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Operational Insights into Safe Underground Hydrogen Storage System

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Today, our energy system is undergoing a transition to reduce greenhouse gas emissions, pursuing more sustainable and environmentally friendly energy solutions. The new renewable energy solutions such as wind and solar power are entering the system with a larger share. However, they also are weather and season dependent, demanding greater operational flexibility in the energy system. Hydrogen is a promising solution to deal with the fluctuations in the system (i.e., unbalanced supply and demand). Nonetheless, utilizing hydrogen for balancing purposes requires efficient and large-scale storage solution. Storing hydrogen safely on a large scale brings about challenges related to technical, human, and social factors that still need further research to be addressed properly. After all, hydrogen is highly flammable and prone to ignition and explosion, so well maintained and specialized storage system is needed to detect and prevent hazardous escalations such as leakages. Human errors made in design and operation are one of the main causes of hydrogen incidents and accidents. Accordingly, human factors aspects should be better addressed to guarantee storage safety. In this paper, based on Hydrogen UnderGround (HUG) research project, we focus on human and social factors in the operation of hydrogen storage. Specifically, we aim to shed light on the demands of underground hydrogen storage from the operator perspective. For this purpose, we conducted work domain analysis, included in cognitive work analysis methodology, to better understand the hydrogen storage as a sociotechnical system and its functional structure with respect to its purposes and constraints on human actors. Creating this understanding is a prerequisite for further development of the system, that is, for setting appropriate requirements and creating an operational concept for the storage system. Our results preliminarily show the complexity and extent of operational perspectives, including human factors, needed in a large-scale underground storage system.

Keywords: Human factors, underground hydrogen storage, operator work, work domain analysis.

1. Introduction

The global energy landscape is undergoing a significant transformation aimed at reducing greenhouse gas emissions and promoting sustainable, environmentally friendly energy solutions. This transition is characterized by an increasing integration of renewable energy sources, such as wind and solar power, into the energy system. While these renewable sources offer substantial environmental benefits, their inherent dependency on weather and seasonal conditions introduces a need for greater operational flexibility within the system.

Hydrogen has emerged as a promising solution to address the fluctuations in energy supply and demand. Its potential to act as a balancing agent in the energy system call for the development of efficient and large-scale storage solutions for hydrogen. However, the safe storage of hydrogen on a large scale presents numerous challenges, encompassing technical, human, and social factors that require thorough research and innovative solutions. For example, it is not well understood yet what would be the best liner solution in the context of lined rock caverns (LRCs), what kind of maintenance work should be carried out during the expected lifetime of the storage and what should and can be monitored in the storage operation.

Hydrogen's high flammability and susceptibility to ignition and explosion necessitate the implementation of specialized storage systems capable of detecting and preventing hazardous incidents, such as leakages. Human errors in the design and operation as well as flaws in organization and management of these storage systems are a primary cause of hydrogen-related accidents (Alfasfos et al., 2024, Wen et al., 2022), underscoring the importance of addressing human factors to ensure storage safety.

This paper is grounded in the Business Finland funded Hydrogen UnderGround (HUG) research project that aims in creating a basis for a large-scale underground hydrogen storage (lined rock cavern, LRC) concept for Finnish needs. Our share of the project focuses on the human and social factors involved in the operation of underground hydrogen storage (UHS) systems. Specifically, we aim to illuminate the demands of UHS from the perspective of operations and critical human tasks.

Developing this holistic understanding is crucial for the further advancement of underground hydrogen storage systems. It lays the foundation for establishing appropriate requirements and creating an operational concept that ensures the safe and efficient storage of hydrogen.

The continuation of this paper is as follows. We first review related research on underground hydrogen storage, focusing on human factors, and summarize key findings. Then, we introduce the specific research project, and the domain analysis method used to model the storage system's operation. We also present an initial model describing the underground hydrogen storage system's functional structure through an abstraction hierarchy.

