STRENGTH OF KNOWLEDGE AND UNCERTAINTIES IN SAFETY REGULATION OF HYDROGEN AS AN ENERGY CARRIER

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ABSTRACT

Ahead of a potential large-scale implementation of hydrogen as an energy carrier in society, safety regulation systems should be in place to provide a systematic consideration of safety related concerns. Knowledge is essential for regulatory activities. At the same time, it is challenging to obtain sufficient information when regulating emerging technologies – it may be difficult to address informational shortcomings in regulatory matters as analysts can be prone to under-communicate the significance of uncertainties. Furthermore, Strength of Knowledge (SoK) has been developed to address the quality of background knowledge in risk analyses. An example of a SoK framework, is based on the following four conditions that is used to assess whether knowledge can be considered weak or strong: the issue of simplifications, availability and reliability of data, consensus among experts, and general understanding of the phenomena in question. In theory, this concept seems relevant for the introduction of hydrogen as an energy carrier, mainly because there is little historical data to develop sound analyses, creating uncertainties. However, there are no clear-cut guidelines as to how knowledge gaps should be handled in the development of regulatory requirements. In this paper, we consider the relevance of a specific approach for SoK assessment in the context of safety and security regulation of hydrogen as an energy carrier in society. We conclude that there are some challenges with the proposed framework and argue that further research should be conducted to identify or develop a method for handling uncertainties in regulatory processes, regarding hydrogen systems as energy carriers in societies.

1.0 INTRODUCTION

In an environmental perspective, hydrogen can be considered a favourable alternative to conventional energy carriers because it can be produced and utilized without emitting carbon dioxide. Therefore, the potential for reducing climate gas emissions in carbon-intensive sectors are significant, which has prompted national and international strategies and roadmaps to identify potential application areas. Based on these documents it is expected that hydrogen-based technologies will be applied in transportation systems, industrial and chemical processes as well as commercial heating in the near future to reduce emissions [1,2]. Though it is expected, based on the European Union's hydrogen strategy for instance, that hydrogen will become an integral part of the future energy supply, it is not yet an important source of energy in the European energy market [3]. Further, technological advances are required to make hydrogen a cost-efficient alternative to conventional energy carriers and sources [1]. The future of hydrogen as an energy carrier is therefore characterised by uncertainties.

Though there are obvious environmental benefits with replacing carbon-intensive solutions with hydrogen-based technologies, there are challenges related to safety and security-related aspects of the regulation of hydrogen. The possibilities of implementing hydrogen as an energy carrier are often highlighted in national and international strategies, while safety related aspects are left out [4]. At the same time, as hydrogen is a reactive chemical, there are safety implications related to the introduction of hydrogen-based technologies in society that call for attention to how these aspects should be addressed. Though knowledge from current hydrogen practices can be utilized, or knowledge transferred from comparable systems (e.g. the oil and gas industry), lack of knowledge and uncertainties may become an issue. We argue that there is an urgent need to reconsider regulations for the piloted systems (ferries, commercial sea transport, heavy goods vehicles, road transport) – the state of knowledge varies within the hydrogen value chain. In this paper we therefore focus on how safety and security should be regulated given a large-scale implementation of hydrogen in society. Our primary focus is on knowledge and uncertainties in the development of a regulatory system for hydrogen as an energy carrier in society.

It cannot be expected that the regulator will have sufficient information to develop a regulatory system without external output and it can be expected that they must rely on input from governmental and non-governmental entities with more in-depth knowledge about phenomena, activities, hazards, etc. to provide a regulatory framework. Because regulators are dependent on different sources of information, the concept Strength of Knowledge (SoK) seems highly relevant to be able to determine the quality of knowledge that the regulatory process will build on.

Since we are addressing safety and security regulation, it seemed logical to search for approaches to address uncertainties within the domain of risk and safety. SoK is a framework used to assess quality of information or knowledge [5–7] . The following four aspects are used to grade the knowledge as either strong, moderate or weak: simplifications, availability and reliability of data, consensus among experts, and general understanding of the phenomena [6]. SoK has primarily been discussed in relation to quantitative risk assessments, probability judgements, resilience analysis, etc. [5,6,8–10]. In this paper, the concept will be used in a slightly different context – to address uncertainties and informational shortcomings in regulatory matters. SoK seems relevant for the introduction of hydrogen-based energy carriers, mainly because there are uncertainties related to an expected increase in production, storage, and distribution of hydrogen in society and the technological developments that may occur in the coming years. Conceptualizations of uncertainty and quality of knowledge could therefore be important to ensure transparency and that the regulations are based upon a solid foundation that is self-reflected by the developers.

