laminar flame speed gas/air mixture [m/s]	0.374	2.933
Minimum ignition energy at NTP [mJ]	0.29	0.02
Flash point [°C]	-188	<-253
Auto ignition temperature in air [°C]	540	585
Thermal conductivity at NTP [W/(m·°C)]	0.0339	0.1825
Quenching distance [mm]	2.0	0.64
Specific volume at NTP [m^3/kg]	1.52	11.94
Enthalpy of vaporization at NTP [J/mole]	8.5	0.92
Energy content per unit mass [MJ/kg]	50.02	119.96
Energy content per unit volume [MJ/L]	21.1	7.9
Vapor specific gravity at 25°C, 1atm (air=1)	0.555	0.0696
Joule-Thomson max. inversion temperature [°C]	736	-72
Wobbe index (interchangeability) [MJ/Nm^3]	47.91-53.28	40.65-48.23
Calorific value (energy of flame) [MJ/m^3]	39.8	12.7

Pipelines and surface facilities

Natural gas storage surface facilities include equipment to compress (compressors, intercoolers) the gas prior to injecting it into the storage reservoir, for cleaning the gas (e.g. Pressure-Swing Adsorbers, Thermal-Swing Adsorbers), and for drying the gas (e.g. glycol-based dryers) upon withdrawal, prior to feeding it back into the grid. Additionally, pipelines are used to transport the gas from production sites to storage and from storage to consumers. DNV-GL (2017) together with GTS (Gasunie Transport Services) assessed the re-use potential of the natural gas transmission and distribution network for hydrogen, and concluded that this is technically feasible, which makes it an attractive option to reduce the costs associated with the integration of hydrogen into our energy system. However, they point out that large and frequent operational pressure variations should be avoided to minimize the risk of crack growth, and that non-metallic (e.g. plastic) parts of valves should be replaced.

[6] Normal Temperature and Pressure (as defined by NIST, USA) = 20°C (68°F) and 1 atm.
[7] The boiling point at 1atm pressure
[8] Heating values are the energy, per gram of fuel, generated by a combustion reaction. Higher heating value (HHV) is obtained when all of the water formed by combustion is liquid. Lower heating value (LHV) is obtained when all of the water formed by combustion is vapor.
[9] Experimentally determined flame temperatures are shown in the table. These values do not differ significantly from theoretical adiabatic flame temperatures

Furthermore, recent studies demonstrated that the durability of metal pipes could degrade when they are exposed to hydrogen over long periods of time, particularly with hydrogen in high concentrations and at high pressures (Melaina et al., 2013), for which the material durability (primarily of pressure regulators and valves) remains to be proven (Weidner et al., 2016). González Díez et al. (2020) investigated the compatibility of hydrogen in mixtures with natural gas, in particular the influence of hydrogen on the fatigue properties of relevant steel grades and the resulting crack propagation. Although they concluded that no significant effects due to hydrogen-enhanced fatigue crack growth are expected for the typical operating conditions and material types (X42-X70) used in pipeline for natural gas, they stress the importance of assessing the current condition of the integrity of the pipelines prior to transporting hydrogen through it.

Surface facilities for hydrogen storage are expected to be very similar to those that are used for UGS. Operating conditions of underground hydrogen storage are also similar to those of natural gas storage. As an industrial gas, hydrogen has been produced (from natural gas, by steam methane reforming), transported (through pipelines), stored (in high pressure cylinders) and used (e.g. in the petrochemical industry) for decades, and the risk and safety aspects are well-known. In fact (as is described in the report of work package 2 of the LSES project), hydrogen storage in salt caverns is already operational at 4 locations in the world, and no safety incidents have been reported. As such, there is confidence in the technology and years of handling hydrogen on an industrial scale have provided the experience to safely operate facilities where hydrogen is produced, stored, or used.

Nonetheless, when using hydrogen in a mix with natural gas in existing equipment such as compressors, care must be taken. Concentrations up to 10%vol of hydrogen have been claimed to be acceptable in existing mechanical compressors without complicating operation and/or degrading performance. However, particular attention must be given to material compatibility and fugitive losses through the seals (González Díez et al., 2020). Furthermore, to compress a (near) pure hydrogen stream with existing (mechanical) compressors such as are currently used will require extensive changes because many more impellors will be required. In fact, to compress a pure hydrogen stream, a reciprocating compressor is a more suitable compressor type than a mechanical compressor. As such, re-use of existing UGS surface facilities for (near) pure hydrogen storage is not straightforward and replacement of existing gas processing units by new ones is likely to be required[10].

<u>Well materials</u>

UGS wells are very similar to gas production wells and use similar materials which are specified by mature standards and guidelines based on decades of experience with production of natural gas. The wells used for hydrogen storage would have to be designed with completion materials that are compatible with hydrogen. Additionally, they would have to be compatible with the products that could be generated from chemical and microbiological reactions with hydrogen during storage operations, e.g. H_2S (see Section 3.2.5). A schematic diagram of a design of a gas (storage) well is shown in Figure 2. One of the well materials that is in direct contact with hydrogen is (alloy) steel. In gas wells the steel (alloy) components of the completion are in direct contact with the storage medium (e.g. inner casing tubing,

[10] Personal communication NAM

production casing / liner, SSSV, packers, etc.), which all need to be hydrogen resistant under a wide range of temperatures (DBI-GUT, 2017). Often recognized processes involving hydrogen that affect the integrity and/or durability of steel alloys are: hydrogen blistering, hydrogen-induced cracking and hydrogen embrittlement (Gilette & Kolpa, 2007; Gonzales-Diez et al., 2020). These processes are influenced by temperature, pressure, hydrogen concentration and stress fields (Reitenbach et al., 2014). Additionally, corrosion could play a role and if that takes place defects can be created on which cracks could develop due to tensile stress build up, which could subsequently result in leakage.

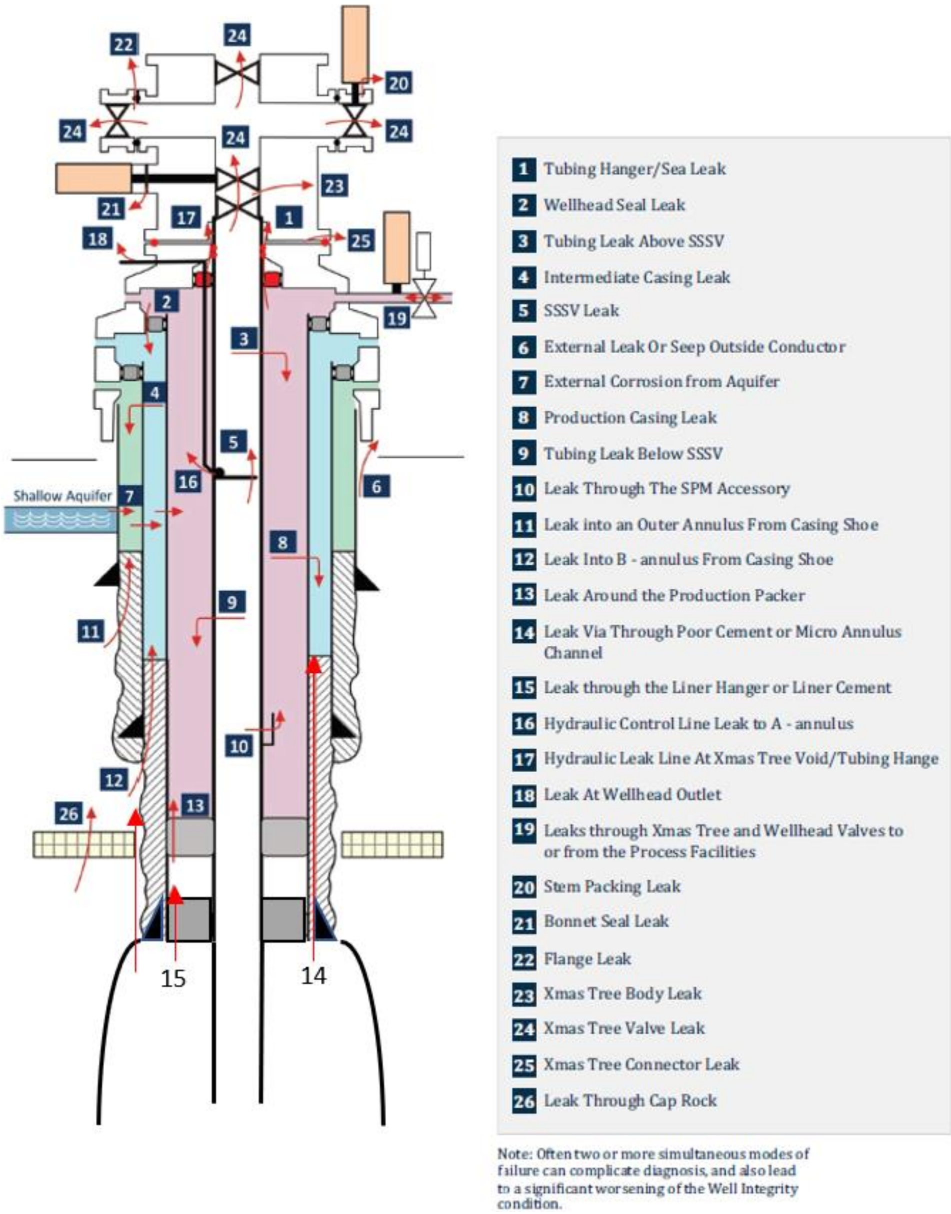

Figure 2: Schematic well installation used for gas wells, representing different failure scenarios of the well (SODM, 2019)

Hydrogen may activate such defects when using the existing UGS infrastructure (Gonzales-Diez et al., 2020). Lastly, hydrogen is expected to be able to flow at higher velocities through the same well, which increases the likelihood of erosion in situations where (solid) particles are present in the production stream. In order to prevent significant erosion of the materials it should be ensured that the flow velocity is always below the erosional velocity specified by the manufacturer, in the industry a velocity of 100 m/s is commonly used (see report of work package 2 of the LSES project).

The second major material used for well construction is cement, which is used to seal off the annulus between the casing and the formation (see Figure 2). In order to prevent migration (or leakage) of gas along the outside of the casing and/or through the cement, it has to be chemically resistant for the stored gas and tight enough to make sure that the gas cannot penetrate through it into the (shallower) rock formations. Therefore, the cementation operations are a critical aspect of the well integrity and specific requirements are stated in the NOGEPA 41 standard on well integrity (NOGEPA OPCOM, 2016). As hydrogen has a smaller size and higher diffusivity compared to methane, the cement must be adjusted in order to prevent migration of the hydrogen through the cement. The risk of chemical alteration of the cement by contact with hydrogen is considered to be low (DBI-GUT, 2017). Lastly, the potential effects of cyclic loading of the well, and especially on the cement, on the integrity (sealing function) of the well have to be taken into account.

The last important material in UGS wells are elastomers, which are used in the packers and fittings. Further investigation on these elastomers must be done in order to define their resistance to the higher diffusivity of hydrogen compared to methane (DBI-GUT, 2017). Penetration of hydrogen through these elements could lead to integrity loss as a result of fast decompression and inner blister fracturing (Reitenbach et al., 2014). It must be noted that during normal operations such sudden decompressions do not take place in gas storage facilities.

Based on the above sections it can be concluded that surface facilities for hydrogen are at similar technology level as for UGS and that they are not expected to increase the risk profile with respect to material integrity and durability. Additionally, re-using the natural gas transmission and distribution network could provide an opportunity to accelerate the implementation of hydrogen at reduced cost, but requires additional research. Lastly, the current state of the art well completion materials for natural gas wells are not confirmed to be fully hydrogen resistant. Therefore, the sealing effectiveness and corrosion resistance of all materials used for the completion (steel alloys, cement, elastomers and seals) have to be subjected to a technical integrity evaluation prior to storing hydrogen using the existing oil and gas infrastructure or well materials.

3.2.2 Risk theme 2: Leakage of hydrogen

Leakage is defined here as the accidental escape of gas out of the facilities. Leakage is one of the most important hazards in any underground storage system and has impact in all of the TEECOPS aspects. Here we focus on causes of potential leakage from the well system and/or the storage reservoir (either a salt cavern or a depleted field), and how these might differ between hydrogen and methane. Surface facilities for hydrogen are advanced and operational and therefor their influence on the risk profile for leakage is expected to be low, therefore these have not been included in the assessment. Furthermore, differences in leakage detection and the potential impact of leakage between hydrogen and methane are discussed. Because of the potential impact of uncontrolled outflow at surface (blow-out), this has been treated as a separate risk theme and will be discussed in Section 3.2.3.