2. Related Research

In this section, we briefly review scientific publications and industry learnings from the perspective of human factors, focusing specifically on the aspects relevant to (underground) storage for (gaseous) hydrogen. It is important to note that the entire content of each publication is not described; instead, we highlight the elements pertinent to our study, that is, the operation of the storage and human operators work tasks. Our review reveals a limited number of publications directly addressing UHS from a human factors perspective. This scarcity underscores also the need for further research in this area.

2.1. *Hydrogen Qualities Affecting the Human Operations*

Hydrogen's extreme flammability and ease of ignition under specific conditions pose significant risks (Lamari et al., 2024). Its high burning velocity increases detonation chances. Hydrogen leaks are more likely and have a higher volume flow rate compared to other inflammable gases, like methane, due to its small molecular size and low viscosity. Being 14 times lighter than air, hydrogen disperses rapidly in open environments but requires careful monitoring in confined spaces, necessitating effective leak detection systems and ventilation. These characteristics demand rigorous safety measures by human operators, and high-capacity storage presents challenges, including simple physical or chemical operations, fast kinetics for intermittent production and delivery, and safe management modes.

Underground hydrogen storage is promising for large-scale storage but involves potential losses due to gas leakage through faults and fractures, and gas loss from underground chemical and biological reactions (Tarkowski & Uliasz-Misiak, 2022). These issues require management during the design and operational phases. The large volume of stored gas necessitates tools to detect and address even small leaks, with procedures in place for identification. Long storage periods can lead to chemical and biological reactions, necessitating detection and control by operators. Hydrogen must be compressed to minimize volume, with system pressure changes monitored to identify leaks.

Limited research on hydrogen behaviour in rock masses makes anticipating operational and maintenance challenges difficult. Cyclic hydrogen injection and withdrawal can affect underground storage integrity, causing pressure changes and stress system alterations, leading to potential hydrogen migration pathways. Safety implications differ from other gases, with hydrogen loss posing significant safety, economic, and environmental concerns. Lessons from underground natural gas storage can be beneficial, but the impact of hydrogen's physical properties on storage safety is not well understood. Methods to monitor hydrogen behaviour and potential surface migration are needed, with main leakage points, such as injection and withdrawal points, requiring monitoring to maintain storage integrity.

2.2. *Lessons Learned from Hydrogen Incidents and Accidents*

Analysis of various datasets reveals that human or 'soft' factors were responsible for more than half of the analyzed hydrogen events (Alfasfos et al., 2024; Wen et al., 2022). In Alfasfos et al. (2024) review, identified causes include equipment failure, design flaws, inadequate venting design, material incompatibility, lack of hydrogen detection equipment, and improper relief valve set points. Human factors such as failure to follow procedures, training issues, individual actions, situational awareness, assembly errors, and poor housekeeping also contributed significantly. Process management deficiencies, including incomplete operation & maintenance (O&M) procedures, lack of protocols, inadequate system monitoring, and communication issues, were also prevalent in the database.

In a review of HIAD 2.0 database (Wen et al., 2022) identified many incidents related to job factors, such as inappropriate design of equipment, missing or unclear instructions, poorly maintained equipment, high workload, and unpleasant working conditions). Individual factors, including inadequate skill levels, tired or disheartened staff, and medical problems, also played a role. Safety management system factors, such as poor planning, lack of safety systems, and poor health and safety culture, further exacerbated risks.

These lessons learned from the Wen et al. (2022) review emphasize the need to consider safety issues early in the design and development process, as similar causes often underlie different incidents. Human error in handling hydrogen can have severe consequences, with most incidents in job and individual factors categories caused by lack of regular maintenance and inspections. Unclear instructions and inadequate staff training were also significant issues. Emergency services often lack knowledge about hydrogen accident scenarios, highlighting the need for quick action and effective emergency response measures.