In this paper, we assume that large-scale implementation of hydrogen as an energy carrier in society is being realised and that this requires the development of a regulatory system that maintain safety and security-related aspects. In this scenario, hydrogen will become more present in society – exposing citizens without knowledge of or experience about hazardous substances with hydrogen in various forms. Furthermore, the expected increase in production, storage, distribution, and application is sufficient reason to consider the need for a regulatory system that account for these amounts. This regulatory system will be based on assumptions about a future state of hydrogen as an energy carrier, creating a need to address the knowledge gaps and related uncertainty. However, it is not obvious how this should be handled in the development of regulatory systems. Due to the complex nature of safety and security regulation – a multitude of actors with different intentions and contributions in terms of knowledge – the overarching aim of the paper is to develop an understanding of how uncertainties and knowledge could be addressed in the development of regulatory systems. We will use examples from a Norwegian scenario for large-scale implementation of hydrogen as an energy carrier because this is a system and a context that the authors are familiar with, and it is useful to provide examples of key aspects. However, we expect that the analysis, discussion, and findings are equally relevant for an international audience.

2.0 THEORETICAL FOUNDATION

To address the issue of knowledge and uncertainty in relation to safety and security regulation, theoretical perspectives on regulation and knowledge will be explained in the following section.

2.1 Safety Regulation

Regulation is commonly referred to as “the sustained and focused attempt to alter the behaviour of others according to defined standards and purposes with the intention of producing a broadly identified outcome or outcomes, which may involve mechanisms of standard-setting, information-gathering and behavior modification” [11]. In this paper, we address safety and security regulation and the broadly identified outcome will therefore be to maintain or enhance safety and security.

Though risk regulation is a commonly used concept in the matter of regulatory efforts related to risk, safety, and security, we address safety and security regulation due to the ambiguous nature of risk and risk regulation. Despite the frequent use of risk regulation, it is not necessarily clear what it entails [12,13] and different aims are stated in the literature [14–16] or not at all [12]. The lack of conceptual clarity for risk regulation is not made easier when risk itself has a multitude of diverging perspectives and definitions – a fact that is often overlooked [17].

Regulatory efforts concerning a thematic area, can be understood as regulatory systems or regulatory regimes [14]. In a systemic perspective, it is assumed that governmental institutions with judicial authority, private entities that are being regulated, and the society will influence a regulatory system [14,18], see Figure 1.

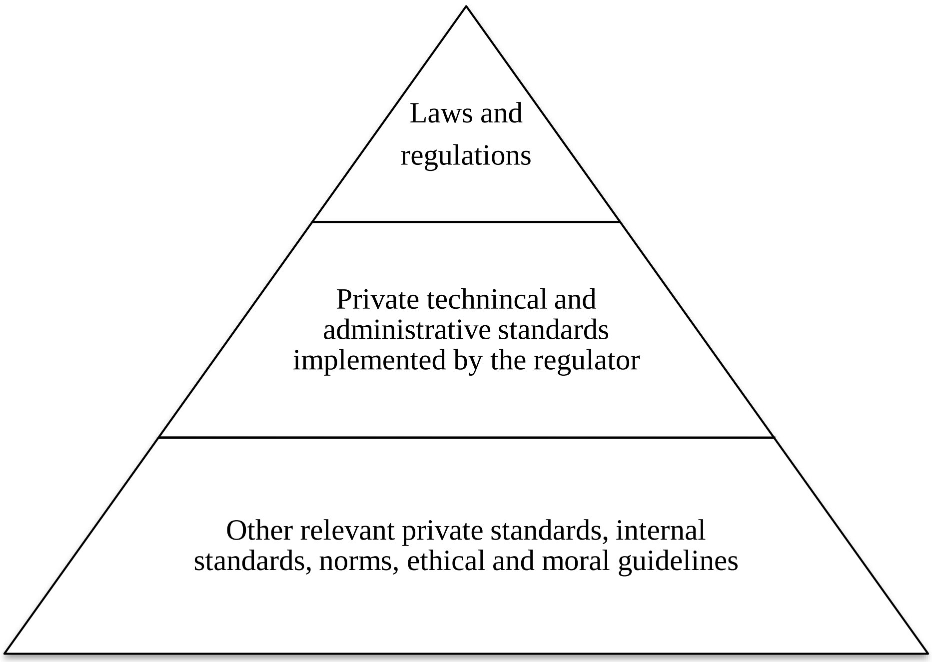

Figure 1. Hierarchical levels of contributions to regulatory systems [18].

The upper two levels of the pyramid consist of regulatory work that is legally binding – either developed or implemented by a regulatory agency. The third level represent aspects that, though not formalized or legally binding, are influential in the life cycle of a regulatory system. The standards referenced at this level have not been adopted by the regulator and compliance with these are therefore voluntary.

As illustrated in Figure 1, though often perceived as a governmental task, private entities can influence regulatory systems, for instance through development of industrial standards or participation in national or international standardization processes. In accordance with this perspective, one can assume that a regulatory system consists of more than formalized legal requirements. Furthermore, all levels in the pyramid can be directly, or indirectly, influenced by international organizations etc. Within the European Union (EU), member states are obliged to implement directives and regulations [19]. For instance, in a Norwegian context the regulation of hydrogen as a hazardous substance is predominantly regulated through EU directives implemented in the national judicial system [20], which exemplifies how international influence could be an important factor to consider when studying regulatory systems.