Well leakage

Wells are considered an important and critical component in the infrastructure to produce, store and distribute natural gas. As long as the integrity of the well is not compromised, stored product cannot leak to the environment. UGS wells are constructed to have multiple barriers to prevent leakage, such that when one barrier (e.g. casing section or valve) fails, other barriers are still in place. Figure 2 displays a typical well configuration and the potential failure scenarios (SODM, 2019). The barriers can be divided into primary and secondary barriers. Primary barriers are the production casing, liner and liner cement below the production packer, the production packer, the completion string below the (Surface-controlled) Subsurface Safety Valve (SSSV), and the SSSV itself. The SSSV, which can be controlled from the surface, is a key component of a gas storage well. In case of an unwanted event (e.g. a flowline rupture) the SSSV will be closed to prevent an uncontrolled, prolonged outflow from the well. It is failsafe, i.e., hydraulic pressure is required to force the valve to its open position, and when the pressure in the hydraulic system drops, the valve will automatically return to the closed (safe) position (EnergyStock, 2017).

Secondary barriers are the production casing, liner and liner cement above the production packer, the completion string above the SSSV, the wellhead (incl. casing hanger with seals and wellhead valves), and the production tree (body and master valves). The performance of the well barriers must be verified through appropriate functional testing. Monitoring of the well barrier elements and application of any changes to the well are to be documented through the entire storage lifecycle (including the abandonment phase). It is the responsibility of the well operator to ensure the well barriers can withstand the anticipated loads (Opedal et al., 2020).

In order to avoid uncontrolled gas leakages in any part of the well, careful evaluation of the well integrity is required under operational storage conditions, for which many technical, operational and organizational procedures must be applied (DBI-GUT, 2017). To our knowledge no specific standards or guidelines exist for well designs for hydrogen storage. SODM shows that storage wells and gas producing wells have a very similar configuration. However, they do regard gas storage as a separate sector and subject it to an additional legal regime (SODM, 2019). Standards for well design of comparable gas wells are mature, e.g. by ISO, API and Norsok. In the Netherlands the NOGEPA standard 41 describes well design requirements and also requires the use of multiple barriers.

The decades of experience in the oil and gas industry, dissemination of new techniques and best practices, advances in well design (e.g. double barrier policy), and testing led to an ongoing reduction in the frequency and severity of incidents (Bérest et al., 2019). However, there is uncertainty about the hydrogen resistance of borehole completions materials currently used for UGS wells, if subjected to hydrogen for a long period of time (see section 3.2.1), and about the tightness of casing and tubing connections. The smaller molecular size and higher diffusion coefficient (more than 3 times higher) of hydrogen compared to methane, in combination with the embrittling nature of hydrogen, increases the probability that it permeates through steels and materials used in wells and distribution systems (Melaina et al., 2013). This could result in higher leakage probabilities of hydrogen compared to methane when using the existing UGS infrastructure and/or materials (H_2Tools, 2020). In order to be able to withstand damage (e.g. corrosion) and subsequently penetration of hydrogen through pipe walls, the well completion components that are in direct contact with hydrogen (steel alloys, cement, seals and elastomer packers) have to be made hydrogen resistant (DBI-GUT, 2017), also see Section 3.2.1 and Figure 2. Furthermore, the tightness of casing and tubing connections must be tested specifically for hydrogen. Finally, while SSSV’s are extensively used in oil and gas industry, their effectiveness in shutting in a flowing hydrogen storage well is yet to be confirmed. In fact, it is likely that acceptable leakage rates for hydrogen and hence verification criteria will be different, in which case an SSSV may have to be designed specifically for the purpose of hydrogen storage.

<u>Leakage from salt cavern or porous reservoir</u>
In order to store gas in the subsurface, the storage container (depleted field or salt cavern) must trap the gas such that it cannot migrate out of the storage complex. Salt is commonly accepted to be impermeable, and therefore a salt cavern, which is essentially a hole in a massive salt body, is considered to be a leak-tight container in which liquids and gases can be effectively and safely stored. In fact, they have proven their great sealing capacity (very low permeability and porosity) by effectively storing a variety of gases including methane and hydrogen (Kruck et al., 2013). Furthermore, in work package 2 of the LSES project, where the effects of cyclic pressure operation on the leak tightness of caverns was investigated, it was shown that leak tightness is not compromised by such cyclic pressure variations.

In natural gas reservoirs, trapping of gas requires the presence of an impermeable caprock (salt, tight shale) that acts as a seal to migration of the gas out of the reservoir. Since the natural gas was trapped in the reservoir for millions of years, the reservoir has proven its effectiveness as a storage container. However, for hydrogen this may not necessarily be the case. Its smaller molecular size and higher diffusivity compared to methane (see Table 1) increase the potential of hydrogen permeation into and subsequently percolation through the surrounding sealing rocks of the storage reservoir. Ultimately, this may lead to loss of tightness and hydraulic integrity of the rock formations (DBI-GUT, 2017). As such, the sealing capabilities of cap rocks for hydrogen storage in depleted fields would have to be assessed on a case by case basis prior to deciding to use the reservoir for this purpose.

Furthermore, geological uncertainties could potentially increase the probability of leakage, because e.g. the occurrence of non-halite interbeds, heterogeneities in sealing formations, and the sealing capacity of faults for hydrogen cannot always be observed or determined. However, leakage incidents associated with subsurface geological uncertainties are relatively unlikely (compared to leakages associated with well failures).

<u>Leakage detection</u>
In case of any leakage at surface, early detection is important to enable a swift response, limit the volume of the leak and thereby the potential impact on health, safety and the environment. However, both gaseous hydrogen and methane are undetectable by human senses as both gasses are colourless, odourless and tasteless. In order to be able to detect natural gas a sulphur-containing odorant has been added. Unfortunately, there are no known odorants light enough to "travel with" hydrogen at the same dispersion rate, making it difficult to detect hydrogen gas (H2Tools, 2020). At hydrocarbon (gas) production platforms several types of gas leakage and flame detectors are used (e.g. ultrasonic gas leak detector, open path gas detector, IR (InfraRed) gas detector, IR flame detectors; (Koelewijn et al., 2019).

However, these detectors are not suited for detecting hydrogen. Specific detectors for hydrogen do exist, for example the catalytic bead detector that is suitable for detecting hydrogen at lower flammable limit (LFL) levels. These sensors can detect any combustible gas that combines with oxygen to generate heat. Additionally, when hydrogen ignites it has an almost invisible pale blue flame and has low radiant heat, which results in decreased detectability of ignited hydrogen compared to methane. Detectors with the ability to sense hydrogen flames include: thermal detectors, UV detectors and/or multispectral IR detectors, which have the ability to sense the non-visible spectrum of electromagnetic radiation (Koelewijn et al., 2020).

Leakage could also happen in the subsurface, either because of unforeseen geological pathways or (more realistically) along the wellbore. Leakage along the wellbore occurs when multiple barriers would fail, and by monitoring these barriers such leakage can be detected at an early stage. For example, to detect leakage of the packer or the production tubing the pressure in the annular space between production tubing and casing is monitored (see Figure 2). If methane or hydrogen were to enter this annular space then the pressure would increase, and this would be detected. Detection of leakage from the storage reservoir itself (salt cavern, porous reservoir) is much more difficult, in particular because rates of leakage are commonly low, whereas the volume of stored product is very large. Although the pressure in the storage system is monitored, the change in pressure due to such slow leakage would not be measurable.

Potential consequences of leakage

In case of leakage, gas escapes into the environment (either surface or subsurface). The potential consequences of leakage are expected to be different for leakage in the subsurface vs. leakage at surface, as well as for leakage of hydrogen vs. leakage of methane. In case of subsurface leakage of methane there are two main scenarios that could occur. Firstly, the stored product migrates towards the surface in the immediate vicinity of the storage facility, which could result in health, safety and environmental hazards (heat radiation, explosion, suffocation, groundwater contamination). Secondly, the stored product leaks into adjacent formations away from the storage facility, where after the product contaminates the groundwater, and, if released to the atmosphere at significantly high rate (not likely), similar health, safety and environmental hazards. Furthermore, in both scenarios there is economic risk in a sense that the gas becomes unrecoverable (Evans, 2008), as well as risk of reputational damage and reduced public support.

If hydrogen is released in an unconfined open environment it will typically rise and disperse more rapidly (several meters per second) compared to the heavier methane (H2Tools, 2020). This rapid dispersion of hydrogen in open spaces (atmosphere) makes it less likely that significant amounts of hydrogen could accumulate that could cause an explosion in case of ignition, this in contrast to methane. Also, on ignition methane radiates heat and creates a flame that is clearly visibly. Ignited hydrogen on the other hand radiates little (infrared) heat (IR), but emits substantial UV (ultraviolet) radiation. The lack of IR gives little sensation of heat but the exposure to a hydrogen flame still causes severe burns because of the UV radiation. Because a burning hydrogen flame is also not easily detectable, it increases the risks associated with hydrogen when it ignites to form a flame. In case of leakage of hydrogen or methane in confined spaces the risks of hydrogen accumulation are likely to be more severe than those for methane accumulation. Although both gases, when mixed with air in a combustible gas cloud, can explode when ignited, hydrogen is more prone to ignite because of the lower ignition energy and wider flammability range (vol% of hydrogen vs. air; Table 1). Furthermore, when a mixture of hydrogen and air explodes, the higher flame propagation speed potentially generates high pressures that could result in an explosion (a pressure shock wave) with massive burst damage, i.e., damage to buildings or even collapse (H2Tools, 2020; Hyde & Ellis, 2019). In contrast, when a mixture of methane and air explodes, the potential for burst damage is lower, but the longer duration of the flame, in combination with the heat that it radiates, can potentially lead to lasting harm (Li et al., 2015).

3.2.3 Risk theme 3: Uncontrolled outflow at the wellhead (blow-out)

The worst-case scenario is an incident that leads to rip-off of the well head with its multiple safety installations, which could lead to an uncontrolled outflow of the stored gas at the wellhead (also referred to as a blow-out). If the gas ignites, it could form a gas flare (flash fire), of which the heat radiation effects are expected to be different between hydrogen and methane (as discussed above). When ignition is not immediate, a cloud of methane or hydrogen could potentially form which, upon ignition, would cause an explosion.

A significant difference between hydrogen and methane in this context is the flammability range (volumetric ratio gas to air) of hydrogen (between 4% and 75% in air; Table 1), which is very wide compared to methane (between 5.3-15% in air; Table 1). Furthermore, although both hydrogen and methane can ignite when mixed even in small amounts with ordinary air, hydrogen requires a much lower ignition energy, which is the energy that is required to initiate hydrogen combustion (0.02 mJ for hydrogen and 0.29 mJ for methane; Table 1). This property gives hydrogen a significantly higher ignition potential than methane. Based on the combination of these properties it can be assumed that ignition is almost certain to happen in case of a hydrogen release, whereas this is not necessarily the case for methane. Although this reduces the risks of explosion of hydrogen vs. methane in case of low outflow rates (leakage), in case of a blow-out, outflow rates are expected to be very high (in the order of tens to a hundred kg/s), and may effectively lead to congestion at the location of release. In such a situation even a minor delay in ignition (e.g. tenths of seconds to seconds) could result in an explosion because significant amounts of hydrogen would have already been released. In the absence of confinement and congestion though, no overpressures are generate, and the consequence of an explosion is limited to a flash fire.

However, a significant outflow in case of a blow-out event is very unlikely if an SSSV has been installed at the correct depth in the well, also see Figure 2. Such safety valves are designed to be failsafe, i.e., to close off the well automatically in case of an incident at surface, and are generally installed below the crater depth. According to NOGEPA standard 41 section 3.5.1 all wells that are capable of sustained free flow are required to have an SSSV installed (NOGEPA OPCOM, 2016). It is only accepted as a functional barrier after having been installed in the well and tested under operational conditions, and is active at all times during the storage operation. It must be removed though when a workover of the well must be performed, in which case an alternative blow-out prevention barrier should be installed, e.g., in the form of a BOP (blow-out preventer) that is suitable to close on hydrogen gas.

3.2.4 *Risk theme 4: Diffusion and dissolution*

The hydrogen molecule is the smallest chemical particle known (see kinetic diameter in Table 1). In its gaseous state this molecule has a high penetrability associated with a high diffusion coefficient in solids, which is more than three times higher than methane (see Table 1, Tarkowski, 2019). This gives a higher potential for diffusional transport of hydrogen compared to methane when stored in (naturally dry) salt structures. Alternatively, when the storage systems are water-enriched porous structures, such as aquifers and depleted gas fields, dissolution processes play a dominant role. In aquifers, the loss of hydrogen is expected to be lower compared to methane, because of the much lower solubility of hydrogen in water, which is more than 13 times lower than for methane (Table 1). However, in depleted fields, the situation will be different, because the formation water is already saturated with methane. As such, no loss is expected when these are re-used for UGS, while their re-use for hydrogen can cause loss because some of the methane in the brine is expected to be substituted with hydrogen.

