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A Nordic Perspective

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Perceived research needs for Battery and Hydrogen Safety

– A Nordic Perspective

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**Perceived Research Needs for Battery and Hydrogen Safety
– A Nordic Perspective**

Lund 2024

Perceived Research Needs for Battery and Hydrogen Safety – A Nordic Perspective
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Summary

Changes in the energy landscape relating both to the ambitions of a green energy transformation as well as increasing global security concerns, have led to increased attention to new energy carriers. These can serve the role of allowing for the electrification of transport and decarbonization of industries as well as to reduce the effects of variation in many sustainable energy sources such as wind and solar. Many alternatives have been proposed, but two technologies at a reasonably high TRL level are batteries, which already have deep market penetration, and hydrogen, which is seen as a promising alternative for the electrification of heavy transport and the decarbonization of industry.

However, as with all technologies, and particularly technologies with large amounts of stored energy, there are safety concerns associated and the very rapid implementation put high demand on standardization and the pre-normative safety research that should underpin it. The challenge is not only to have enough safety research, but also to focus on the most important research questions.

The project presented in this report is an attempt to map out some of the most important research areas for both hydrogen and battery safety and prioritize between them with a combination of interviews and a quantitative survey. It should be noted that no mapping of the state-of-the-art has been performed in the scope of the project, so it is likely that several topics already is covered in the literature, making them into a need for research communication rather than for new empirical research. Therefore, such an assessment should be done through research review projects from funding agencies or when researchers develop applications.

The results indicate that several important areas for hydrogen safety are related to specific mitigation methods such as safety distance, barriers, pressure relief, and detection, as well as knowledge on the reliability of those measures. When it comes to more fundamental understanding, it was seen as important to understand the overpressure generated by combustion inhomogeneous clouds of hydrogen and delayed ignition of jets. There were also some needs regarding liquid hydrogen. For steel-based materials, most non-researchers seemed to be of the opinion that enough was known while researchers pointed to several specific aspects requiring further investigation.

For batteries, more focus should be placed on a fundamental understanding of the consequences of a thermal runaway and, not least, gas explosions. However, in parallel, there is a need to develop research to underpin guidelines on placement in buildings, ventilation, and fire barriers, as well as prevention of the propagation of thermal runaway. There was also a wide range of other specific needs regarding, for example, statistics on BESS fires, transport and storage of damaged batteries as well as solid-state batteries and tactics for BESS.

The aspiration of the project is that the prioritized list of 113 specific research needs (61 for hydrogen and 52 for batteries) will be useful for both funding agencies developing research programs as well as for researchers writing applications and in the strategic development of their research.

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1 Introduction

In this chapter, the background of the project is described, both regarding energy carriers in general and specifics for hydrogen and battery safety. This is followed by a description of the goal, aim and delimitations of the project.

1.1 Background

New energy carriers have come high on the agenda in later years due to several different reasons. The main reasons are linked to the green transition, which requires new ways to store energy to both allow the electrification of transport and to compensate for variation in production from several renewable energy sources, such as wind and solar. Another important reason, not directly linked to the green transition, is the deteriorated relations between several major countries, as well as recent disturbances of international trade through Covid and other events, stressing the importance of energy independence.

There is a range of different technologies for energy storage available at very different TRL levels¹. One of the most mature methods is probably batteries, but there has been a significant growth in variants from the traditional NiMH and lead accumulator via the current Li-ion² batteries to coming solid state batteries. Li-ion is also a family of different types of batteries having vastly different properties, not least in a safety context.

Hydrogen, produced from electrolysis instead of the traditional reforming process, is also seen as a potential method for energy storage for later use in either fuel cells, serving the same role as a battery, or in various thermal processes (i.e., iron reduction and combustion engines). The hydrogen is typically stored as compressed gas, with pressures typically in the range of 300-1000 bar, or as a liquid at -253°C (20 K).

There are also a large number of other methods available for energy storage such as pumped hydro, electrofuels (e.g. e-methanol, ammonia), and much more. Many of those have relevant safety concerns, for example, the non-visible flame from methanol and the high toxicity of ammonia. However, in the project presented in this report, the focus is on batteries and hydrogen, which are technologies already on the market or approaching a planned implementation in society.