Currently, hydrogen is not regulated as an energy carrier with the possibility of a large-scale implementation in mind. However, the Norwegian Directorate for Civil Protection have provided an overview of current regulations that may be relevant in the context of hydrogen as an energy carrier that consist of: Regulations concerning Major Accident Hazards (The Seveso Directive), Regulations relating to the Handling of Hazardous Substances (a national regulation), The Pressure Equipment Directive, Regulation on Health and Safety in Explosive Atmospheres (ATEX), Regulations concerning the International Carriage of Dangerous Goods by Road and by Rail (ADR / RID), Regulations relating to Transportable Pressure Equipment, and Regulations relating to Systematic Health, Environmental, and Safety Activities in Enterprises – Internal Control Regulations. These are mainly, with two exceptions, EU directives that target different aspects of hydrogen as a hazardous substance. A large-scale introduction of hydrogen as an energy carrier will significantly alter the preconditions for the current regulation – as mentioned the amounts of hydrogen will increase as well as the presence of hydrogen in society (and people without in-depth knowledge about its chemical properties and hazardous potential). Though it may not require a full set of new laws, regulations, handbooks, etc. it is highly relevant to consider the shift from relatively restricted activities (in terms of amounts and enclosure) to more widespread presence of hydrogen in many new spheres and the safety related implications. Moreover, it is important to note that in terms of standards, there are ongoing efforts to develop regulations that account for a possible large-scale implementation of hydrogen as an energy carrier [21].

2.1.1 Developing and Designing Regulatory Systems

Knowledge about the field that is being regulated is essential for regulatory processes – e.g., for the identification of regulatory gaps, developing proposals, providing, and receiving feedback from affected actors (industry etc.), and for ensuring compliance. In the context of safety and security regulation, one source of information may be risk and vulnerability assessments to identify critical processes or areas that should be given regulatory attention to avoid incidents. Though risk assessments are a natural source of information in the context of the system in question, it is important to note that there may be challenges in the implementation / use of the information provided. In a study of how to better the use of science in EU Regulations, Schrefler and Pelkmans address the potential shortcomings in regards to decision-makers lack of experience with risk assessments in general [22]. Further, van Asselt, Vos and Wildhaber argue that it is important to recognize the influence of social, ethical, and political concerns in regulatory matters, in addition to e.g., risk assessments [23]. The interpretation and use of information from reports, assessments etc. can be affected by factors such as educational background, past experiences, etc. – which might be especially important to keep in mind considering the (political) pressure towards achieving net zero and therefore the need to balance environmental benefits and safety-related concerns.

The European Commission has addressed the need for regulations in relation to the introduction of hydrogen as an energy carrier [24]. Interestingly, the primary focus of this regulatory work seems to be on economic regulation and particularly concerning pipelines that could be the main form of distribution of hydrogen across Europe [25]. Though the focus has not been on the safety related aspects, it is interesting to note that it is assumed that the EU can draw on knowledge and experience from other regulatory processes, such as electric power and gas, when considering regulations for the hydrogen sector [25].

Furthermore, the development of regulatory systems requires choosing suitable and efficient regulatory strategies which is a process that could be affected by the availability of knowledge and the degree of uncertainty. The matter of designing a regulatory system can be complex, as there are different regulatory strategies that each have strengths and weaknesses [26–28]. Sometimes, this complexity is reduced to the choice between two overarching regulatory strategies; prescriptive or performance-based regulation [29]. Whereas performance-based regulation defines a goal that should be achieved, and the means is determined by the regulated, a prescriptive strategy details which solutions etc. that should be implemented by the regulated entity [28]. Here, a major difference is the degree of governmental control versus freedom for the regulated entities. At the same time, the perspective on regulatory strategies can be broadened to allow for a more nuanced viewpoint. It is assumed that some regulatory strategies can prove more or less efficient based on characteristics in the system that is being regulated (such as knowledge about the regulated area) [27] though establishing the most efficient strategy may be a complex process [30]. Regulatory strategies are relevant for this paper since the availability of knowledge may be a factor that affect the suitability and choice of strategies.

2.2 Knowledge and Uncertainties

The future of hydrogen as an energy carrier is unknown. Though we can assume, based on strategy documents, research efforts, etc., that e.g., hydrogen technologies will be introduced in the maritime sector, we lack knowledge about when, to what extent, etc. and the related safety and security related aspects that should be handled through regulatory measures. Knowledge is essential for regulatory activities – and regulators developing a regulatory system for hydrogen as an energy carrier may be dependent on a variety of actors to provide necessary information. The field is too complex to assume that the regulator can have sufficient knowledge independently from entities involved in the value chain. Therefore, it is relevant to consider how the quality or strength of the knowledge provided can be assessed. In this section, we will clarify our perspective on knowledge (and its relation to uncertainty) and present an SoK framework. The latter will be discussed in relation to the development of a safety and security regulatory system for hydrogen as an energy carrier in society.

2.2.1 What is Knowledge?

In the context of SoK assessments, Aven and Flage state that "uncertainties are related to knowledge, and hence, describing uncertainties is about describing not only the knowledge itself but also the quality of this knowledge" [31]. Furthermore, it is often assumed that "if we had adequate knowledge we could reduce uncertainty and hence predict the future with greater accuracy" [32]. Njå et al claim that this is a misunderstood approach and it assume that uncertainty is a well-defined specific concept independent of contexts. It is not. There are huge differences in the interpretation of scientific uncertainty of the present, lack of knowledge amongst the regulators/analysts, the uncertainty related to historical data and uncertainty about the future. In order to understand SoK it is important to note the difference between uncertainties in the past and present and uncertainties about the future.