3.2.5 *Risk theme 5: Loss of H2 and/or contamination of the production stream*

One of the major operational challenges in underground storage systems is associated with the loss or contamination of the stored product through geo- and biochemical reactions (Foh et al., 1979; Lord, 2009). Such reactions could result in:

- the formation of corrosive and toxic fluids (most notably H_2S) that would enter into the production stream, thereby contaminating it;
- dissolution and precipitation of minerals that could affect flow of fluids through the reservoir, and
- accelerated growth of microbial populations that would clog in particular the region of the reservoir in the direct vicinity of the wellbore (near-wellbore region);
- loss of hydrogen from the storage system.

Ultimately, this could lead to deterioration of the cap- and reservoir rock, integrity loss of wellbore materials and interfaces, alteration of crucial reservoir properties, pressure loss, water cuts, and possible temperature changes in the reservoir (DBI-GUT, 2017; Hemme & van Berk, 2017).

The kinetics of geo- and biochemical reactions and the number of reacting elements/micro-organisms are the key influencers on the amount of generated and released harmful products. In general, higher temperatures, pressures (with greater depths), catalysts and salinity levels can increase the occurrence and rate of chemical reactions and microbial activity (Tarkowski, 2019). The potential for chemical and microbiological reactions are generally thought to be lower in salt caverns (due to less water, microbiological activity and mineral concentrations) than in porous depleted gas fields and aquifers (DBI-GUT, 2017; Hemme & van Berk, 2018). Hydrogen chemical reactivity, being restricted to redox reactions, is known to be kinetically limited, likely because of the apolar nature of the molecule and the strong H–H binding energy (436 kJ/mol) that requires the overstepping of a high energetic barrier before an eventual electronic transfer can take place (Truche et al., 2013). Therefore, most of the possible redox reactions induced by hydrogen remain insignificant at low temperature, even on a geological time scale, provided that no catalyst (bacteria, mineral surfaces, engineered materials) is present.

However, some hydrogen-induced redox reactions may be significant at low temperatures. In particular H_2S was demonstrated to form geochemically under medium-hydrothermal condition (Truche et al., 2010) by an hydrogen-induced redox reaction with the mineral pyrite (FeS_2) as a potential oxidant for hydrogen, which thereby transforms to pyrrhotite (FeS). This reaction exhibits all the characteristics of a coupled dissolution-precipitation mechanism occurring at the pyrite–pyrrhotite interface, and can modify the redox potential and pH of the formation water. It is considered an important potential risk of underground hydrogen storage, in particular in depleted fields, and requires further research to better understand under what subsurface conditions and at which rates H_2S forms, what the effects are, and to what extent the associated risks can be mitigated.

A second mechanism by which H_2S can form is bacterial sulfate reduction, i.e., whereby bacteria reduce $SO4^{2-}$ to H_2S in the presence of hydrogen. H_2S is a highly toxic gas even in small quantities, very aggressive towards storage facilities (weak acid if dissolved in water and highly corrosive), can pose a threat to the environment and can reduce the quality of the stored gas (Hemme & van Berk, 2017; SPCS, 2020; DGI-BUT, 2017).There is ample experience with H_2S in production streams from oil and gas industry, and procedures for making borehole completion materials H_2S resistant are well established, which provides confidence that the risks of H_2S to wellbore integrity can be managed (DBIGUT, 2017; Lord, 2009), albeit at increased cost (for H_2S-resistant materials). In the Netherlands some fields produced so called sour gas with considerable H_2S concentrations, e.g. above 1 mol% (10,000 ppm). If the presence of H_2S is suspected additional safety measures, like using low alloy H_2S resistant steel materials and H_2S detectors, are required. While stationary H_2S detectors generate an evacuation alarm at 5 ppm, personal (H_2S) gas detectors already generate an evacuation alarm at 1.6 ppm (this is the legal threshold value, i.e., the max. concentration of H_2S a person is allowed to work in for max. 8 hours), after which the person involved will go to the muster location. Above 5 ppm the use of breathing protection is required, either by using an independent breathing apparatus or by a personal H_2S detector in combination with an escape mask (SPCS, 2020).

Furthermore, for storage in depleted fields, pore clogging (i.e. filling/obstruction of the pores) is an important risk because it could affect reservoir performance by decreasing the permeability and porosity of the storage reservoir. This is particularly relevant for the near-wellbore region (DBIGUT, 2017; Hemme & van Berk, 2018; Panfilov, 2010). Clogging can either be the result of physical, biological or chemical reactions (Maliva, 2020). Physical clogging can result from the mobilization of clay particles, suspended matter or clay swelling (Konikow et al., 2001; Pavelic et al., 2007). Biological clogging could take place during microbial growth and bacterial accumulation. This process could accelerate when nutrient-rich water or organic matter is present, which could stimulate microbially mediated redox reactions and biomass growth (National Research Council, 2008). Chemical clogging can result from hydrogeochemical reactions that lead to mineral precipitation (e.g. calcite, gypsum, phosphates and oxides). Also, H_2S can lead to the precipitation of amorphous ferrous sulfide, which may cause plugging (Hemme & van Berk, 2018).

Before injecting hydrogen into any reservoir or cavern it is recommended to study the mineralogical, chemical, physical and microbiological status of the storage reservoir by measuring rock and fluid compositions, establishing the presence of bacterial populations in the formation water, and by performing laboratory tests of reactions of hydrogen with rocks and fluids in the reservoir under reservoir conditions. From these tests the impact of geo- and biochemical reactions on reservoir properties (performance), integrity and durability of rocks, well materials and interfaces between them, and fluid flow in the reservoir and along the wells can be evaluated (HyINTEGER, 2017). Additionally, the composition of the production stream must be analyzed continuously, e.g. to be able to detect an increase in the H_2S concentration (Hemme & van Berk, 2017).

3.2.6 *Risk theme 6: Subsidence and induced seismicity*

Induced seismicity and subsidence have increasingly become important risks that the wider public in the Netherlands is aware of, especially because of the issues with the Groningen gas field. Over the past decade, several earthquakes have occurred in the Groningen area, the largest one being the Huizinge earthquake in 2012 (3.6 on the Richter scale), which are attributed to the production of natural gas from this field (Vlek, 2019). Furthermore, it has been known for a long time that extraction of natural gas and salt from the subsurface causes subsidence at the surface. In the case of salt caverns, the amount and rate of subsidence depend on the rate of salt creep, which itself is a function of salt type, pressure and temperature. In the case of porous reservoirs, the amount and rate of subsidence area function of compaction, which in turn is a function of the pressure inside the reservoir, the friction angle, the type of reservoir rock, and he properties of surrounding formations (Wang et al., 2013).

In depleting gas fields, induced seismicity is generally caused by a pressure decline in the reservoir. When operating pressures are too low, the reservoir rock is progressively unable to support the overlying rock mass (overburden), and compaction could take place. Because compaction does not occur at the same speed at every location in the reservoir (it depends on the properties of the reservoir rock, which vary in space), faults form that absorb the vertical movement brought about by the (differential) compaction process. This movement along faults, which commonly occurs abruptly (stress builds up and when too high it is released suddenly), potentially causes earthquakes (induced seismicity). A similar effect could potentially occur in porous reservoirs when used for storage. If storage pressures are allowed to become lower than the pressure at time of cessation of production of gas and conversion to a storage reservoir, compaction can continue, potentially leading to induced seismic events. Furthermore, the pressure inside the storage reservoir should not exceed a certain maximum pressure (lithostatic pressure) to avoid fracturing of the rock. In practice, a safe operational pressure range is commonly agreed with the regulator. It is key to remain within this operational pressure range to reduce the magnitude and rate of surface subsidence and/or induced seismicity (Liu et al., 2014). Under normal operating conditions (between the minimum and maximum pressures) and assuming that a similar approach for UHS is used as for UGS (with wide safety margins), no contrasting differences between the two storage options are expected with respect to subsidence or induced seismicity.

In salt, stress build-up leading to faulting is highly unlikely because it behaves visco-plastically, i.e., it bends rather than breaks, and therefore the risk of earthquakes induced directly by the storage operations (as a consequence of cavern convergence) must be considered negligible. Notwithstanding the above, prolonged plastic deformation in salt may lead to movement along existing faults in brittle rock layers above the salt, in particular above and around salt domes, which are often very high but laterally confined. As an example, a very low magnitude (Mw=1) event was recorded near the Zuidwending gas storage facility in January 2019. Although the mechanism that caused it remains to be investigated, it is hypothesized that the brittle rock overlying the salt dome or in its vicinity might have moved due to salt creep (Ruigrok et al., Royal Netherlands Meteorological Institute, 2019). An alternative cause could have been the breaking off of a (part of a) rock bench from the roof of the cavern, which also generates a detectible seismic signal. To what extent the local gas storage operations triggered the event or contributed to its occurrence is unknown.

4 Discussion and conclusions

An important aspect of underground energy storage is the awareness of potential risks associated with the use of the subsurface for this purpose. In this study the potential risks associated with Underground Hydrogen Storage (UHS) and Compressed Air Energy Storage (CAES) in salt caverns, and UHS in depleted gas fields (porous media) were identified, and possible mitigation measures were explored. Risks were inventoried by conducting a literature review, and supplemented with expert knowledge. In total, 159 risks were identified, and included in a risk inventory that categorizes the risks into their relevant project phase, system component, and reservoir storage type (cavern vs. reservoir) and classifies them according to the TEECOPS criteria[1]. Of the 159 risks, 17 are categorized as being relevant during the pre-execution phase, 32 as relevant during the execute phase, 75 as relevant during the operational phase, 21 as relevant during the decommissioning phase, and 12 as relevant during the post-abandonment phase. The purpose of the risk inventory is to serve as a starting point for identifying and managing risks in development projects, and to provide guidance on potential mitigation measures to reduce the risks. A similar inventory was created for HT-ATES and successfully applied in a preparatory study of a HT-ATES (high-temperature aquifer thermal energy storage) demonstration project (Van Unen et al., 2020) to select key risks and rank them. As such, this RI and approach is also recommended in a preparatory study for CAES or UHS to select the most relevant risks and rank them in a risk matrix, as a precursor to e.g. a more detailed bowtie analysis of causes and consequences of specific undesired events.

For UHS to become an attractive solution the associated risks remain to be thoroughly evaluated. As a step towards achieving this, here a selection of six key risk themes associated with storage of hydrogen was made: material integrity/durability, leakage of hydrogen, blow-out, diffusion and dissolution, loss and/or contamination of hydrogen, and ground motion (subsidence, induced seismicity). A qualitative non site-specific comparison was made for these risk themes between UGS and UHS, primarily based on differences in gas properties (with the properties of methane assumed representative for natural gas). Overall aim of this comparison was to leverage the experience from UGS to provide useful information to better understand and reduce risks and consequences, increase control and inform stakeholders. Although in general, UGS and UHS have a similar risk profile, there are also differences that were highlighted in this study.

One important difference between UHS and UGS is the way in which hydrogen and methane affect material integrity and durability, and this has implications for re-use of pipelines and surface facilities that are currently used to transport and store natural gas. Hydrogen is a smaller and more diffusive molecule that can more easily permeate through materials, especially when they contain defects and/or cracks. Additionally, the embrittling nature of hydrogen can lead to progressive growth of such defects and cracks when subjected to large, frequent pressure variations such as are to be expected in UHS. The compatibility of hydrogen in mixtures with natural gas, in particular the influence of hydrogen on the fatigue properties of relevant steel grades and the resulting crack propagation was investigated by González Díez et al. (2020). Although they concluded that no significant effects due to hydrogen-enhanced fatigue crack growth are expected for the typical operating conditions (65-80 bar) and material types (X42-X70) used in pipelines for natural gas, they stress the importance of assessing the current condition of the integrity of the pipelines prior to transporting hydrogen through it. Furthermore, re-use of existing UGS surface facilities for (near) pure hydrogen storage is not straightforward. For example, to compress a (near) pure hydrogen stream with existing (mechanical) compressors such as are currently used will require extensive changes because many more impellors will be required. In fact, to compress a pure hydrogen stream, a reciprocating compressor is a more suitable compressor type than a mechanical compressor. As such, replacement of existing gas processing units by new ones is likely to be required[10].