Hydrogen has been used for a long time in the industrial sector, but this has typically been performed at large industrial sites far from densely populated areas and in companies with a long experience from chemical processes. This is vastly different from the hydrogen refueling stations currently being rolled out across Europe in the “hydrogen corridor” initiative. Also, liquid hydrogen is implemented in some areas to increase the efficiency of bulk transport, which up until today has mostly been used for space travel and the semi-conductor industry. A significant amount of research has been performed over the last 50 years (not least following the three-miles-island incident). However, since the applications have shifted, new issues have surfaced, and there is a general need to translate the research performed into a new context.

Less research has probably been performed historically on battery safety, including Li-ion, even if it is currently high on the agenda at many universities and research institutes. However, the pre-normative research is significantly lagging behind the need for standards and regulations, which is further exaggerated by the imbalance of information where even end-product producers have difficulties obtaining detailed information about the batteries they use in their applications. For researchers, this lack of information is even more prominent, and the significant variation in properties of different

¹ Technology Readiness Level (TRL) level is a method to estimate the maturity of technologies on a nine-step-scale. A low TRL-level refers to a technology being far from market implementation (i.e. basic technology research) while a high value refers to that it is expected to reach the market soon.

² Lithium-ion battery is a family of rechargeable batteries based on the transport of lithium ions through a separator. The transport is taking place in an electrolyte which is in liquid or gel form and usually flammable.

battery chemistries, as well as variation due to initiation method for the thermal runaway, state-of-charge (SOC), and the history/aging of batteries, significantly challenges the possibility of generating generalizable research.

Rapid technology development and rollout in society put a high demand on safety research to underpin standards and regulations and provide a basis for sound technology development and implementation. The number of relevant research questions in relation to these technologies is almost endless, therefore, it is of vital importance to focus the research on the most stressing issues.

The purpose of the project presented in this report is not only to identify relevant research topics for hydrogen and batteries, but also, in line with the argument in the previous paragraph, to prioritize between them to allow a swift and safe implementation in society. This is not only important to prevent injuries and potential loss of lives due to accidents, but it is also of vital importance for a rapid implementation in society without major setbacks since the experience from other fields is that even relatively minor accidents in new technologies can cause significant setbacks in the implementation. One relevant example is the explosion in the hydrogen refueling station in Sandvika in Norway in 2019, which, despite no significant consequences, caused the closing of all the hydrogen refueling stations in Norway over several years.

1.2 Introduction to hydrogen safety

The purpose of this report is not to provide a textbook on hydrogen safety; the interested reader is referred to other sources, not least the handbook on hydrogen safety for energy applications recently published by HySafe (Kotchourko & Jordan, 2022). However, it is judged relevant to start the report by setting the stage for some of the most important concepts covered in the various research topics presented later in this report. The description is based on the event diagram below, which describes some of the most important scenarios for gaseous hydrogen.

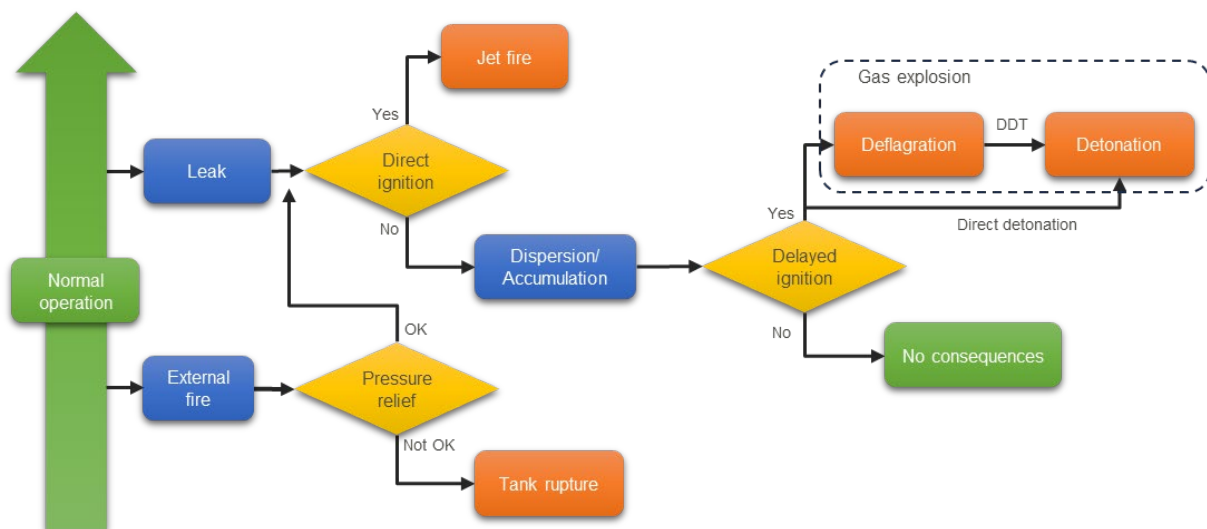


Figure 1 – Some essential scenarios for gaseous hydrogen.