Thus, knowledge is about the epistemological reflection about hydrogen systems being applied to society. Knowledge could be considered as justified true beliefs about hydrogen systems in the actual contexts. Although there exists no universal scientific accepted definition of knowledge, its connection with uncertainty is important. Uncertainty of the past influence knowledge through causality assessments, observations and understanding of contexts in which events occurred. Furthermore, uncertainties of the present relate to how well hydrogen phenomena are scientifically understood, for example ignition phenomena or social hydrogen risk and safety perception, or deflagration to detonation (DDT) phenomena in various contexts and systems. Expertise and expert performance have become scientific domain describing humans and systems that correctly assess and execute problems within their fields [33]. The situation is complex, and SOK-assessments need to address these issues.

2.2.2 Strength of Knowledge

SoK can be used to assess the quality of knowledge in relation to risk assessments [5,6,9,34,35] and may affect "the trust one has on the results obtained by the risk assessment and the decisions that are based on them" [34]. The element of trust has two important aspects in relation to regulation – firstly, the implementation of a regulatory framework is dependent on mutual trust between the regulated entity and the regulator and secondly, citizens should feel assured that their safety is maintained through the established regulatory framework. In this sense, SoK assessments could provide transparency and enlist trust in the foundation of which the regulatory system has been developed.

Aven and colleagues have developed a framework for SoK-assessments that consists of four conditions indicating whether knowledge can be considered weak, moderate, or strong [5,6,9,34]. If one of the conditions below are true, the knowledge is considered weak:

1. "The assumptions made represent strong simplifications.
2. Data are not available, or are unreliable.
3. There is a lack of agreement / consensus among experts.

4. The phenomenon involved are not well understood: models are non-existent or known / believed to give poor predictions.” [6]

On the other hand, the knowledge is assumed to be strong if all the following conditions are correct:

1. “The assumptions made seem very reasonable.

2. Much reliable data are available.

3. There is broad agreement / consensus among experts.

4. The phenomenon involved are well understood; the models used are known to give predictions with the required accuracy.” [6]

In instances where some conditions are correct while others are incorrect, the knowledge is defined as moderate strong or weak, depending on the situation. Further, while one can claim that strong knowledge is indicative of low uncertainty and weak knowledge suggest a higher degree of uncertainty, Aven warns against this perception because it may be unclear what the uncertainty is related to [6]. It is assumed that an assessment of the strength of knowledge could provide useful input to decision-makers – for instance, Bani-Mustafa claim that “simply choosing the alternative with a lower risk estimate without considering the degree of knowledge might not be the right choice” [34].

Bani-Mustafa et al. claim that the framework is “intangible in practice” and that the definition of the conditions “remain ambiguous” [36]. They propose a quantitative framework based on the overarching categories of solidity of assumptions, availability of reliable data, and understanding of phenomena – accompanied by more concrete sub-attributes, more detailed aspects, to ease the assessment process [34,36].

3.0 METHODOLOGICAL APPROACH

The work with this paper has been conducted as a case study in which we analyse the SoK framework in relation to the development of a regulatory system for a large-scale introduction of hydrogen. The case in question is a scenario of a large-scale implementation of hydrogen as an energy carrier. In this section, we will describe how the analysis has been conducted and describe key characteristics with the case: a large-scale implementation of hydrogen in a Norwegian context.

In the analysis, we have considered the value of applying the SoK framework to assess background knowledge in a regulatory process for hydrogen. The positive contributions have been described as well as problematic aspects of utilizing the framework in a regulatory context. The analysis is based on a case description of what a large-scale implementation of hydrogen may entail. Though the analysis may be relevant for other systems, we have focused on characteristics with hydrogen.

Globally, the current use of hydrogen is mostly related to oil refining and production of fertilizer, and the use has been relatively limited considering predictions of a large-scale implementation [2,37]. However, the global demands for replacing oil, gas and coal with less carbon-intensive solutions have created space for application of hydrogen-based technologies in many areas [1,2,38]. Globally, hydrogen is considered especially relevant in the transportation and building sector, for power generation and industrial processes (such as the steel and chemical sector) [1,2]. Due to the availability of clean electric power in Norway, hydrogen is most relevant in areas where electrification has been difficult [37,39]. Therefore, it is the transportation sector, mainly heavy goods vehicles, and maritime transportation, as well as industrial sector that is most relevant for application of hydrogen-based technologies in Norway. In a long-term perspective, hydrogen is considered for air travel [37].