Leakage of hydrogen below-ground caused by integrity failure of wellbore materials (steels/joints, cement, elastomers) and interfaces is an important potential risk of UHS. UHS wells will be very similar to UGS wells, which in turn are very similar to gas production wells. As such, standard practice would be to use similar well materials that are specified by mature standards and guidelines based on decades of experience with (production and) storage of natural gas. However, current state-of-the-art well completion materials for gas storage wells are not proven to be fully hydrogen resistant. Therefore, UHS wells must be designed with completion materials that are proven compatible with hydrogen, i.e., all materials (steel alloys, cement, elastomers and seals) used must have been subjected to a specific technical integrity evaluation for hydrogen. Additionally, they would have to be compatible with the products that could be generated from chemical and microbiological reactions with hydrogen during storage operations, in particular H_2S.

If leakage above-ground were to happen, in an unconfined open environment, then hydrogen is expected to flow out faster and rise and disperse more rapidly than methane. This rapid dispersion of hydrogen in open spaces (atmosphere) makes it less likely that significant amounts of hydrogen could accumulate that could lead to suffocation, or an explosion in case of ignition, this in contrast to methane. Both gases are flammable, but hydrogen has a much wider flammability range and a much lower ignition energy compared to methane, which gives hydrogen a higher ignition potential compared to methane. In fact, based on the combination of these properties it can be assumed that ignition is almost certain to happen in case of a hydrogen release, whereas this is not necessarily the case for methane. On ignition methane radiates heat and creates a flame that is clearly visibly. Ignited hydrogen on the other hand radiates little (infrared) heat (IR), but emits substantial UV (ultraviolet) radiation. The lack of IR gives little sensation of heat but the exposure to a hydrogen flame still causes severe burns because of the UV radiation. Because a burning hydrogen flame is also not easily detectable (contrary to methane), it increases the risks associated with hydrogen when it ignites to form a flame. Detection sensors validated for hydrogen should be used to detect possible hydrogen releases.

In case of leakage of hydrogen or methane in confined spaces, there is an elevated risk of explosion for both hydrogen and methane, however, the effects of a hydrogen explosion are different compared to methane. When a mixture of hydrogen and air explodes, the higher flame propagation speed potentially generates high pressures that could result in an explosion (a pressure shock wave) with massive burst damage, i.e., damage to buildings or even collapse (H2Tools, 2020; Hyde & Ellis, 2019). In contrast, when a mixture of methane and air explodes, the potential for burst damage is lower, but the longer duration of the flame, in combination with the heat that it radiates, can potentially lead to lasting harm (Li et al., 2015). In the absence of confinement and congestion though, no overpressures are generated, and the consequence of an explosion is limited to a flash fire.

A catastrophic event on the wellpad (e.g. an accident with a heavy truck, or a dropped object) could lead to complete or partial removal the wellhead and/or Xmas tree with all valves, which could lead to uncontrolled outflow of gas (also referred to as a blow-out). A properly installed and operationally tested SSSV, which is mandatory for gas (production and) storage wells, must prevent significant outflow in case of such catastrophic event. Although SSSV's are extensively used in oil and gas industry, their effectiveness in shutting in a flowing hydrogen storage well is yet to be confirmed. In fact, it is likely that acceptable leakage rates for hydrogen and hence verification criteria will be different, in which case an SSSV may have to be designed specifically for the purpose of hydrogen storage.

The retrievability of the gas from the subsurface reservoir is influenced by diffusion and dissolution, by geochemical reactions, and by microbiological activity. Because hydrogen is a lighter gas with a smaller molecular size and higher diffusivity compared to methane gas, it is more prone to migrate through caprocks, wellbore materials and materials used in surface facilities. Additionally, hydrogen has more potential for reacting with rocks, reservoir fluids and interacting with microbes in the reservoir compared to methane. This might affect reservoir performance (e.g. by pore clogging due to precipitation of minerals or rapid bacterial growth in the near-wellbore region) and/or could result in loss of hydrogen and/or contamination of the production stream due to the formation of H_2S, a toxic, corrosive gas that degrades wellbore materials and poses a threat to human health when released to the atmosphere.

In UGS operations wide safety margins are applied to minimize the risks associated with too high pressures that might either fracture the rock and/or re-activate faults (and induce seismic events), and too low pressures that would cause further (differential) compaction (and subsidence or induced seismic events). In this way, the risks of subsidence and induced seismicity are minimized.

To conclude, although the risks associated with UHS are generally known, further research is required in particular on the long-term durability of materials subjected to hydrogen, and interactions of hydrogen with rocks, fluids and microbes in reservoirs. Furthermore, the availability of specific standards, guidelines and perhaps even a regulatory framework (laws) would be beneficial for the application of hydrogen storage, but currently (to our knowledge) this does not exist, although the development of a separate policy framework aimed at mitigating the risks of hydrogen is currently ongoing. To analyse and demonstrate the causal relations between potential threats, failing barriers, and consequences, it is recommended to perform a bow-tie analysis for selected risk themes relevant for a specific use case of UHS. As a pre-cursor to such a bow-tie analysis, a workshop with experts in the relevant field could be organized to rank the risks (quantitively) associated with the specific use case of UHS in a risk matrix based on their consequence and probability rating, and leveraging the risk inventory developed here.

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Appendix 1 – Risk Inventory

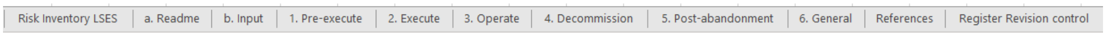
Please find below the full risk inventory. The Excel file of the risk inventory can be shared on request by sending an email to:

Marianne.vanunen[at]tno.nl or Kaj.vandervalk[at]tno.nl.

The following pages will show the inventory in the order of the tabs that are in the Excel file, and which also include how the inventory is set-up and could be used.

Tabs:

- Risk Inventory
- a. Readme
- b. Input
- 1. Pre-Execute
- 2. Execute
- 3. Operate
- 4. Decommission
- 5. Post Abandonment
- 6. All Phases
- Review sheet
- References
- Revision control



TAB: Risk Inventory LSES

TNO innovation for life

TNO Risk Inventory for Subsurface Energy Storage in Salt Caverns and Depleted Fields **Version** **1.0**

General description

This risk inventory for subsurface energy storage projects has been produced by TNO in the context of the TKI LSES project. It details risks associated with the subsurface energy storage technologies CAES, hydrogen in salt caverns and hydrogen in depleted fields.

It is compiled from risks found in literature, supplemented with expertise from partners in the project consortium. References used can be found listed in the 'References' tab, the reference is numbered to be able to trace back the risks in this sheet to the literature. It is suggested to use this as an inventory from which the most relevant risks for a particular project can be identified. This procedure has been successfully used for a similar risk inventory as part of the Dutch Heatstore demonstration case, the method is described in Van Unen et al., 2020, HEATSTORE risk assessment approach for HT-ATES applied to demonstration case Middenmeer, The Netherlands. 15 pp. (reference 39).

Authors: M. van Unen, K. van der Valk and R. Groenenberg
Contributors: L. Brunner
Project Manager: M. Halter

DISCLAIMER: This risk inventory is based on risks and mitigations that are found in literature. Some of the risks are a combination of multiple references or interpretations of risks that are found in literature. The mitigations in this inventory are found in literature and are supplemented by the team. Please refer back to the references if anything is unclear. The inventory of risks and associated mitigations is not necessarily complete and can be used as a starting point in identifying the most relevant risks for a project. Using this risk inventory does not replace a dedicated risk assessment workshop with the required expertise.

Please cite this inventory as: van Unen, M et al., 2020b: Risk Inventory for large scale subsurface energy storage

Start using this Risk Register by making a separate copy of the file before adjusting it, then please go to sheet a. 'Readme' to understand how the sheet works.

Go to sheet a. Readme

a TNO – Applied Geosciences, Princetonlaan 6, Utrecht 3584 CB, The Netherlands

TAB a: Readme

Readme

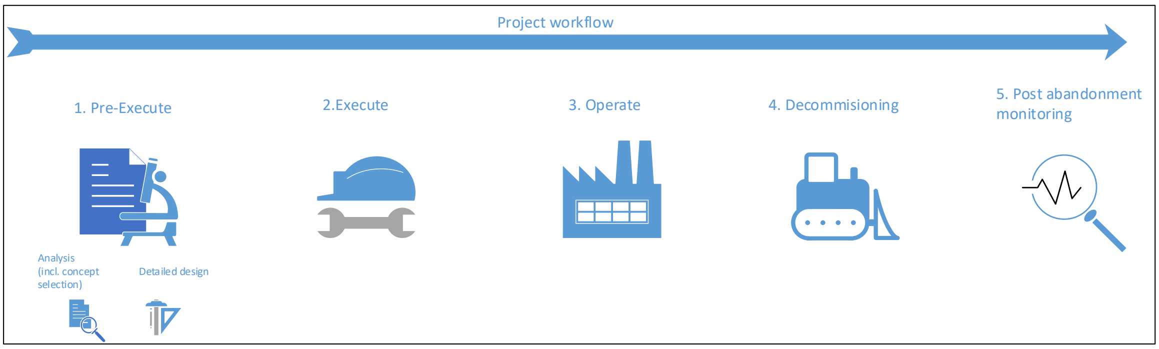
This Readme is prepared to make it easier to understand how this Risk Register is set-up. Below definitions for the structure of the risks has been defined (TEECOPS, project phases, risk ratings, system components and storage types). Tab b. 'Input' gives the option to define the project. Tabs 1. to 6. are the core of the risk register; they contain the risks and allow for ranking of the risks (both unmitigated and mitigated). The risk ranking (color code) will automatically follow from what is chosen as likelihood and as consequence rating.

Filtering:
In the risk register it is possible to filter on application; storage facility. This can be done by clicking the drop-down button in the 'Storage type' cell and selecting only the relevant storage types (and blanks). If you are interested in any storage (CAES and hydrogen) in salt caverns, please select: blanks + CAES in salt caverns + Hydrogen in salt caverns + Hydrogen storage + Storage in salt caverns + All subsurface storafe reservoirs. If you want to only have risks relevant for Hydrogen in depleted reservoirs, please select: blanks + Hydrogen in depleted fields + Hydrogen storage + All subsurface storage reservoirs.
Alternatively, one could filter on the risks earmarked with relevant TEECOPS category by clocking the dropdown button in any of the blue coloured TEECOPS cells and only select

TEECOPS Definitions

TEECOPS Definitions[1]		
T	Technical	(Sub)surface, Infrastructure, Technology, Operability, Availability, Integrity, Sustainability, Maintenance
Ec	Economical	Life-Cycle Cost, Phasing, Valuation method, Capacity, Economic model, Regret costs
En	Environmental	Surface exposure, Subsurface environment
C	Commercial	Contracting & Procurement, Financing, Business controls, Legal, Terms & Conditions, Competition, Marketing, Liabilities, Collaboration Agreement
O	Organisational	Structure, Resources, Procedures, Project Controls, Knowledge Management, Systems & IT, Interfaces, Partners, Governance
P	Political	Government, Stakeholders, Employment, Regulation, Security, Reputation, NGOs, Export Control, Localisation
S	Societal	Community, Public opinion, Social License to Operate

Project phase definitions



Project work flow phases; Risk associated with the underground storage of hydrogen and CAES (excluding UGS and CO2) during	
1. Pre-execute	All work done prior to the start of the execution phase; including analysis and design
2. Execute	The Execution phase; in this phase the facility is built (or updated) for energy storage
3. Operate	The operational phase; the actual phase where energy is stored and produced
4. Decommission	The Decommissioning phase; this includes the abandonment of wells, removal of the surface facilities and clearing the site for future use
5. Post-abandonment	The post decommisioning phase; these include risks that could come to light by monitorring of the abandoned site
6. General	All of the above defined project phases (to prevent having them in all phases)

Risk rating

Risk rating			
Probability / Consequence	Low	Medium	High
Low	L	L	M
Medium	L	M	H
High	M	H	H

System components

System component definition	
General	Risks that are relevant for all (or multiple) of the system components
Surface Facilities	These include compressors, piping, instrumentation, process facilities
Well	This includes the X-mas tree, wellhead, well (completion and cemented casings), sand-face completion
Subsurface (reservoir)	The target storage reservoir, the caprock and overburden
Project specific	Any risks that are project specific and probably not relevant for (most) other projects

Storage types

Hydrogen in salt cavern
Hydrogen in depleted gas fields
CAES in salt caverns
Storage in salt caverns
Hydrogen storage
All subsurface storage reservoirs

[1] These definitions are based on reference 38 from the reference list; Risk management plan for the Peterhead project

TAB: b. Input

Input (project definition)	
Date:	02 July 2020
Risk assessor:	LSES consortium
Project name:	TKI LSES
Project type:	TKI
Type of Energy Storage:	