The green arrow to the left is the system in normal operations. Due to a large number of different reasons, including generic reasons such as installation errors and hydrogen-specific phenomena such as hydrogen embrittlement, a leak can occur in the system. If the release is ignited immediately, a high-momentum flame, typically called a jet flame, will emerge. Depending on the environment, the flame is often invisible and releases a low amount of radiative energy, but it may readily be detected due to the high sound emitted.

If the release is not immediately ignited, the hydrogen is dispersed in the environment, mixed with air, and can also potentially accumulate in enclosures. If the mixture is then ignited, even after such slight delays as one second, a gas explosion occurs, generating some level of overpressure and impulse. Unless the ignition source is very strong (several kJ), the combustion starts as a deflagration, which is a combustion wave traveling below the speed of sound and typically generating relatively modest pressures unless the expansion of gases is hindered by walls or an enclosure. However, instabilities in the flame, combined with turbulence generated by interactions between the flow field and obstacles, will lead to a distortion of the flame and, thereby an increase in flame area. This increases the effective burning velocity, and, if the burning velocity reaches the local speed of sound, a pressure discontinuity, known as a shockwave, will form and this is called the DDT process (Deflagration-to-Detonation-Transition). This shockwave is capable of igniting the mixture through adiabatic compression and, with the expansion of the combustion products, the speed of the shockwave can be several thousand meters per second. This process generates very high pressures, causing significant damage to the surroundings. If no ignition of the mixture occurs, there are rarely any consequences since hydrogen is nontoxic.

A separate event is a tank rupture where an external fire, or other form of abuse, leads to that the hydrogen container losing its integrity, leading to an almost instant release of all its content. This also causes a significant pressure increase in the surroundings due to both the physical expansion of the compressed gas and the expansion due to the combustion of the gas.

Liquid hydrogen differs from gaseous in several ways, and many of the risks introduced are related more to the low temperature (-253°C) rather than the chemical properties of the hydrogen. This is due to the fact that the low temperature not only can cause a significant thermal shock on objects exposed to the liquified hydrogen, but even defects in the insulation can lead to the condensation of oxygen, introducing hazards associated with oxygen-enriched environments. Also, even if the burning velocities of hydrogen/air mixtures are reduced compared to normal conditions, the speed of sound is even more reduced, causing an expected³ increased risk of transition to detonation. It has also been found that it is common for liquid hydrogen spilled on water to spontaneously ignite and cryogenic hydrogen vapors are much denser influencing dispersion.

There are also reduced risks with liquid hydrogen compared to gaseous. For example, the flammability range is more narrow, and the high level of insulation needed for tanks to prevent excessive boil-off prevents, or at least significantly delays, tank ruptures, which in the case of liquified gas is called BLEVE (Boiling-Liquid-Expanding-Vapor-Explosion) and have a difference in the physics involved.

1.3 Introduction to battery safety

The main safety related issue regarding Lithium-ion-batteries is their ability to reach a condition known as thermal runaway, where more heat is being released inside the batteries, due to internal electrochemical processes and/or the charging/discharging process, than can be dissipated to the environment. The increase in temperature of a reacting system is typically associated with an exponential growth in reaction rate (and thereby heat release rate), while the heat dissipation is only linear with temperature (known as the Semenov theory). This introduces the possibility of reaching an unstable situation of the same kind as the auto-ignition of linseed oil-soaked cloths, where the system spirals into constantly increasing temperatures unless the heat generation is significantly reduced, or dissipation is significantly enhanced. During the process, the heat is dissipated not only to the surrounding but also to neighboring battery cells, potentially heating those cells above the temperature of no return, a phenomenon known as the propagation of thermal runaway.