Guo et al. (2024) have reviewed hydrogen safety issues during its production, transportation, storage, and utilization. According to them, ensuring the safety and reliability of hydrogen energy is essential both for public acceptance as well as hydrogen economy at large. According to Guo et al. the incompatibility between hydrogen and steel materials can cause hydrogen embrittlement in storage vessels, while hydrogen's wide flammability range in air raises concerns about large-scale deployment. Consequently, ensuring safety is a prerequisite for the widespread application of hydrogen energy. One key issue according to them is that the large-scale application of hydrogen energy requires safe and cost-effective storage solutions, which face challenges due to high permeation, low temperature, and high operating pressure. Moreover, potentially resulting hydrogen leakage, due to its low density and high diffusivity, is difficult to detect and thus poses a risk of explosive accidents. Recent reviews on hydrogen industry have identified human errors as major cause of hydrogen accidents, which Guo et al. states to highlight the need for improved safety design and training. The authors conclude that, addressing safety issues in hydrogen production, storage, delivery, and utilization is vital for the hydrogen economy's development.

Schultz et al., (2022) emphasize the importance of large-scale approach in developing underground energy-related product storages. For example, risk analysis is essential for identifying and evaluating threats and hazards, and their potential impact on facilities. After which, development of adequate risk anticipation and mitigation plans from a human operator perspective may take place. Also, a comprehensive monitoring program is needed to ensure facilities operate as designed and to identify and mitigate unforeseen issues. Authors state that human factors play a critical role in the site characterization, construction, and operational phases of projects. Which is why establishing an industry-wide collaborative process for documenting and sharing operative experiences and information about incidents and near-misses is necessary.

As reported in above studies, the human and social factors in hydrogen industry are still not very well covered and discussed. Realizing safe hydrogen storage and operation demands holistic and systematic methods that consider multiple perspectives, including human and social factors. Many issues still require further research and in-depth understanding.

3. Study on the Operation of UHS

The operation-centered tasks in HUG project are expected to support the designing of responsible operations, critical operator roles and resources. The literature review that we conducted at the beginning of the project revealed that not much is published about hydrogen storage operations. To establish a solid foundation for this operational point of view, we conducted a work domain analysis to understand UHS as a sociotechnical system. The analysis is based on publications about hydrogen; part of the publications is directly about hydrogen related operations and part about hydrogen qualities, which assumably affect hydrogen related operations.

4. Method and Data Acquisition

Cognitive work analysis (CWA) is a framework that is used to analyse complex sociotechnical systems, focusing on how work can be done in a system (e.g., Naikar, 2013). It includes several analysis methods, each focusing on some perspective on operator work. Common to all these methods is the emphasis on understanding the constraints the work environment sets on operators and on how operators adapt to these constraints to achieve work goals.

In this study, we used work domain analysis (WDA) that represents one branch in CWA. WDA is a large-scale analysis focusing on understanding the constraints and affordances of the work environment (e.g., Naikar, 2013). This analysis examines the functional structure of the system, evaluating the system independent from the tasks or specific users. It helps in understanding operators' needs, requirements and demands for designing human-centred-systems; hence, it is especially suitable for our present phase of research in the HUG project.

WDA is composed of five hierarchical system levels to be analysed, from highest to lowest, as follows (Salmon et al., 2024):

- *Functional purpose*: the overall purposes of the system and its reasons for existence,
- *Values and priority measures*: the values that are used to measure the system's progress towards the purposes,
- *Purpose-related functions:* the general functions of the system that must be undertaken to achieve the functional purposes,
- *Object-related processes*: the processes that the physical objects within the system enable, and
- *Physical and cognitive objects*: the physical and cognitive objects that are used for object-related processes.

The five levels of the system serve each other; a higher level answers the question "Why", the lower level next to it answers the question "What", and the level below that answers the level "How" (Fig. 1). We used the above-mentioned system levels for describing the underground hydrogen storage system operation.