TAB: 1. Pre-Execute

	Date last modified:	Risk category	Risk assessor:	Project:	Type of energy storage	Version
	14 September 2020		LSES consortium	TKI LSES		1

1. Pre-execute (scoping, analysis, concept select, detailed design)

Risk ID	Risk description	Storage type	Reference	T	Ec	En	C	O	P	S	Consequence	Probability of consequence	Unmitigated Risk rating	Mitigations	Mitigated consequence	Mitigated prob. of consequence	Mitigated risk rating	Comments
General																		
PE-G1	Unsuitable contracts (roles and responsibility not clearly defined) leading to suboptimal performance or exploding costs	All subsurface storage reservoirs	28	T	Ec			O						- Select experienced and suitable management				
PE-G2	Demand analysis and forecast are inaccurate	All subsurface storage reservoirs	28	T	Ec		C			S				- Get a good overview on the demand and forecasts and estimate uncertainties				
PE-G3	Lack of financing for the executing phase	All subsurface storage reservoirs	28		Ec			O						- Thorough feasibility study including risks - Thorough cost management - Thorough analysis of funding opportunities				
PE-G4	Low social acceptance for hydrogen storage stops project	Hydrogen storage	28		Ec		C	O	P	S				- Prepare and execute communication and participation plans - Early inclusion of stakeholders in decision making - Stakeholder analysis/mapping				
PE-G5	Low social acceptance for CAES storage stops project	CAES in salt caverns	28		Ec		C	O	P	S				- Prepare and execute communication and participation plans - Early inclusion of stakeholders in decision making - Stakeholder analysis/mapping				
PE-G6	Organization is not experienced / financially robust enough for the challenge	All subsurface storage reservoirs	2					O						- contactor / investor shall hire additional proper external experts (domestic, foreign) the projects				
PE-G7																		
Surface facilities																		
PE-S1	Inappropiate/inadequate surface technologies design	All subsurface storage reservoirs	1	T										- Design with flexibility - Detailed design surface facilities after well test (also postponing start date)				
PE-S2																		
Well																		
PE-W1	Inappropiate/inadequate well design	All subsurface storage reservoirs	1	T										- material selection (suitable for gas with anticipated composition), - casing/ tubing connection - loading applied on the well during operations (P, T, stress) - well verification (how the existing well envelope was tested? what T-range? are tests applicable to H2?)				
PE-W2	Inappropriate packer selection / installation	All subsurface storage reservoirs	1	T										- material, elastomer selection, well loading				
PE-W3	Inappropriate wellhead / x-mas tree selection / installation	All subsurface storage reservoirs	1	T										- elastomer selection, steel selection (esp. if H2S present), pressure rating				
PE-W4	Inappropriate SSSV design	All subsurface storage reservoirs	1	T										- material, tightness against H2				
PE-W5	Inappropriate cement design/specs	All subsurface storage reservoirs	1	T										- "hydrogen" tightness, potential (corrosive) reaction to cement, other chemical reaction that could reduce sealing performance, cycling pressure				
PE-W6	Inappropriate completion design	All subsurface storage reservoirs	1	T										- material (especially if H2S present), suspension fluid				
PE-W7	Integrity control not failsafe	All subsurface storage reservoirs	1	T										- robustness of primary and secondary envelope e.g. if tubing is leaking - functioning of primary and secondary barrier during operations vs. during drilling/workover, well control barrier				
Reservoir (subsurface)																		
PE-R1	Not able to find a suitable storage site in the area of interest	All subsurface storage reservoirs	26	T	Ec									- Careful site characterization - Drill extra wells				
PE-R2	Insufficient knowledge on subsurface site characteristics, leading to higher risks	All subsurface storage reservoirs	10	T	Ec	En	C	O	P	S				- Gather more data (2D or 3D seismic) - Look at offset wells (if available) - Drill additional exploration wells				
PE-R3	Unfavourable subsurface conditions lowering the economic value of the storage site	All subsurface storage reservoirs	7		Ec									- Good reservoir thickness and petrophysical properties are required. - Reservoirs need good connected porosities and high permeabilities - Reservoir should be positioned at a depth allowing for a wide pressure range for the applicable and approved minimum and maximum injection and withdrawal pressures. - Extensive reservoir characterisation and reservoir modelling needs to be performed - Host rock must be strong enough to enable the construction of a self-supporting cavern				
PE-R4																		
Project specific																		
PE-P1																		

TAB: 2. Execute

Date last modified:	Risk category	Risk assessor:	Project:	Type of energy storage	Version
14 September 2020		LSES consortium	TKI LSES		1

2. Execute (incl. well test and injectivity test)

Risk ID	Risk description	Storage type	Reference	T	Ec	En	C	O	P	S	Consequence	Probability of consequence	Unmitigated Risk rating	Mitigations	Mitigated consequence	Mitigated prob. of consequence	Mitigated risk rating	Comments
General																		
E-G1	Unanticipated delays and costs (materials, services, maintenance)	All subsurface storage reservoirs	28	T	Ec			O						- Include time/cost buffer in the planning				
E-G2	Roles and responsibility not clearly defined leading to suboptimal performance or exploding costs	All subsurface storage reservoirs	28	T	Ec			O						- Select experienced and suitable management				
E-G3	Over expenditure on CAPEX (CAPEX overrun) because of unforeseen costs or unfavourable tender	All subsurface storage reservoirs	29		Ec		C	O						- Design fit for urban environment - Tender strategy fit for market supply - Detailed design narrow down the uncertainty range				
E-G4	Interruptions in signal transfers due to failures or maintenance	All subsurface storage reservoirs	18	T				O						- In order to have a continuously active data transfer, two communication connections will be needed. One of the two connections functions as a backup, with functionality to switch over automatically if the primary connection is interrupted.				
E-G5	Lack of financing for next phases	All subsurface storage reservoirs	28		Ec		C	O	P	S				- Thorough feasibility study including risks - Thorough cost management - Thorough analysis of funding opportunities				
E-G6	Contamination of groundwater due to any type of leakages or emissions	All subsurface storage reservoirs	2; 7; 12	T	Ec	En	C		P	S				- Evaluate the cap rock layers and sealing capacity. - The spill point of the targeted structure and any flow must be determined - Leakage along fractures must be excluded - Monitoring water levels and water chemistry in observation wells completed above the cap rock.				
E-G7																		
Surface facilities																		
E-S1	Failure of above ground infrastructure (valve, pipes, wellhead or compressor units)	All subsurface storage reservoirs	1; 9	T										- Check and repair above ground infrastructure - Fit for purpose design				
E-S2	General surface facility construction risks	All subsurface storage reservoirs	1	T										- Early involvement of contractors/experts - Follow standards and guideline - Best Practices - QA/QC - Collapse of infrastructure				
E-S3	Failure of facilities due to uncontrolled leaching during cavern construction	Storage in salt caverns	9	T										During leaching the rock mechanical limitations must not be exceeded, otherwise the strategy must be modified which will also lead to a lower cavern volume.				Contribute to the instability, breaching and collapse of solution mined salt caverns Might lead to problems with cavern construction, producing unstable or poorly shaped and inefficient voids for gas storage. Problems might occur if, for example, more soluble evaporitic horizons (e.g. potash) are present within the bedded salt, unexpectedly thick non-halite interbeds are present or wet rockhead is developed
E-S4	Malfunction of the control panel that is connected to the transformer facility leading to an interruption in the electricity cycle	All subsurface storage reservoirs	25	T										- Additional wires for most risky connections - Additional transformers that can step in when needed				
E-S5																		
Well																		
E-W1	Not able to lower the casing string	All subsurface storage reservoirs	28	T										- Ensure safe clearance and drift diameter of the well				
E-W2	Trajectory issues (deviation from target)	All subsurface storage reservoirs	28	T		En								- Thorough Drill Plan/Program and its execution				
E-W3	Drilling is more complicated/more expensive than anticipated	All subsurface storage reservoirs	28	T	Ec									- Thorough Drill Plan/Program and its execution				
E-W4	Issues in transporting/handling radioactive sources for logging	All subsurface storage reservoirs	28	T		En								- Radioactive waste management plan - Applying radiation safety protocols				
E-W5	Standard drilling risks also common to O&G operations (e.g. rig issues, failure of the well or casing, hitting over pressured layer, shallow gas pockets, getting stuck, losses, losing circulation)	All subsurface storage reservoirs	1	T										- Drill according to newest lessons learned - Early involvement of contractors and experts - state of the art drilling program				
E-W6	Geostatic (isostatic) stress increase in salt during injection of water for creating the cavern (which can lead to fracturing and loss of cavern integrity or induced seismicity)	Storage in salt caverns	5;7	T										- Pressure monitoring of the subsurface				
E-W7	The injection of the brine during each cavern emptying-filling cycle could dissolve the salt wall, causing structural weakness and ultimately failure	Storage in salt caverns	9; 25	T										- Good monitoring and control of pressure changes in the cavern - Careful site characterization (subsurface mapping etc. using high resolution seismic reflection data for example)				
E-W8	Damage of the wells due to seismicity and collapse of the subsurface structures	All subsurface storage reservoirs	5; 7	T	Ec	En								- Pressure monitoring of the subsurface - Seismic monitoring				
E-W9																		

TAB: 2. Execute (continued)

									Reservoir (subsurface)									
E-R1	Wrong choice of fluids or techniques damaging the reservoir	All subsurface storage reservoirs	28	T		En								- Training and certifying of the personnel - Select Experienced and suitable Management - Thorough geological survey/core sample analysis				
E-R2	Flow rate lower than expected during flow test (e.g. because of lower permeability, heterogeneity of the reservoir)	Hydrogen in depleted gas fields	28	T										- Adaptation of the drill path to reach multiple targets - Avoid excessive contamination of the well - Use of clay-mineral free drilling mud - Avoid the use of loss control material during drilling of the production section - Avoid the cementing of previous casing string in the production section - Try to drill long enough production section for securing the expected yield - Use of external casing packer between the loose formation and the productive layer - In case of porous reservoir use of under reaming and gravel pack in the production section - Accurate collection and interpretation of productivity data of wells for securing information for the expected yields - Doing new measurements in existing wells for securing information for the expected yield - Dedicated exploration well - Update design and include more sources to increase supply - Include potential extra wells in risk margin for project				
E-R3	Fluid chemistry / gas content / physical properties are different than expected, which can alter the well or change the composition of the injected energy	All subsurface storage reservoirs	28	T		En								- Adapt the material selection to the chemical/physical properties of the fluid - Additional chemical sampling and hydrogeological analyses - Re-evaluate hydrogeological model				
E-R4	Well ends up in a non-suitable part of the salt layer during the cavern build-up	Storage in salt caverns	28	T	Ec									- Thorough geological survey/core sample analysis - Accurate collection an interpretation of expected geology to provide information on the target reservoir - Doing new surface geophysical measurements for the better understanding of expected geology - Drilling further, side-tracking				
E-R5	Geological lithology or stratigraphy is different than expected	All subsurface storage reservoirs	28	T										- Thorough geological survey/core sample analysis - Accurate collection an interpretation of expected geology for securing information on the target reservoir - Doing new surface geophysical measurements for the better understanding of expected geology for securing information on the target reservoir				
E-R6	(Re-)injection of the stored product is more difficult than expected	All subsurface storage reservoirs	28	T										- Thorough geological survey/core sample analysis - Adapt the power plant design under given temperature/pressure - Adaptation of the drill path to reach multiple targets - In case of porous aquifers use of under reaming and gravel pack in the production section				
E-R7	Mud losses leading to severe technical issues	All subsurface storage reservoirs	28	T										- Avoid extreme overpressure drilling - Proper composition and parameters of drilling fluid /mud program - Detailed subsurface analysis to identify potential loss zones and adapt drilling program				
E-R8	Well misses target formation	Hydrogen in depleted gas fields	28	T	Ec									- Thorough geological survey/core sample analysis - Accurate collection an interpretation of expected geology to provide information on the target reservoir - Doing new surface geophysical measurements for the better understanding of expected geology - Drilling further, side-tracking				
E-R9	Induced seismicity (e.g. during drilling or stimulation)	All subsurface storage reservoirs	28	T	Ec	En				S				- Installation of seismic monitoring system				
E-R10	Presence of faults or fractures in the storing sequences, which can lead to leakages or losses	All subsurface storage reservoirs	9	T	Ec									- Geological explorations, determine the presence of faults/fractures, the sealing capacity of the faults and the presence of halite beds.				
E-R11	Leakage of subsurface fluids due to seismicity	All subsurface storage reservoirs	2; 7	T	Ec	En	C	O	P	S				- Find locations which benefit from a second sealing formation above the storage				
E-R12	Subsidence due to seismicity and collapse of the subsurface structures	All subsurface storage reservoirs	5; 7	T	Ec	En								- Pressure monitoring of the subsurface				
E-R13	Brine pressure increase will result in a figure larger than the geostatic pressure, leading to hydrofracturing, which can lead to leaking (water pollution), cavern / reservoir collapse and subsidence	Hydrogen storage	11	T	Ec	En								- Careful pressure monitoring				
E-R14	Once a salt cavern is penetrated there is a risk for fast deterioration of the salt cavern, because of their large widths and thin heights.	Storage in salt caverns	26	T				O						- Careful penetration during drilling together with subsurface monitoring - It is recommended to limit the cavern height to diameter ratio so that it would not exceed 5.0				
E-R15																		
									Project specific									
E-P1																		