Despite the obvious potential for hydrogen as an energy carrier, there are challenges that may affect both the possibility of a large-scale introduction in society as well as the timeline. The ambitions of implementing hydrogen in a large scale is high. At the same time, the realization of these ambitions is dependent on overcoming the two main barriers towards implementation: development of technologies and the costs of hydrogen in all parts of the value chain [37]. Currently, one percent of the global hydrogen production stem from low-emission production methods [2]. Though carbon-neutral production technologies exist, technological developments are required to upscale and increase cost-efficiency. The production costs for carbon-neutral hydrogen are still higher than for conventional fuels and technologies – incentives, taxes and technological development of cost-efficient solutions are therefore relevant factors to consider in terms of predicting a timeline [2,40]. More efficient means of transportation (metal hydrides, repurposed pipelines, etc.) and storage must also be developed to make hydrogen a realistic alternative to conventional energy carriers. Further, lack of infrastructure development makes transportation and distribution of hydrogen challenging and may affect the appeal [1,2,37]. All of which create uncertainties in predictions of if / when hydrogen may become an important part of a future energy system.

It is challenging to describe a large-scale implementation scenario because there are uncertainties related to factors such as development and maturity of technologies, cost-efficiency, etc. However, with a large-scale implementation, we assume that hydrogen is an important part of the energy mix. Some estimate that hydrogen will constitute around 12% of the energy mix by 2050 [41]. Hydrogen-based technologies will be a vital part of important societal functions both directly and indirectly. For instance, we can assume that hydrogen fuel cell technologies will be important for short and long-haul maritime transportation, to power ferries and cargo ships. Hydrogen will be integrated in the energy system and thereby important for the continued functioning of vital societal functions. Furthermore, it will be an increased presence of hydrogen technologies in many aspects of society – with production facilities, pipelines, transportation on road networks, storage facilities, etc.

In conclusion, there is great optimism for the opportunities of introducing hydrogen in sectors that are currently contributing to significant carbon emissions. National and international roadmaps and strategies are sources of information in regard to predicting what a hydrogen future might look like. However, these documents outline possibilities – there are major uncertainties about the current knowledge on a future scenario in which hydrogen is implemented at a large scale due to an inability to accurately predict the pace of technological development, cost-efficiency (as this is dependent on factors like financial incentives, taxation of carbon-intensive solutions and so on), etc. we can only assume a scenario of large-scale implementation of hydrogen as an energy carrier – creating challenges for a regulatory process. Furthermore, we do not have lessons learnt from these emerging technologies, new application areas and the upscaling of existing hydrogen technologies.

4.0 ANALYSIS

As stated, lack of knowledge and uncertainties is a significant challenge when considering developing and implementing a regulatory system for hydrogen as an energy carrier. Regulators are dependent on knowledge from different actors. Therefore, conceptualizations of uncertainty and knowledge could be important to maintain transparency, accountability, and quality of the background knowledge to improve the foundation for, and thereby the end-result, of the regulatory process. In this section, we will analyse the potential for using the SoK assessment framework in the context of developing a regulatory system for hydrogen.

As mentioned, SoK can be assessed through the topics of assumptions / simplifications, availability of data, degree of consensus among experts, and level of understanding of the phenomena in question [6]. In this section, we will address each condition in the context of hydrogen regulation – attempting to identify and address both relevance and possible shortcomings.

Firstly, assumptions are a prerequisite for decision-making regarding a future scenario that is also affected by complexities. For instance, we assume that a large-scale implementation of hydrogen will occur. To develop a regulatory system – further assumptions must be made to fill in the large knowledge gaps. Therefore, it seems relevant and logical to consider the quality of these assumptions as part of an assessment of the overall quality of background knowledge.

The framework distinguishes between very reasonable assumptions and strong simplifications – reasonable assumptions indicating strong knowledge and the latter weak knowledge. Simplifications are a prerequisite for developing a regulation for a complex system such as the hydrogen value chain. However, the difference between necessary and strong simplifications can be difficult to identify without providing further details and additional guidelines may be required to ease the assessment process.

Secondly, the availability of data is a key concern in regard to the development of a regulatory system for hydrogen. Though part of the background knowledge can be based on data from relatable systems or small-scale production, distribution, etc., the reliability of such data material must be discussed. In a large-scale implementation scenario, there will be new methods and technologies for production, distribution, storage, and end-use – and data from previous solutions are not necessarily applicable and may have reduced validity in the new context.

Though it is logical to assume that a lack of reliable data or unreliable data should be used as an indicator for weak knowledge, it is not clear why the quantity of reliable data should be used as a criterion for strong knowledge. The criteria for strong knowledge is formulated as much reliable data being available [6] and the relevance of the quantity of reliable data can be questioned. Similar to the aspect of assumptions, it may prove difficult to make an assessment based on the limited guidelines of what may constitute *much* reliable data. Furthermore, in a regulatory context, it is more logical to consider how a regulator should handle the data that is available to them.

Third, it makes sense that experts agreeing can be an indicator of trustworthiness. We are considering a regulatory system developed for a possible future scenario and it is not likely possible to identify actors that can be considered experts on a large-scale implementation of hydrogen. However, if the scope is restricted it is possible to point to experts on individual parts of the value chain in the context of a large-scale implementation, such as storage of liquid hydrogen, hydrogen fuel cells for maritime application, etc.

In terms of increasing trustworthiness in the background knowledge – the process of selecting experts is important. Even though one established expert group may agree on a chosen topic, a different constellation of people may yield a different conclusion / result. Experts do not have objective knowledge, they are coloured by their experiences, perspectives, etc. Additionally, there are several practical questions such as how may experts are required to establish consensus?