There are various reasons for the initial heating of the first cell to this inherently unstable state, and those can be categorized into three groups: thermal, mechanical, and electrical abuse. The thermal

³ The word “expected” is important since there is a lack of research on DDT in cryogenic hydrogen as described in chapter 3.2.

causes are linked to an external heat source, which could be weather-related, fire-related, or electrical due to resistive heating (e.g., damage wiring). The mechanical sources are linked to some mechanical force damaging the batteries, such as drop, vibration, or penetration. Finally, electrical abuse is related to various short circuits or over(dis)charge. The mechanisms involved are relatively complex, typically including separator tearing for mechanical abuse, dendrite growth and separator piercing for electrical abuse, and separator collapse for thermal abuse. More information on the process of thermal runaway and its causes can be found in, for example, Feng et al. (2018).

Regardless of the method of initiation, the thermal runaway leads to pyrolysis of the liquid electrolyte, decomposing it into smaller molecules such as carbon dioxide (CO₂), carbon monoxide (CO), Hydrogen (H₂), and many others. Most, if not all, of those molecules are in a gaseous state at the temperature where they are formed, increasing the pressure in the cell and thereby introducing the risk of a cell rupture unless appropriate pressure relief is provided. Regardless of whether pressure relief is provided or not, the gas is sooner or later released to the surroundings unless the thermal runaway is stopped.

Depending on the type of chemistry, SOC, and method of initiation, the gas can be non-combustible, often consisting mainly of CO₂, or highly combustible with large amounts of H₂ and CO. If the gas released is exposed to a sufficiently strong ignition source (which is dependent on the composition of the gas released), a fire will occur. Sometimes, the ignition can also be due to glowing metal embers produced by the battery itself. The fire plume is often rather inertial, at least in the early phases of the scenario, resembling a jet fire.

If no appropriate ignition source is available at the time of the release, the released gases will accumulate in the enclosure, introducing a risk of gas explosion causing significant pressure rise in enclosure. Even if there is no ignition, the dispersion of the gas poses a hazard since the gases typically include a range of toxic gases.

An overview of the scenarios is presented in Figure 2. It is worth noting that, except for the initiating events, the event diagram has large similarities to the diagram for gaseous hydrogen in Figure 1.

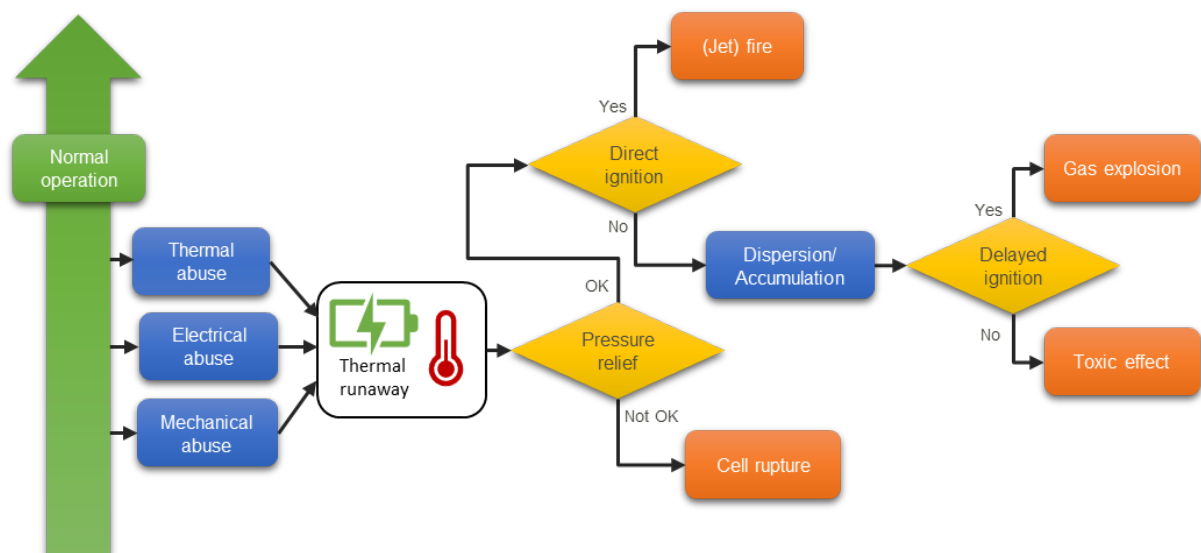


Figure 2 – Some essential scenarios for Li-ion batteries.

For non-Li-ion batteries, both the causes and consequences of potential fires are quite different. While the risk of fire is small for some technologies, some variants, such as lithium-metal batteries, can also pose significant fire hazards, as illustrated by the “Blue bus” fire in Paris in 2022 where a very large amount of glowing metal particles were produced and released to the surrounding.