TAB: 3. Operate

Date last modified:	Risk category	Risk assessor:	Project:	Type of energy storage	Version
14 September 2020		LSES consortium	TKI LSES		1

3. Operate

Risk ID	Risk description	Storage type	Reference	T	Ec	En	C	O	P	S	Consequence	Probability of consequence	Unmitigated Risk rating	Mitigations	Mitigated consequence	Mitigated prob. of consequence	Mitigated risk rating	Comments
General																		
O-G1	Contamination of groundwater due to any types of leakages or emissions	All subsurface storage reservoirs	2; 7; 12	T	Ec	En	C		P	S				- Evaluate the cap rock layers and sealing capacity. - The spill point of the targeted structure and any flow must be determined - Leakage along fractures must be excluded - Monitoring water levels and water chemistry in observation wells completed above the cap rock.				
O-G2	Malfunction of technical operating system	All subsurface storage reservoirs	6	T										- Measurement of mass flow and volume, pressure, temperature and pumping rate				
O-G3	Leakage of gas from well or wellhead leading to explosions, fires or suffocation	Hydrogen storage	11; 12		Ec	En								- Running down-hole logs in the injection/withdrawal wells (e.g., temperature logs to identify thermal anomalies, neutron logs to detect gas behind the casings above the storage formation, cement bond logs to determine the integrity of the cement behind the casings, calliper logs to find mechanical breaks in the casings, noise logs to "listen" to the flow of gas behind the casings, and a variety of casing inspection logs to determine the thickness and general condition of well casings and joints)				
O-G4	Unanticipated delays and costs during operations and maintenance (reparation of materials, services)	All subsurface storage reservoirs	28	T	Ec			O						- Include time/cost buffer in the planning				
O-G6	Incident that leads to rip off of the very robust well head with its multiple safety installations	All subsurface storage reservoirs	7	T	Ec	En								- Carefully monitor the well head - Blow-out can be prevented by an automatically closing subsurface safety valve, installed some meters below the well head				
O-G7	Too high heat generation when compressing air due to a malfunction in heat exchangers	CAES in salt caverns	9	T				O						- Careful temperature monitoring - Emergency stop system				
O-G8	Too little income generated to pay back the loan	All subsurface storage reservoirs	16		Ec			O						- Significantly reducing uncertainty around encountering less favourable hydrologic properties than expected at the site - Reducing the pressure required to achieve the targeted injection rate and increasing the air storage volume efficiency in the structure.				
O-G9	Too little income generated to pay back the loan	All subsurface storage reservoirs	28		Ec			O						- Thorough feasibility study including risks - Thorough cost management - Thorough analysis of funding opportunities				
O-G10	Interruptions in signal transfers due to failures or maintenance	All subsurface storage reservoirs	18	T										- In order to have a continuously active data transfer, two communication connections will be needed. One of the two connections functions as a backup, with functionality to switch over automatically if the primary connection is interrupted.				
O-G11	Economic risks (e.g. larger amounts of hydrogen gets trapped, leakage of the energy source)	All subsurface storage reservoirs	20		Ec			O						- Careful site management - Determine potential flow paths - Do injection tests when exploration wells are drilled. - Pipe storage should be located at an appropriately safe distance from surrounding buildings and settlements				
O-G12	Nuisance / emissions such as noise, dust, light	All subsurface storage reservoirs	7		Ec			O	P	S				- Keep continuous monitoring of standards, technologies and political situation - LPG storage withdrawal operations have optimum saturated brine injection rates to prevent excessive tubing vibration. - Maximum noise levels and noise plan (day night rhythm) - Insulation - Early involvement of neighbourhood				
O-G13																		

TAB: 3. Operate (continued)

														Well				
O-W1	Geostatic (isostatic) stress increase in salt during injection of H2 or air (this can lead to fracturing or seismicity)	Storage in salt caverns	5;7	T										- Pressure monitoring of the subsurface				
O-W2	Excessive tubing vibrations can lead to well failure, but can be mitigated by a good design and keeping a safety margin on the speed at which air or H2 is injected/withdrawn.	All subsurface storage reservoirs	13	T		En				S				- a good design and keeping a safety margin on the speed at which air or H2 is injected/withdrawn.				
O-W3	Corrosion of pipelines and components (buried), flanges, valves, fittings, pressure vessels, pumps, compressors and injectors, wells and their casings/cements	All subsurface storage reservoirs	9	T										- Material selection and design principles fit for expected potential corrosion mechanisms - Corrosion avoidance by the injection of dry air between steel and the casings - Strict monitoring of minimum pressures				
O-W4	Erosion of pipelines and components during hydrogen of CAES storage	All subsurface storage reservoirs	1	T										- Well checks and maintenance - Check erosional velocities acceptable for the equipment and base operating strategy on it				
O-W5	Damage to production wells	All subsurface storage reservoirs	3; 7; 9; 20; 22	T	Ec	En								- Following analysis and inspections (mechanical integrity test, cement logs, mechanical assessment of the stress/strain experienced when at atmospheric pressure). - Careful check of the blowout-prevention system - Installing subsurface safety valves. Safety shut-off valves are installed in gas caverns about 50 m below the surface.				
O-W6	Thermal stress of the salt during high withdrawal rates of compressed air	CAES in salt caverns	15	T										- Careful monitoring of the pressure and temperature changes in the subsurface. - Careful monitoring of the withdrawal velocities.				
O-W7	Failure in cementation leading to permeable cements	All subsurface storage reservoirs	20	T		En								- During operation the rock mechanical limitations must not be exceeded, otherwise the strategy must be modified which will also lead to a lower cavern volume.				
O-W8	Failure of the Subsurface Safety Valve during storage in salt caverns (leading to a blow-out)	Storage in salt caverns	7	T		En								- Make sure the safety valve is working well, e.g. preventative maintenance - Make a safety assessment in the case of a blow-out				The energy released versus time by a blow-out during storage in depleted gas fields is smaller than for a cavern blow out because common well diameters for porous storages are smaller. Because of the commonly much larger inventory of aquifer storages the duration of the blow-out could last longer. It is impossible for the gas stored in the aquifer to ignite within the formation itself because of the absence of oxygen which completely prevents the formation of a combustible mixture
O-W9	Failure of the Subsurface Safety Valve during the storage in depleted gas fields (leading to a blow-out)	Hydrogen in depleted gas fields	7	T		En								- Make sure the safety valve is working well, e.g. preventative maintenance - Make a safety assessment in the case of a blow-out				The energy released versus time by a blow-out during storage in depleted gas fields is smaller than for a cavern blow out because common well diameters for porous storages are smaller. Because of the commonly much larger inventory of aquifer storages the duration of the blow-out could last longer. It is impossible for the gas stored in the aquifer to ignite within the formation itself because of the absence of oxygen which completely prevents the formation of a combustible mixture
O-W10	Leakage along the well through the cements	All subsurface storage reservoirs	9	T	Ec	En								- Inject/squeeze cements to fill up the leakage paths				
O-W11	Cyclic loading of the wells used for both injecting as "producing" introduces risk of fatigue loads for the steel and cement (e.g. cycles: inject - idle - produce - idle - inject)	All subsurface storage reservoirs	1	T										- Well design and material selection fit for purpose with respect to cyclic loads				
O-W12	Uncontrolled gas release (blowout)	All subsurface storage reservoirs	3; 7; 9	T	Ec	En	C	O	P	S				- Following analysis and inspections (mechanical integrity test, cement logs, mechanical assessment of the stress/strain experienced when at atmospheric pressure). - Install an automatically closing subsurface safety valve some meters below the well head (SSSV)				
O-W13																		
														Reservoir (subsurface)				
O-R1	Subsidence associated with pressure loss in the cavern	Storage in salt caverns	9	T										- Careful monitoring of pressure and changes in surface characteristics				
O-R2	Underground fire or explosion	CAES in salt caverns	4	T	Ec	En								- Monitor the pressure and temperature in the reservoir - Ensure that the composition of natural gas and air remains outside the ignition envelope - Determine the flammability limits - Determine the heat provided by the reservoir - Determine local failures of the reservoir, which could produce rapid pressurization - The geologic conditions and geometry of the underground storage facility must be investigated (e.g. density differences between the natural gas and air, and permeability contrasts could influence the mixture between the natural gas and air.				
O-R3	Rock salt creeps and begins to deform when affected by high formation pressures.	Storage in salt caverns	5; 7; 9	T		En								- Passive seismic Monitoring - Cavern stability assessment - Determine and monitor operating pressures - Estimate geostatic stress in salt at the depth of the cavern - Long term stability of the cavern is ensured by many years of experience and by site-specific lab testing in combination with rock-mechanical models - Groundwater control method, which maintains the internal cavern pressure below the natural prevailed water pressure within the rock - Pressure and mechanical integrity testing wells and cavern				

TAB: 3. Operate (continued)

O-R4	Geostatic (isostatic) stress increase and cavern volume loss	Storage in salt caverns	5; 7; 9	T	Ec	En								- Passive seismic Monitoring - Cavern stability assessment - Determine and monitor operating pressures - Estimate geostatic stress in salt at the depth of the cavern - long term stability of the cavern is ensured by many years of experience and by site-specific lab testing in combination with rock-mechanical models - groundwater control method, which maintains the internal cavern pressure below the natural prevailed water pressure within the rock - Pressure and mechanical integrity testing wells and cavern				
O-R5	Leakage during hydrogen storage in salt caverns	Hydrogen storage	5; 9	T	Ec	En			P	S				- Lowering storage pressures within the storage reservoir or cavern - Accumulated gas in shallow traps can be pumped out to prevent further migration and surface releases - Monitoring of injection/production/abandoned wells to detect damage or leakage - Repair of leaking injection/production/abandoned wells - Quantify health and ecological risk				
O-R6	Daily temperature variations can lead to compression and decompression of compressed air (possibly leading to generation of tensile fractures in the reservoir).	CAES in salt caverns	5; 7	T										- Careful with withdrawal rates - Commissioning of cavers/pressure testing				
O-R7	Reservoir seismicity	All subsurface storage reservoirs	6	T		En								- Usage of 5D QM Storage Monitor, which is permanently recording the seismo-acoustic background and any signal and information contained therein.				
O-R8	Occurrence of non-halite interbeds leading to reduced cavern size	Storage in salt caverns	7	T	Ec									- Increase geological knowledge by exploration				
O-R9	Occurrence of faults leading to different operational pressure range	All subsurface storage reservoirs	7		Ec									- Increase geological knowledge by exploration				
O-R10	Slow uncontrolled leakage of gas through the subsurface	All subsurface storage reservoirs	7		Ec	En								- Exploration of geological structures - The cover rock needs to separate the reservoir from shallow structures to prevent gas escape - Groundwater control method, which maintains the internal cavern pressure below the natural prevailed water pressure within the rock				
O-R11	Subsidence characterised by predominantly brittle (collapse) deformation	Storage in salt caverns	9	T	Ec	En								- In a brittle collapse zone, water ingress could lead to ongoing dissolution but facilitate relatively rapid creep of adjacent salts (as a result of the presence of water), back into the dissolution cavity. This could conceivably help to prevent the formation of large cavities and subsequent catastrophic collapse.				
O-R12	Overfilling of caverns resulting in cavern instability and collapse	Storage in salt caverns	9	T										- Good monitoring and control, so that undetected enlargement of the cavern and inaccuracies in storage volumes can be indicated. - Accurate inventories of stored or injected product - the salt cavern operations are mainly restricted by the maximum pressure change rate per unit time to ensure stability, and also by the maximum flow velocities inside the well				
O-R13	Release of stored product through cracks in the cavern wall	Storage in salt caverns	9	T	Ec	En								- Careful site characterization (subsurface mapping etc. using high resolution seismic reflection data for example)				
O-R14	(Partial) cavern roof collapses (loss of cavern integrity) leading to thinning of the 'protective' cavern roof salt associated with failure of the cavern seal	Storage in salt caverns	9	T	Ec	En								- Careful site characterization (subsurface mapping etc. using high resolution seismic reflection data for example)				
O-R15	Collapse of internal ledges or benches formed by non salt interbeds	Storage in salt caverns	9	T	Ec	En								- Good monitoring and control of pressure changes in the cavern - Careful site characterization (subsurface mapping etc. using high resolution seismic reflection data for example)				
O-R16	Microorganisms could speed up geo-chemical reactions leading to corrosion and acidification of the reservoir fluids through accumulation of hydrogen sulphide (H2S) and organic acids. Enhanced microbial activity can also lead to a potential decrease in storage capacity and production of CO2	Hydrogen in depleted gas fields	23	T	Ec	En								- Monitor the quality and the amounts of the product - Performing basic microbiological analyses of the reservoir environment followed by laboratory experiments to estimate the kinetics of nutrient/energy usage and by-product formation.				
O-R17	Decrease of permeability through iron sulphide (FeS) precipitation, biofilms and extra-cellular substances	Hydrogen in depleted gas fields	23	T	Ec	En								- Monitor the quality and the amounts of the product				
O-R18	Reduction of gas quality through hydrogen consumption and hydrogen sulphide (H2S) formation	Hydrogen in depleted gas fields	23	T	Ec	En								- Monitor the quality and the amounts of the product				
O-R19	Trigger geo-chemical reactions with rock minerals and reservoir fluids during the storage of hydrogen (could lead to energy loss and other undesirable effects such as damage in the rock and mineral structure leading to alteration of reservoir properties).	Hydrogen storage	23	T	Ec	En								- Porosity and Permeability monitoring of the reservoir - Subsurface monitoring of the pressure and temperature				
O-R20	Undesired water suction during large well penetrations	CAES in salt caverns	26	T										- To investigate the risk of water suction in CAES reservoirs, the critical flow rate and interface height can be determined				