Fourth, a thorough understanding of the involved phenomenon can also be considered a reasonable criterion for establishing strength of knowledge. Additionally, it points to an important challenge in relation to large-scale implementation of hydrogen as an energy carrier. Though we can understand different aspects of the value chain well, such as the chemical properties of hydrogen and application in vehicles, the same does not apply for the complexities and interactions these individual phenomena will have in a large-scale implementation scenario. Addressing the uncertainties that this will cause in the background knowledge is therefore relevant.

Again, it is not clear how the statement is supposed to be assessed. Should the most important phenomenon be selected for an assessment, or should the phenomenon be defined as the system as a whole? Furthermore, the vagueness is challenging – "well understood" can have different meanings depending on the recipient / analyst.

To summarize, the statements point to challenges related to the development of a regulatory system for hydrogen – where assumptions are required, reliability of data is key due to contextual differences and understanding of the phenomenon is a challenge. It brings attention to sources of uncertainty in the context of developing a regulatory system for hydrogen. However, this does not necessarily mean that the proposed framework is the best method to assess the strength or quality of knowledge. We do not dispute the general relevance of the proposed uncertainty factors. The exception perhaps being the condition of the degree of consensus or agreement amongst experts. The main objection is the practical challenges, as well as the possibility of exclusion of other factors that could be equally relevant to consider in relation to uncertainties.

The framework is general and does not provide guidelines for application, besides the formulation of the statements. Though this provides a degree of flexibility, as indicated, it may be difficult to apply in practice and to determine standards that should be upheld. Particularly difficult is the matter of objectivity and it is therefore difficult to see how a SoK assessment can, unconditionally, provide transparency and increase trustworthiness in the background knowledge.

5.0 DISCUSSION

Based on the previous sections, we will present and discuss the applicability of SoK in the context of complexities and uncertainties in a regulatory system that seek to maintain safety and security in the implementation of hydrogen as an energy carrier in society.

A SoK assessment can increase transparency – providing an arena for reflection on possible weaknesses in background knowledge. In a regulatory process, the regulator is dependent on knowledge from different sources. It is therefore important to consider the quality of this knowledge – if a report, risk assessment, etc. is presented as facts without considering the quality, it could lead to poor decisions being made about regulatory matters. Hence, it is important that the SoK assessment in itself is transparent and can provide trustworthiness in the context of decision-making. Though there are benefits with the approach being simplistic, there are pitfalls, and we argue that more guidelines or requirements may be needed to ensure a minimum requirement of quality in the assessment. This is especially relevant considering that there are different interests and motives involved in a regulatory process – with some wishing to increase production or establish activities and some being invested in reducing carbon emissions for instance.

There is a tendency towards under-communicate uncertainties and knowledge may be portrayed as "true". However, when considering a future scenario, a state that has not yet occurred, it is not possible to provide facts or true knowledge. We lack knowledge – and although it is possible to define a possible scenario, this will be affected by different degrees of uncertainty. The quality of knowledge should therefore be relevant when developing a regulatory system – because the quality of assumptions, data, etc. could be of varying quality and this should affect the regulatory process. Consider the establishment of hydrogen refuelling stations in a populated area, with houses and other commercial properties in proximity. If it turns out that the design of the refuelling station is based on weak knowledge, it will be relevant to consider introducing the precautionary principle. Additionally, knowledge can affect the choice of regulatory strategy. If there is extensive knowledge about the system that is being regulated for both the regulator and the regulated entities, a prescriptive approach can provide efficiency. At the same time, little knowledge or uncertainties could make a performance-based approach necessary.

It is important to emphasize that the framework has been developed for quantitative risk assessments. The background knowledge in our context is not limited to QRAs and the questions raised in this paper are therefore not necessarily applicable in other context – though we assume that the practical issues and lack of guidelines are somewhat transferable – see for example Bani-Mustafa et al. who have questioned the frameworks simplicity and practicality [34,36].

The SoK framework indicate that uncertainties can be addressed through four overarching conditions or factors, defined as statements. It is stated that the conditions are "partly based on well-known methods, but new ideas have been incorporated for how to perform the analyses" [6], but, to the knowledge of the authors of this paper, a more thorough descriptions of what these well-known methods are and the new elements are has not been clearly stated. Though we do not dispute that an assessment of assumptions, availability of reliable data and understanding of the phenomena can reveal uncertainties, they are not necessarily the only relevant factors. Therefore, other possible sources of uncertainty should be investigated further to establish if these criteria, and not others, are the most suitable for a SoK assessment in the context of regulation. The framework has not been developed for a regulatory context. Though the strength of knowledge is universal – the uncertainty factors may be more or less relevant in different contexts. We do not have ground for stating that the four proposed conditions are not relevant for QRAs, but we argue that in a regulatory context we have some key concerns in terms of utilizing the existing framework to address uncertainties in the background knowledge – and in the context of hydrogen (that can be characterized by uncertainties and complexities).