1.4 Goal and aim of the project

The goal of the project is to map the perceived research needs for hydrogen and battery safety from both researchers and companies/authorities. The word "*perceived*" is essential since the goal is not to map the research front, which is not possible given the size of the project and the wide scope. It is likely that several of the identified research needs are indeed already covered in the literature, making it into a need for research communication rather than new empirical research. Regardless, the identified needs are relevant for society, and researchers who are aware of relevant research are encouraged to communicate this to a wider audience.

The aim is to develop a basis for funding agencies to define areas for review projects, develop research programs, and evaluate applications. The report also aims to be useful for researchers as they write applications and for strategic planning for research groups.

1.5 Delimitations

The empirical material used in this project, except for the reports, is limited to the Nordic countries. The reason for this limitation is mostly practical since the limited size of the project prevented an extensive investigation. However, it might also be that the industrial structure and goals of the Nordic countries might affect the priorities between the different areas. Further discussion on this delimitation can be found in chapter 6.

2 Method

The method was inspired by the “Research Priority Workshop”, which is a recurring activity within the HySafe network. In those events, a number of researchers and representatives from authorities and industries are gathered on a biannual basis with a couple of days of presentations of research needs followed by individual prioritization.

In the variant employed in this project, the presentations are replaced by 20 interviews, which are then transcribed and coded in accordance with the principles of manifest content analysis (e.g. Kleinheksel et al., 2020) using NVIVO 14. The information from the interviews was complemented with a few reports from previous research needs mappings already known to the author or provided by the respondents. The reports were imported into NVIVO and coded in the same way as the transcribed interviews. The method is outlined in the Figure 3.

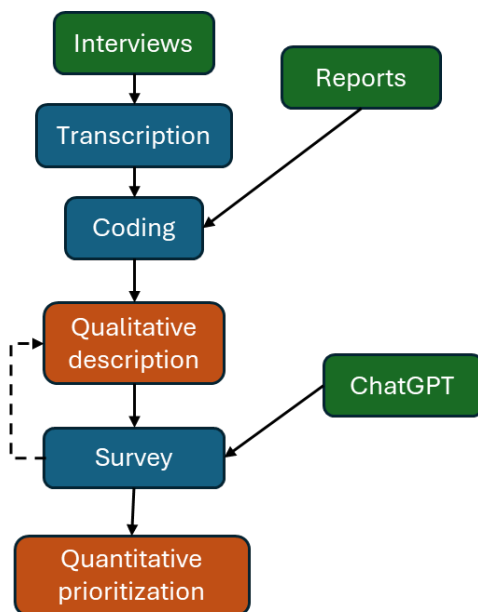


Figure 3 – Overview of the method employed.

The interviews were performed as semi-structured interviews based on the following three questions.

1. Can you describe what you are doing in the area of [hydrogen/battery] safety?
2. What knowledge do you think is missing in the area?
3. Are you aware of any mappings of research needs?

The first question was mostly to understand the context of the interviews and to “warm up” for the more difficult question. The first and third question were not transcribed, but notes were taken if any research needs were mentioned. As the themes were identified in parallel to the interviews, probing questions were added to the second question where the interviewer would ask questions similar to “Do you think that there are any needs related to liquid hydrogen?” to help the respondent cover a wider area.

The respondents came from a variety of organizations covering both universities and research institutes, as well as companies and authorities. A comprehensive list of respondents can be found in Table 1. In total, the transcribed interviews covered 150 pages (82 for hydrogen and 68 for batteries).

Table 1 – List of respondents interviewed.

	Hydrogen safety	Battery safety
Researchers	Pedro Vilaca, Aalto University Tian Li, RISE Fire Research Norway Trygve Sjold, U. of Bergen Federico Ustolin, NTNU Thomas Hulin, DBI Michael Försth, LTU Knut Vågsæter, USN Paul Adams, RISE SE ¹	Tian Li, RISE Fire Research Norway Jonna Hynynen, RISE SE Elna Heimdal-Nilsson, LTH Elena Funk, DBI
Non-Researchers	Daniel Lundberg, Ramböll Sanna Pietikäinen, Tukkes Ben Bock, Lhyfe Carina Fredström, MSB (Per-Ola Malmqvist, Utkiken) ²	Roeland Bisshop, Volvo Energy Mikael Carlsson, ElsäkV Jan Ottosson, WSP Martin Karlsson, Northvolt (Per-Ola Malmqvist, Utkiken) ²

¹ The interview was not transcribed since this was not approved by the respondent. The coding was based solely on notes taken during the interview.