TAB: 3. Operate (continued)

O-R21	Hydrogen admixture leading to undesired energy losses	Hydrogen storage	23	T	Ec									- The influence of other gas components like carbon monoxide and oxygen must be considered - Must consider all boundary conditions like pressure, partial pressure, temperature, water or condensate content, geo-chemical context, etc.				
O-R22	Loss of cavern capacity as a consequence of having operated at pressures too low to maintain cavern walls	Storage in salt caverns	9	T	Ec									- Careful monitoring of pressure				
O-R23	The stored product is dissolved into the water of the caprock, whereupon it is not recoverable and a valuable commodity is lost.	Hydrogen in depleted gas fields	9; 23		Ec	En								- Risk analysis of geological storage facilities - Determine significance of risk				
O-R24	Leakage from the cavern (through the well) during salt cavern storage	Storage in salt caverns	9	T	Ec	En	C		P	S				- Perform regular sonar scans to accurately map the cavern walls and monitor closure - The installation, during cavern construction, of a remote second well system that would allow safe draw down of the stored product in the event of an incident				
O-R25	Unexpected hydrogeologic conditions	All subsurface storage reservoirs	16	T										- Careful site management (e.g. land ownership, proximity to critical infrastructure (natural gas pipeline and transmission), and nearby exploration wells)				
O-R26	Leakage during hydrogen storage in depleted gas fields	Hydrogen in depleted gas fields	5; 9	T	Ec	En	C		P	S				- Lowering storage pressures within the storage reservoir or cavern - Accumulated gas in shallow traps can be pumped out to prevent further migration and surface releases - Monitoring of injection/production/abandoned wells to detect damage or leakage - Repair of leaking injection/production/abandoned wells - Quantify health and ecological risk				
O-R27	Presence of anomalous zones (higher solubility or porosity) in what has been assumed to be homogenous salt, which includes leaky interbeds	Storage in salt caverns	9	T	Ec	En								- Adequate subsurface characterization by wells, seismic etc.				
O-R28	The stored product migrates away from the storage area, whereupon it is not recoverable and a valuable commodity is lost.	All subsurface storage reservoirs	9		Ec	En								- Risk analysis of geological storage facilities - Determine significance of risk				
O-R29	Leakage through the caprock/ overburden	All subsurface storage reservoirs	9		Ec	En								- Adequate cap rock characterization				
O-R30	Isostacy can change the pressure conditions of the reservoir	All subsurface storage reservoirs	14	T	Ec									- Careful pressure monitoring and changes in subsidence				
O-R31	Cooling, contraction and thermal stressing of salt at cavern walls (can lead to generation of tensile fractures).	CAES in salt caverns	5; 7	T										- Careful with withdrawal rates - Commissioning of cavers/pressure testing				
O-R32	Small leaks developing along the contact surfaces of the sealing structure	All subsurface storage reservoirs	20	T	Ec	En								- Monitoring can continuously check the stability and integrity of the sealing structure				
O-R33	Piezoelectricity generating an electric potential when specific stress/strain conditions are applied (cycled stress conditions especially near boreholes, may facilitate this phenomenon).	All subsurface storage reservoirs	4	T										- Monitor the cycles stress conditions near the borehole - Purge the reservoir of natural gas before use (site-specific analyses). - Install an in-situ gas monitor down hole to provide near source measure of natural gas presence				
O-R34	Static electricity caused by the proximal position of two materials with an imbalance of positive and negative charges. This could provide an ignition source for the fuel-air mixture.	CAES in salt caverns	4	T										- Monitor the build up of charge by particles - Monitor the natural gas content to adjust the air-fuel ratio in the gas turbine - Grounding of all piping				
O-R35	Gas leakage through unknown fractures or the spill point or other potential leak paths.	Hydrogen in depleted gas fields	20	T	Ec	En								- Drilling of monitoring wells in the perimeter of the formation and the overlying cap rock. These are measures that are done additionally to wells which monitor the gas to liquid interface within the storage range of the formation.				
O-R36	Thermal expansion of the cavern fluid, leading to pressure build-up in the cavern	Storage in salt caverns	9, 11	T	Ec									- Continuous temperature and pressure monitoring of the cavern				
O-R37																		
												Project specific						
O-P1																		

TAB: 4. Decommission

Date last modified:	Risk category	Risk assessor:	Project:	Type of energy storage	Version
14 September 2020		LSES consortium	TKI LSES		1

4. Decommission (including post decommission phase)

Risk ID	Risk description	Storage type	Reference	T	Ec	En	C	O	P	S	Consequence	Probability of consequence	Unmitigated Risk rating	Mitigations	Mitigated consequence	Mitigated prob. of consequence	Mitigated risk rating	Comments
General																		
D-G1	Contamination of groundwater due to any type of leakages or emissions	All subsurface storage reservoirs	2	T	Ec	En			P	S				- Modelling of leakage and monitoring of the well				
D-G2	Leakage of the stored product in salt caverns during the decommissioning phase	Storage in salt caverns	9	T	Ec	En								- On abandonment, closure and monitoring of salt cavern stability and internal pressure to prevent over pressurization and possible failure of he walls or roof rock and the wellhead/valves				
D-G3	Leakage of the stored product in a depleted gas fields during the decommissioning phase	Hydrogen in depleted gas fields	9	T	Ec	En								- On abandonment of depleted fields, withdrawal of injected stored gas to below cushion gas levels, as undertaken in some decommissioned facilities				
D-G4	Leakage of gas from well or wellhead leading to explosions, fires or suffocation	Hydrogen storage	11; 12		Ec	En								- Running down-hole logs in the injection/withdrawal wells (e.g., temperature logs to identify thermal anomalies, neutron logs to detect gas behind the casings above the storage formation, cement bond logs to determine the integrity of the cement behind the casings, calliper logs to find mechanical breaks in the casings, noise logs to "listen" to the flow of gas behind the casings, and a variety of casing inspection logs to determine the thickness and general condition of well casings and joints)				
D-G5	Unanticipated delays and costs in decommission operations (materials, services, maintenance)	All subsurface storage reservoirs	28	T	Ec			O						- Include time/cost buffer in the planning				
D-G6	Postponing decommissioning because of economical attractiveness increasing difficulty of decommissioning	All subsurface storage reservoirs	1	T	Ec			O		S				- Have clear cut-off point and decommissioning moment based on equipment properties				
D-G7	Interruptions in signal transfers due to failures or maintenance	All subsurface storage reservoirs	18	T				O						- In order to have a continuously active data transfer, two communication connections will be needed. One of the two connections functions as a backup, with functionality to switch over automatically if the primary connection is interrupted.				
D-G8	Lack of financing for next phases	All subsurface storage reservoirs	28		Ec		C	O		S				- Thorough feasibility study including risks - Thorough cost management - Thorough analysis of funding opportunities				
D-G9	Financial risk during the decommissioning phase	All subsurface storage reservoirs	16		Ec			O		S				- Significantly reducing uncertainty around encountering less favourable hydrologic properties than expected at the site - Reducing the pressure required to achieve the targeted injection rate and increasing the air storage volume efficiency in the structure.				
D-G10	Subsidence	All subsurface storage reservoirs	9	T										- Careful pressure monitoring				
D-G11	Availability of brine for refill of caverns	Storage in salt caverns		T	Ec	En								- As part of the decommissioning all the gas must be withdrawn and caverns refilled with saturated brine - in the order of billions of liters				
Surface facilities																		
D-S1	Failure of above ground infrastructure (valve, pipes, wellhead or compressor units)	All subsurface storage reservoirs	9	T										- Technical status survey before decommissioning				
D-S2	Interruptions in signal transfers due to failures or maintenance	All subsurface storage reservoirs	18	T				O						- In order to have a continuously active data transfer, two communication connections will be needed. One of the two connections functions as a backup, with functionality to switch over automatically if the primary connection is interrupted.				
D-S3	Obstruction of pump turbine	All subsurface storage reservoirs	25	T										- If necessary double pump turbines or extra maintenance				
D-S4	Control panel connection malfunction	All subsurface storage reservoirs	25	T										- Additional wires for most risky connections				
D-S5	Radioactive contamination	All subsurface storage reservoirs	37	T		En								- Determine the radioactive characteristic of the facility - Determine the extent and detail of the characterization of the radioactive content of the facility should be influenced by the expected risk level, concerning, for example, the measurement of dose rates, determination of the contamination levels, determination of activation in reactor facilities, the use of scaling factors between key radionuclides and hard to detect radionuclides				
D-S6																		

TAB: 4. Decommission (continued)

Well																		
D-W1	General well decommissioning risks from O&G (stuck items, phishes in hole, unable to create barrier)	All subsurface storage reservoirs	1	T	Ec									- Use lessons learned from industry - Design for decommissioning already at start - include decommission in all decisions - Monitoring				
D-W2	Uncontrolled gas release (blowout)	All subsurface storage reservoirs	3	T	Ec	En	C	O	P	S				- Make a safety and performance assessment in order to mitigate the risk, allowing for low safety, health and economical risks				
D-W3																		
Reservoir (subsurface)																		
D-R1	Micro seismicity	All subsurface storage reservoirs	9	T		En				S				- Seismic monitoring				
D-R2	Seismicity	All subsurface storage reservoirs	9	T		En				S				- Seismic monitoring				
D-R3	Collapse of the subsurface stratigraphy / reservoirs (can lead to subsidence)	All subsurface storage reservoirs	9	T	Ec	En	C			S				- Careful pressure monitoring				
D-R4																		
Project specific																		
D-P1																		