The framework mentioned is not the only approach that can be utilized to assess background knowledge or quality of knowledge. Given the challenges mentioned, it is reason to view whether other approaches could enhance a regulatory process. Bani Mustafa et al. present an approach in which each condition is broken down into more detailed sub-attributes in an attempt to quantify SoK assessments. Though a more complex quantification of aspects that are inherently qualitative in nature is not necessarily positive in regard to hydrogen regulation it illustrates that there are possibilities for adapting the existing framework.

In this paper, we have focused on one specific approach for assessing SoK that has been developed in the context of risk assessments. However, this is by no means the only approach that address quality of knowledge. Since the applicability of this framework, in the context of hydrogen regulation, can be questioned, it is relevant to consider other approaches from other disciplines. For instance, as part of a scientific approach it is commonly believed that internal and external validity, reliability and objectivity can be used at quality criteria for research using quantitative methods [42,43]. Furthermore, Lincoln and Guba propose the following four criteria to provide trustworthiness in naturalistic inquiry or qualitative research: (i) credibility, (ii) transferability, (iii) dependability, and (iv) confirmability [42,43]. The latter may be more relevant in relation to our context given that a regulatory process most likely will be based on different sources of knowledge – reports, experience from relatable systems, risk analyses, etc.

The framework that has been considered may not be the most suitable approach for addressing knowledge and uncertainties in the context of hydrogen regulation. Therefore, future work is necessary to develop an approach that is suited for the challenges related to regulating a large-scale implementation of hydrogen as an energy carrier.

6.0 CONCLUSION

Knowledge and uncertainties are undoubtedly an important aspect of introducing hydrogen as an energy carrier at a large scale. Furthermore, it is necessary to look at the regulatory implications of a large-scale implementation scenario. Therefore, it is important to consider how knowledge and uncertainties can be handled and addressed in the context of hydrogen regulation – it will provide transparency in the background knowledge which is important for the regulatory process and the choices that is made.

We have considered if a commonly used framework for assessing SoK can be useful in addressing knowledge-related challenges in a regulatory process for hydrogen. The analysis indicates that though the conditions seem reasonable and logical, there may be some challenges related to the practical application. Besides the statements, there are no guidelines as to how the assessment should be made – meaning that it is left to the analyst to determine what constitute a very reasonable assumption etc. However, there are other ways of assessing quality of knowledge that could be relevant in the context of developing a regulatory system for hydrogen. We have briefly outlined some approaches that could be useful. Further work should be conducted to make recommendations for how to cope with the lack of knowledge that regulators are faced with when developing safety and security regulations for a large-scale introduction of hydrogen as an energy carrier.

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REFERENCES

1. European Commission. A Hydrogen Strategy for a Climate-Neutral Europe, 2020, COM(2020) 301.
2. International Energy Agency. The Future of Hydrogen: Seizing Today's Opportunities, 2019.
3. European Commission. Hydrogen. Available from: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en
4. Derempouka, E., Skjold, T., Njå, O. and Haarstad, H. The Role of Safety in the Framing of Hydrogen Economy by Selected Groups of Stakeholders, *Chemical Engineering and Transactions*, **90**, 2022, pp. 757-762.
5. Berner, C. and Flage, R. Strengthening Quantitative Risk Assessments by Systematic Treatment of Uncertain Assumptions, *Reliability Engineering & System Safety*, **151**, 2016, pp. 45-59.
6. Aven, T. Practical Implications of the new Risk Perspectives, *Reliability Engineering & System Safety*, **115**, 2013, pp. 136-145.
7. Khorsadi, J. and Aven, T. Incorporating Assumption Deviation Risk in Quantitative Risk Assessments: A Semi-Quantitative Approach, *Reliability Engineering & System Safety*, **163**, 2017, pp. 22-32.
8. Flage, R. and Askeland, T. Assumptions in Quantitative Risk Assessments: When Explicit and When Tacit, *Reliability Engineering & System Safety*, **197**, 2017.
9. Bjørnsen, K., Jensen, A. and Aven, T. Using Qualitative Types of Risk Assessments in Conjunctions with FRAM to Strengthen the Resilience of Systems, *Journal of Risk Research*, **23**, No. 2, 2020.
10. Aven, T. How Some Types of Risk Assessments can Support Resilience Analysis and Management, *Reliability Engineering & System Safety*, **167**, 2017, pp. 536-543.
11. Black, J. Regulatory Conversations, *Journal of Law and Society*, **29**, No. 1, 2002, pp. 163-196.
12. Le Coze, J.C. and Wiig, S. Beyond Procedures: Can "Safety Culture" be Regulated? (Bieder, C., Bourrier, M. Eds.), Routledge, 2013, p. 191-203.
13. van Heijden, J. Risk Governance and Risk-Based Regulation: A Review of the International Academic Literature, Report from Victoria Wellington University, 2019.
14. Hood, C., Rothstein, H. and Baldwin, R. The Government of Risk: Understanding Risk Regulation Regimes, 2001, Oxford University Press, London.
15. Society for Risk Analysis. Society for Risk Analysis Glossary, 2018.
16. Lindøe, P.H., Kringen, J. and Braut, G.S. Regulering og standardisering: perspektiver og praksis [Regulation and Standardization: Perspectives and Practice], 2018, Universitetsforlaget, Oslo.
17. Aven, T. Misconceptions of Risk, 2001, John Wiley & Sons.
18. Lindøe, P.H. and Baram, M.S. Standards and Approaches to Safety Regulation (Olsen, O.E., Juhl, K., Lindøe, P.H. and Engen, O.A. Eds.), Routledge, 2020.
19. European Commission. Implementing EU Law. Available from: https://commission.europa.eu/law/application-eu-law/implementing-eu-law_en
20. Tonheim, C. Regelverk for håndtering av hydrogen [Regulation for Handling of Hydrogen], 2019. Available from: https://www.sintef.no/globalassets/sintef-industri/arrangement/sh2ift/gjeldende-regelverk-for-handtering-av-hydrogen-dsb.pdf
21. Moretto, P., Quong, S. Legal Requirements, Technical Regulations, Codes, and Standards for Hydrogen Safety (Kotchourko, A. and Jordan, T.), Elsevier, 2022, p. 345-396.
22. Schrefler, L. and Pelkmans, J. Better Use of Science for Better EU Regulation, *European Journal of Risk Regulation*, **5**, No. 3, 2014, pp. 314-323.
23. van Asselt, M.B.A., Vos, E. and Wildhaber, I. Some Reflections on EU Governance of Critical Infrastructure Risks, *European Journal of Risk Regulation*, **6**, No. 2, 2015, pp. 185.190.
24. Cihlar, J., Krabbe, O., Deng, Y., Peters, D., Bothe, D., Janssen, M. et al. Assistance to the Impact Assessment for Designing a Regulatory Framework for Hydrogen, 2021.
25. European Commission. Impact Assessment Report Accompanying the Proposal for a Directive of the European Parliament and of the Council on Common Rules for the Internal Markets in Renewable and Natural Gases and in Hydrogen, Report No. SWD(2021) 455.
26. Baldwin, R., Cave, M. and Lodge, M. Understanding Regulation: Theory, Strategy, and Practice, 2012, Oxford University Press.
27. Coglianese, C. Management-based Regulation: Implications for Public Policy (OECD, Eds.), 2010, p. 159-184.