² No interview was possible, but the respondent provided a detailed e-mail coded in the same way as the transcribed interviews.

Few previous mappings of research needs were mentioned during the interviews, but the ones finally included in the coding was the following;

- Hydrogen safety
 - HSE (2020) *“International Association for Hydrogen Safety ‘Research Priorities Workshop’, September 2018, Buxton, UK”*, Report RR1159, Health and Safety Executive
 - Keller, J. et al. (202X) *“Research Priorities Workshop 2022”*, DRAFT version 2023-03-21, International Association for Hydrogen Safety (HySafe)
- Battery safety
 - Funk, E., Willstrand, O., Malmqvist, P.-O., Wilkens, K. & Rein, G. (2023) *“Fire Safety of Electric Vehicles”*, Unpublished manuscript
 - Sandia *“Safety Research Priorities”* (no date). Downloaded on Aug. 10th, 2023, from <https://www.sandia.gov/energystoragesafety/research-development/safety-research-priorities/>
 - Gaudet, B. *“Full- and Large-Scale Testing of Lithium-Ion Batteries – Research Needs and Gaps”*, Presented at the Battery Workshop at the 14th International Symposium on Fire Safety Science, IAFSS2023 in Tsukuba, Japan
 - Funk, E. *“Future Battery Firefighting Tactics”*, Presented at the Battery Workshop at the 14th International Symposium on Fire Safety Science, IAFSS2023 in Tsukuba, Japan

From the coding, a total of 113 research needs were identified (61 for hydrogen and 52 for batteries), which are described in chapters 3 and 4. The research needs were then converted into a quantitative survey where the respondent was first asked to rate the relevance of each theme (9 for hydrogen and batteries, respectively) on a seven-point Likert-type scale from “Not important” (-3) to “Very important” (3), with zero being “Neutral”. For areas where the rater judged the area to be “Neutral” or above, which

was the great majority of cases with 96% for hydrogen and 95% for batteries, the respondent was asked to prioritize each specific research item within that area. A screenshot from the survey with both the general assessment and the area-specific prioritization is found in Figure 4.

6. General assessment of research areas

	1 (Not important)	2	3	4 (Neutral)	5	6	7 (Very important)
Gaseous hydrogen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Liquid hydrogen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Materials and storage methods	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Mitigation techniques	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Risk analysis (e.g. frequencies)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Consequence models	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Rescue service intervention	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Applications	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Non-technical aspects (e.g. safety culture, social acceptance)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

8. Liquid hydrogen

	1 (Not important)	2	3	4 (Neutral)	5	6	7 (Very important)
Release and evaporation	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ignition of liquid hydrogen releases	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Jet flames from liquid releases	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
DDT in cryogenic hydrogen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Auto-ignition of LH2 released on water	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Influence of condensed oxygen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Effect of liquid spill on different targets	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
BLEVE	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Additional research needs in the area (Liquid hydrogen)

Figure 4 – Screenshots from the online survey.

The survey was constructed and distributed through the “Sunet Survey” system maintained by the Swedish universities. The survey was sent using a list comprising of 36 individuals for batteries and 49 for hydrogen based on previous contacts from the author. The respondents were asked to forward the request to people they thought would be interested in filling out the survey but were asked not to post it on social media to maintain some level of control of the respondents. The respondents on the list received one reminder approximately one week after the survey was sent out, and the survey was then left open for two additional weeks.

The items from the coding of interviews and reports were complemented by prompts in ChatGPT 3.5 in the form “*What research is needed for [hydrogen/battery] safety?*”. Although no new items were identified through this, it is still interesting to realize that this new opportunity provided several of the same needs as identified through the interviews and reports. The prompts and results can be found in Appendix C and D for hydrogen and battery respectively.

In the survey, the respondents were also asked if there were any additional research needs in each area not covered by the various items. A description of those areas was then added to the qualitative description in this report, but since it was not possible to iterate the survey, it was not included in the list of priorities.

3 Research needs for hydrogen safety

This chapter briefly describes the nine different areas identified for hydrogen safety and the subtopics within each area. The large number of identified subtopics prevents a detailed description of the areas and a certain background knowledge of the reader is assumed. At least, the reader should be familiar with the concepts introduced in chapter 1.2. The presentation is based on the information provided by the respondents and the reports analyzed and the author has tried to limit any own evaluation of the suggestions.