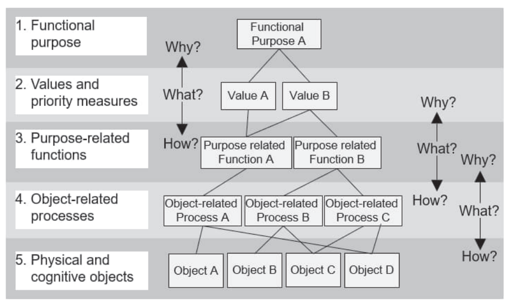

Fig. 1. A schematic illustration of the means-ends links in an abstraction hierarchy model; redrawn and modified from Salmon et al., 2024.

5. Results

Based on the review of the literature and discussions in the HUG project meetings and workshops, a preliminary WDA model describing an underground hydrogen storage system was developed (Figure 2, see in more readable form in Appendix A.1). The resulting model is rather general in nature. However, this initial model is expected to be iterated and modified further, for example, to accommodate specific business models or physical storage solutions.

For the UHS in Finnish LRC context, two main functional purposes (i.e., reasons for existence) were identified: firstly, to have a safe and efficient underground storage of large amount of hydrogen for extended period of time and, secondly, to enable clean energy (hydrogen) delivery for intermittent energy production and demand.

Thereafter, when proceeding analysing lower levels in the mode, the model expands strongly. We identified 12 value and priority measures (see Figure 2, 2. level), such as (i) maximise structural integrity, (ii) maximise surveillability of storage system, (iii) maximise the adherence on regulations and industrial standards, and (iv) maximise the control of storage system (e.g., optimal human-automation function allocation).

Examples for purpose-related functions (3. level in Figure 2), functions of the UHS that must be undertaken to achieve its functional purposes, 11 in total in our model, are (i) real-time monitoring, (ii) hydrogen injection, storage, and withdrawal management, (iii) maintaining human situation awareness over the storage system. and (iv) safety and emergency management.

The number of object-related processes (4. level in Figure2) is already triple, 31 objects, such as (i) data collection and archiving from sensors, (ii) pressure control, (iii) risk assessment and management, and (iv) environmental inspection.

The number of physical and cognitive objects, objects that are used for producing object-related processes, is already exceeding hundreds in quantity in our analysis. However, for illustrative purposes in UHS model in the Figure 2 the lowest level objects are grouped under three main categories/entities that are (i) storage as a physical object and structure (e.g., layout of the storage, cavern/s shape & size, liner material and structure), (ii) storage equipment (e.g., automation

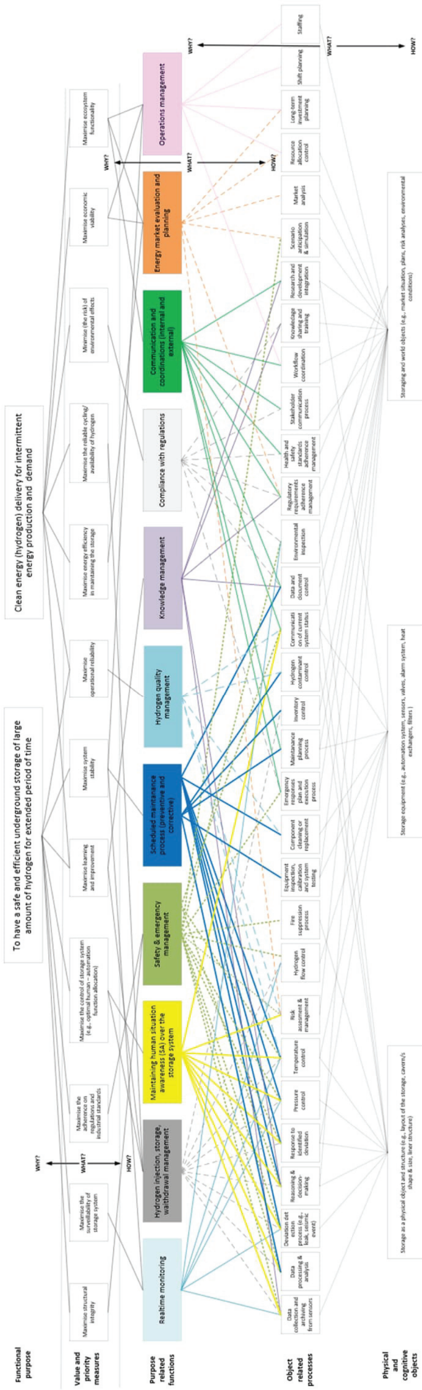

Fig. 2. A preliminary WDA model of UHS (with better resolution in Appendix A.1).