28. Baldwin, R., Cave, M. and Lodge, M. The Oxford Handbook of Regulation, 2010, Oxford University Press.
29. National Academy of Sciences. Designing Safety Regulations for High-Hazard Industries, National Academy of Sciences Press, 2018.
30. Stavland, B. and Njå, O. Factors That Enable the Choice of Regulatory Strategy in the Case of Hydrogen as an Energy Carrier.
31. Aven, T. and Flage, R. Risk Assessment with Broad Uncertainty and Knowledge Characterisation: An Illustrating Case (Aven, T. and Zio, E. Eds.), John Wiley & Sons, 2018.
32. Njå, O., Solberg, Ø. and Braut, G.S. Uncertainty – Its Ontological Status and Relation to Safety (Motet, G. and Bieder, C. Eds.), Springer Charm, 2017, p. 5-21.
33. Hoffman, R.R., Ericsson, K.A., Williams, A.M. and Kozbelt, A. The Cambridge Handbook of Expertise and Expert Performance, 2018, Cambridge University Press.
34. Bani-Mustafa, T., Zeng, Z, Zio, E. and Vasseur, D. A Practical Approach for Evaluating the Strength of Knowledge Supporting Risk Assessment Models, *Safety Science*, **124**, 2020.
35. Aven, T. and Thekdi, S. Risk Science: An Introduction, 2021, Routledge.
36. Bani-Mustafa, T., Zeng, Z., Zio, E. and Vassuer, D. Strength of Knowledge Assessment for Risk Informed Decision Making, Safe Societies in a Changing World - 28th European Safety and Reliability Conference, 2018.
37. The Norwegian Government. Regjeringens hydrogenstrategi: på vei mot lavutslippssamfunnet [Hydrogen Strategy], 2020.
38. International Energy Agency. Global Hydrogen Review, 2022.
39. Ministry of Petroleum and Energy. Energi til arbeid – langsiktig verdiskaping fra norske energiressurser [Long-term Value Creation from Norwegian Energy Resources], Report No. Meld. St. 36 (2020-2021).
40. Rosen, M.A. and Koohi-Fayegh, S. The Prospects for Hydrogen as an Energy Carrier: An Overview of Hydrogne Energy and Hydrogen Energy Systems, *Energy, Ecology and Environment*, **1**, No. 1, 2016, pp. 10-29.
41. International Renewable Energy Agency. A Quarter of Global Hydrogen Set for Trading by 2050. International Renewable Energy Agency (IRENA), 2022. Available from: https://www.irena.org/News/pressreleases/2022/Jul/A-Quarter-of-Global-Hydrogen-Set--for-Trading-by-2050
42. Lincoln, Y.S. and Guba, E.G. Naturalistic Inquiry, 1985, SAGE Publications.
43. Nowell, L.S., Norris, J.M., White, D.E. and Moules, N.J. Thematic Analysis Striving to Meet the Trustworthiness Criteria, *International Journal of Qualitative Methods*, **16**, No. 1, 2017, pp. 1-13.