TAB: 5. Post abandonment

	Date last modified:			Risk category							Risk assessor:		Project:		Type of energy storage			Version
	14 September 2020										LSES consortium		TKI LSES					1
5. Post-abandonment																		
Risk ID	**Risk description**	**Storage type**	**Reference**	**T**	**Ec**	**En**	**C**	**O**	**P**	**S**	**Consequence**	**Probability of consequence**	**Unmitigated Risk rating**	**Mitigations**	**Mitigated consequence**	**Mitigated prob. of consequence**	**Mitigated risk rating**	**Comments**
General																		
PA-G1	Subsidence and sinkhole formation (can be associated with damage to infrastructure)	All subsurface storage reservoirs	9	T	Ec	En				S				- Renewed injection of other substituents - Pressure monitoring				
PA-G2	Uncertainty on future utilisation	All subsurface storage reservoirs	24		Ec									- Make a clear time schedule on the operation time of the plants				
PA-G3	Seismicity	All subsurface storage reservoirs	9	T										- Seismic monitoring				
PA-G4																		
Surface facilities																		
PA-S1	Damage/changes to buildings and agriculture, which will change the energy demand	All subsurface storage reservoirs	31		Ec	En			P	S				- Monitor the areas (buildings, agriculture) that are making use of the energy -Monitor the adjacent and overlying areas for damage/problems				
PA-S2	Induced seismicity, which can result in alteration of the storage site (surface and subsurface)	All subsurface storage reservoirs	1			En		O	P	S				- Careful post-abandonment monitoring of seismic activity				
PA-S3																		
Well																		
PA-W1	Abandonment plug deteriorating over time	All subsurface storage reservoirs	1	T		En			P	S				- Monitoring if possible				
PA-W2																		
Reservoir (subsurface)																		
PA-R1	Long term pressure changes due to thermal expansion of the cavern fluid. Differences in thermal gradients can also lead to additional dissolution and precipitation of the salt in the cavern	Storage in salt caverns	9, 11	T	Ec									- Post-abandonment temperature and pressure monitoring of the cavern				In a brine-filled cavern of great vertical extent, slow downward growth can take place because salt solubility is fractionally higher at the base; the thermal gradients generate slow convection currents causing salt deposition at the top of the cavern. However, the effects and potential problems might be less in a bedded salt deposit where the brine is saturated and the vertical cavern extent is perhaps only 50-100 m, with only a very small temperature difference likely across the cavern height.
PA-R2	Asymptotic pressurization, which is the gradual closure of large caverns due to salt creep. This can lead to substantial flexure and high strains in the overburden strata, which in turn can substantially increase their permeability.	Storage in salt caverns	9, 11	T	Ec									- Filling the cavern to a pressure just below that of lithostatic pressure before the cavern is sealed and abandoned is a means of restricting excessive strains, perhaps indefinitely. This requires that the cavern and access well(s) do not leak, which is not always the case and should this occur, brings with it problems that require previous planning. Thus post-gas storage cavern decommissioning/abandonment/mitigation planning strategies are worthy of note at this stage.				Asymptotic pressurization of a cavern relates more to when storage operations have ceased and the cavern has been abandoned following operations The analysis of creep effects alone shows that cavern pressure approaches that of the lithostatic only asymptotically if creep is the only process (i.e. no leakage). Over pressuring and possible hydraulic fracturing as a result is a possibility, but is thought unlikely.
PA-R3	Leakage/transport of the fluid out of the cavern into surrounding porous strata via porous non-salt interbeds	Storage in salt caverns	9	T										- water curtain represents an effective way of increasing hydrostatic pressure and preventing gas leakage - The gas tightness should have been studied for the operational phase				
PA-R4	Micro seismicity	All subsurface storage reservoirs	9	T										- Seismic monitoring				
PA-R5	Seismicity	All subsurface storage reservoirs	9	T										- Seismic monitoring				
PA-R6	Uncertainty on the lon-term creep- and permeation behavior of abandoned caverns that were used for storing gas	Storage in salt caverns																
Project specific																		
PA-P1																		

TAB: 6.All phases

	Date last modified:			Risk category							Risk assessor:		Project:		Type of energy storage			Version
	02 July 2020										LSES consortium		TKI LSES					1
6. General (for all subsurface storage types/applications)																		
Risk ID	**Risk description**	**Storage type**	**Reference**	**T**	**Ec**	**En**	**C**	**O**	**P**	**S**	**Consequence**	**Probability of consequence**	**Unmitigated Risk rating**	**Mitigations**	**Mitigated consequence**	**Mitigated prob. of consequence**	**Mitigated risk rating**	**Comments**
General																		
G-G1	Market distortions	All subsurface storage reservoirs	19		Ec		C		P	S				- Start with a low maximum energy production value, to reduce the occurrence of unforeseen rejected offers.				
G-G2	Best practices not applied leading to incidents or decreased performance	All subsurface storage reservoirs	28		Ec			O		S				- Detailed safety and health assessment - Assess the possible risks for each step				
G-G3	Changes in policies, laws, taxes and regulations put development / economy in jeopardy	All subsurface storage reservoirs	28		Ec		C	O	P	S				- Keep continuous monitoring of standards, technologies and political situation				
G-G4	Lack or loss of clients	All subsurface storage reservoirs	28				C	O		S				- Good bonding with the clients - Make the clients feel comfortable and keep them posted at all steps				
G-G5	Low financing for work leading to low safety standards	All subsurface storage reservoirs	28		Ec			O		S				- Preparation of cash reserves				
G-G6	Unsuitable contracts (roles and responsibility not clearly defined) leading to suboptimal performance or exploding costs	All subsurface storage reservoirs	28	T	Ec			O		S				- Select experienced and suitable management				
G-G7	Demand analysis and forecast are inaccurate	All subsurface storage reservoirs	28	T	Ec		C	O		S				- Get a good overview on the demand and forecasts				
G-G8	Financial risk prior to the start of the project	All subsurface storage reservoirs	16		Ec			O						- Significantly reducing uncertainty around encountering less favourable hydrologic properties than expected at the site - Reducing the pressure required to achieve the targeted injection rate and increasing the air storage volume efficiency in the structure.				
G-G9	Unanticipated delays and costs (materials, services, maintenance)	All subsurface storage reservoirs	28		Ec			O						- Include time/cost buffer in the planning				
Surface facilities																		
G-S1	External natural hazard damaging surface infrastructure	All subsurface storage reservoirs	28	T	Ec	En				S				- Thorough emergency planning (ERP) - Include adequate specifications for possible emergency scenarios				
G-S2	Anthropogenic hazard damaging surface infrastructure	All subsurface storage reservoirs	28	T	Ec	En				S				- Thorough emergency planning (ERP) - Include adequate specifications for possible emergency scenarios				
Well																		
G-W1	External natural hazard damaging well	All subsurface storage reservoirs	28	T	Ec	En				S				- Thorough emergency planning (ERP) - Include adequate specifications for possible emergency scenarios - Well design has safety measures (e.g. SSSV) if well can flow by itself				
G-W2	Anthropogenic hazard damaging well	All subsurface storage reservoirs	28	T	Ec	En				S				- Thorough emergency planning (ERP) - Include adequate specifications for possible emergency scenarios - Well design has safety measures (e.g. SSSV) if well can flow by itself				
G-W3	No (international) (design) standards available	All subsurface storage reservoirs	1	T					P					- Start procedure for international standards - Determine fit for purpose design considerations				
Reservoir (subsurface)																		
G-R1																		
Project specific																		
G-P1																		

TAB: 6.References

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Appendix 2 – Consequence & Probability matrix

Gevolgen			Waarschijnlijkheid (kans)				
ERNST (effect)	**Ernst label**	**Project**	**1**	**2**	**3**	**4**	**7**
			Zeldzaam	Onwaarschijnlijk	Geloofwaardig	Waarschijnlijk	Zeer waarschijnlijk
			Nog nooit voorgekomen in de industrie	Kan wel eens voorkomen in de industrie	Heeft zich voorgedaan in de industrie	Komt enkele keren per jaar voor in de industrie	Komt meerdere keren per jaar voor in de industrie
1	**A**	Geringe gevolgen	**1**	**2**	**3**	**4**	**7**
2	**B**	Kleine gevolgen	**2**	**4**	**6**	**8**	**14**
3	**C**	Aanzienlijke gevolgen	**3**	**6**	**9**	**12**	**21**
4	**D**	Grote gevolgen	**4**	**8**	**12**	**16**	**28**
7	**E**	Uitgebreide gevolgen	**7**	**14**	**21**	**28**	**49**

Streven naar continue verbetering

Niet acceptabel: Maatregelen nemen tot verlaging van het risico

Niet acceptabel: project stoppen!

Figure 3: Consequence – Probability ranking matrix for identifying whether the effect of the risk is acceptable or not acceptable, and whether mitigations should be taken or the project should stop. The matrix is based on DAGO, 2019. 20190903 DAGO Risico Matrix (QHSEP).

	Gevolgen									
ERNST (effect)	***Q = Kwaliteit***		***H = Gezondheid***		***S = Veiligheid***		***E = Milieu***		***P = Publieke Acceptatie***	
1	Geringe schade	Geen storing in het proces, geschatte reparatiekosten lager dan EUR 5.000.	Gering gezondheids effect/letsel	Niet schadelijk voor de individuele inzetbaarheid of voor de uitvoering van het werk.	Gering risico	Gering lichamelijke of psychische schade aan personen. Gering verlies / schade aan installatie(delen). Geringe verstoring van de productie.	Gering effect	Verwaarloosbare financiële gevolgen. Lokaal milieurisico, binnen de installatie en/of systeem.	Geringe invloed	Geringe invloed op de publieke acceptatie.
2	Kleine schade	Mogelijk korte verstoring van het proces, geschatte reparatiekosten lager dan EUR 50.000.	Klein gezondheids effect/letsel	Schadelijk voor de uitvoering van het werk, beperking van de activiteit, maximaal één week nodig voor volledig herstel. Gebruik chemische middelen die in beperkte mate op de gezondheid van invloed zijn, zoals bijvoorbeeld irriterende stoffen.	Klein risico	Gewonden hebben lichte medische zorg nodig en kunnen het werk direct hervatten. Beperkt verlies / schade aan installatie(delen). Beperkte verstoring van de productie.	Klein effect	Verontreiniging; schade zodanig dat er gevolgen zijn voor het milieu. Kleine incidentele overschrijding van wettelijke criteria. Geen permanent effect op het milieu.	Kleine invloed	Lichte lokale media en/of lokale politieke aandacht, met potentieel negatieve aspecten voor de operator.
3	Lokale schade	Langdurige verstoring van het proces, geschatte reparatiekosten lager dan EUR 500.000.	Groot gezondheids effect/letsel	Leidt tot blijvende of gedeeltelijke arbeidsongeschiktheid. Of ongeschikt voor het verrichten van werk over een langere periode, langdurige afwezigheid. Gebruik chemische middelen die onomkeerbare schade veroorzaken - zonder enrstige handicap, bijvoorbeeld lawaai, slechte arbeidsomstandigheden.	Lokaal risico	Gewonden hebben medische zorg nodig en kunnen het werk niet hervatten. Vervanging / reparatie van installatie(delen) beperkt zich tot een paar dagen stilstand. Berichtgeving door lokale media.	Lokaal effect	Beperkte lozing op de omgeving van een bekende stof met geringe toxiciteit. Herhaalde overschrijding van wettelijke criteria.	Aanzienlijke invloed	Regionale publieke bezorgdheid. Uitgebreide negatieve aandacht in de lokale media en/of politiek. Met als gevolg een mogelijk negatieve houding bij de lokale overheid en vorming van actiegroepen.
4	Grote schade	Installatie voor maximaal zes maanden buiten bedrijf en/of geschatte reparatiekosten lager dan EUR 5.000,000.	Permanent arbeidsongeschikt tot 1 dode	Permanente invaliditeit of de mogelijkheid tot één dode als gevolg van een incident, bijvoorbeeld een explosie. Gebruik chemische middelen die onomkeerbare schade veroorzaken met ernstige handicap of overlijden, bijvoorbeeld corrosieve stoffen of bekende carcinogene stoffen.	Groot risico	Een ernstig gewonde of zelfs een enkel sterfgeval. Herstel van installatie(delen) leidt tot een verstoring van de productie van meer dan een maand. Berichtgeving door nationale media.	Groot effect	Ernstige milieuschade; het bedrijf moet uitgebreide maatregelen treffen om de vervuilde omgeving weer in de oorspronkelijke staat te herstellen. Uitgebreide overschrijding van wettelijke criteria.	Nationale invloed	Nationale publieke bezorgdheid. Uitgebreide negatieve aandacht in de nationale media en/of politiek. Met als gevolg een mogelijk negatieve houding bij de nationale overheid en vorming van landelijke actiegroepen.
7	Uitgebreide schade	Uitvallen van delen van de installatie, geschatte reparatiekosten meer dan EUR 10.000.000	Meer dan 1 dode	Mogelijk meerdere doden als gevolg van een incident, bijvoorbeeld een explosie. Gebruik van chemicaliën met acute toxiteitseffecten (waterstofsulfide, koolmonoxide) of bekende carcinogene stoffen.	Enorm risico	Meerdere ernstig gewonden of doden. Significant verlies / schade van installatie(delen), met enkele maanden stilstand tot gevolg. Berichtgeving door internationale media.	Enorm effect	Aanhoudende ernstige milieuschade of overlast die zich uitstrekt over een groot gebied. Een groot verlies van natuurwaarde. Constante hoge overschrijding van wettelijke criteria.	Internationale invloed	Internationale publieke bezorgdheid. Uitgebreide negatieve aandacht in de internationale media en/of politiek, met potentieel ernstige gevolgen voor toegang tot nieuwe wingebieden. Vorming van internationale actiegroepen.

Figure 4: Matrix for interpreting the consequence – probability relationship of a risk. The matrix is based on DAGO, 2019. 20190903 DAGO Risico Matrix (QHSEP).