system, sensors, valves, alarm system, heat exchangers, filters), (iii) storaging and world objects (e.g., market situation, plans, risk analyses, environmental conditions). To gain an initial understanding of UHS operation, it may not be meaningful or even possible to list all physical and cognitive objects (5. level) related to the storage system. However, as the design process progresses and engineering plans become more concrete, examining the operation of individual systems (e.g., critical human tasks and potential sources of human errors) also in this lowest level may prove helpful.

6. Discussion and Conclusions

The aim of the study was to create a general-level description of a safe hydrogen storage system through a work domain analysis. The concept of safe operations seems to include, in our WDA model, a myriad of functions that cannot be found in human factors literature related to hydrogen industry but can only be concluded based on incident and accident databases or more technical publications. Even less can be found in the literature regarding human factors research related to hydrogen storage, not to mention the local socio-technical conditions in Finland and the opportunities and challenges they create.

The resulting model (although still described at a very general level) is rather large with many objects, especially in the lower levels. The general nature was not easy to maintain for two reasons; firstly, any system tends to have its own specific purpose especially when there are not many such systems, so the development of a general-level model is a somewhat impossible task, and secondly, the poor availability of information may have resulted in having gaps and even misunderstandings in initial model formation. To further develop the model and make it more elaborated, it should be iterated with experts and specialists who understand the various functions and content.

There were also challenges in model formation. It was sometimes hard to maintain the same level of abstraction in each level of the WDA model. For instance, in the lowest level about the physical objects there could be sensors valves and the like, but we also chose to include there automated response systems and other, higher-level objects to ensure that everything relevant is included.

The HUG project aims to develop a comprehensive understanding of underground hydrogen storage in Finnish context, with a focus on three specific use cases. The project will culminate in an in-depth exploration of one of these three use cases. It is anticipated that the WDA models for the different use cases will vary to some extent, as the functional purpose (i.e., reasons for existence) of the storage in each case is unique. This functional purpose influences the content of the other levels as one moves down the abstraction hierarchy. Consequently, it is expected to highlight the specifics of each use case and guide their further development. From the human factors and social point of view the WDA models may also help to identify the critical human – system interactions that need to be supported and actively addressed in the design and development in order to the future underground hydrogen storage to be safely operated and maintained.

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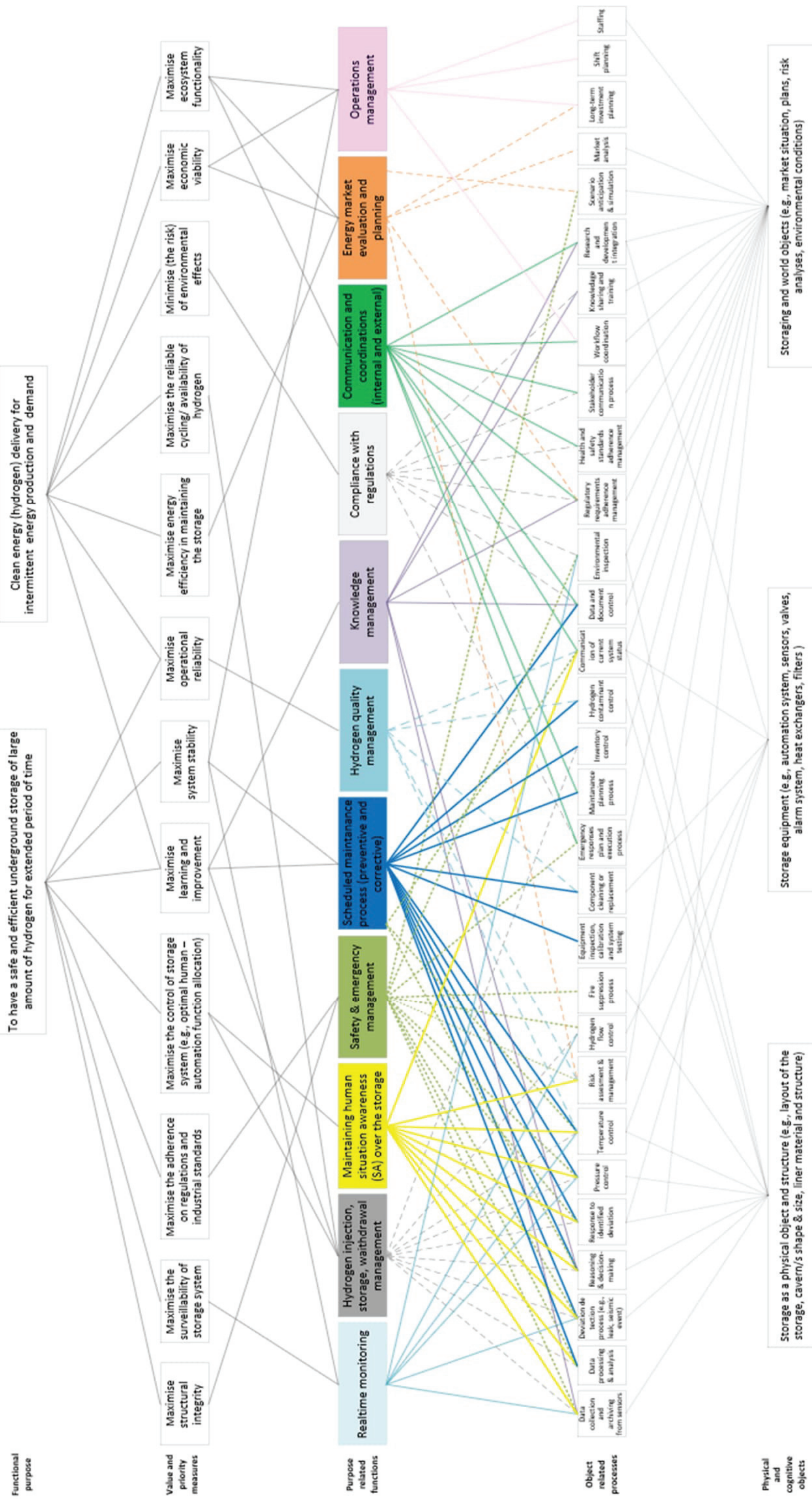
Appendix A.1


Functional purpose
Value and priority measures
Purpose related functions
Object related processes
Physical and cognitive objects
Clean energy (hydrogen) delivery for intermittent energy production and demand
To have a safe and efficient underground storage of large amount of hydrogen for extended period of time
Maximise ecosystem functionality
Maximise economic viability
Minimise (the risk) of environmental effects
Maximise the reliable cycling/ availability of hydrogen
Maximise energy efficiency in maintaining the storage
Maximise operational reliability
Maximise system stability
Maximise learning and improvement
Maximise the control of storage system (e.g., optimal human – automation function allocation)
Maximise the adherence on regulations and industrial standards
Maximise the surveillability of storage system
Maximise structural integrity
Operations management
Energy market evaluation and planning
Communication and coordinations (internal and external)
Compliance with regulations
Knowledge management
Hydrogen quality management
Scheduled maintanance process (preventive and corrective)
Safety & emergency management
Maintaining human situation awareness (SA) over the storage
Hydrogen injection, storage, waithdrawal management
Realtime monitoring
Storaging and world objects (e.g., market situation, plans, risk analyses, environmental conditions)
Storage equipment (e.g., automation system, sensors, valves, alarm system, heat exchangers, filters)
Storage as a physical object and structure (e.g., layout of the storage, cavern/s shape & size, liner material and structure)

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