3.1 Gaseous hydrogen

This research area covers various aspects related to the release, dispersion, ignition, jet flame, and gas explosion of gaseous hydrogen as well as potential risks related to the storage.

Several topics in the material were related to ignition of hydrogen. This included various sources of ignition, specifically self-ignition at high pressures⁴, as well as ignition from mechanical sparks and hot objects. The respondents were also interested in the safety relevant concentration of hydrogen, where it is well known that the lower flammability limit is 4% of hydrogen in air, but also that this limit applies only for upward flame spread, and therefore, the pressure increase is generally negligible up until a concentration of 8%. Therefore, it is important to further establish when 8% can be used as a criterion for safety. Ignition is also of relevance in relation to specific applications such as potential sources of ignition inside an electrolyzer in case of accidental mixing of oxygen and hydrogen in the stack.

The only topic brought up by the respondents in relation to dispersion was the ability of hydrogen to diffuse through the ground after an underground release. This was deemed to be relevant for both hydrogen pipelines and underground storage.

For hydrogen jet flames, one respondent pointed to a perceived need for understanding flames from very high pressures, above 500 bar(g). Others were interested in how the surrounding of the jet influence the visibility and radiative emissions from jet flames. This was both related to the ambient atmosphere, with the effect of water condensation on the nozzle and particles, and to the effect of materials and surface treatments, such as paints, on realistic jet flames. Other respondents were more interested in the convective heat in the combustion products and the buoyancy associated. Hydrogen jet flames were also of interest for the damage caused by flames impinging, or radiating, on composite tanks as well as on other equipment.

A large number of respondents also brought up topics related to gas explosions where one part was related to pressure effects of delayed ignition of jets, not least from designed releases from vent stacks. Another part was related to understanding the Deflagration-to-Detonation-Transition (DDT) in more detail, specifically for more realistic situations, including inhomogeneous clouds and complex geometries. This need was also related to a perceived modeling need described in chapter 3.6. Some respondents also described a need to further understand the effect of overpressure on materials and people as well as understanding the Pressure-Peaking-Phenomenon (PPP)⁵.

3.2 Liquid hydrogen

A general tendency of the respondents, especially from non-research institutions, was that liquid hydrogen was not seen as a priority for the Nordic countries at this point in time. However, due to less

⁴ The reason for self-ignition is typically attributed to the, so called, diffusion-ignition-phenomenon where the hydrogen, under certain conditions, can be ignited by interactions with the shockwave formed for sudden releases where the adiabatic compression can heat the gas/air-mixture to its ignition point.

⁵ PPP is the phenomenon occurs when a gas of lower density compared to the gas already in the compartment (e.g. hydrogen released in an enclosure with air) is released into an enclosure causing an initial pressure peak due to the difference in density between the gas injected and the gas released through the ventilation.

research performed in this area historically, a number of research gaps were found in the reports and from the researchers interviewed.

Several of the identified needs were related to the release and dispersion of liquid hydrogen. This included the physics underlying the release itself with spray formation and discharge coefficients as well as the heat transfer between the pool and ground influencing the evaporation. The effect of the cold liquid on various targets was also brought up, as well as the influence of oxygen condensation potentially causing oxygen-enriched atmospheres.

Apart from the initial release, the dispersion of cryogenic jets as well as jet flames from liquid releases, was also brought up. There was also a perceived need to derive fundamental quantities such as flammability limits, reaction kinetics, induction times, and detonation cell size for cryogenic hydrogen⁶, as well as understanding the auto-ignition of liquid spills on water experienced during several experiments. Also, experiments related to Deflagration-Detonation-Transition (DDT) cryogenic hydrogen gas just evaporated, was seen as something that required investigation.

Finally, aspects related to fire-exposed vessels for liquid hydrogen were brought up with both an investigation of the potential and consequences of a BLEVE as well as a model for the prediction of its consequences. The performance of multi-layer-insulation (MLI) under external heating was also seen as relevant.

3.3 Materials and storage methods

Interestingly, there seemed to be a relative consensus among the companies, consultants and some authorities that enough was known about steel materials, commonly referring to the established standards in the field. Several researchers on the other hand, pointed to issues that they deemed as still relatively unknown. One such issue was long-term degradation and the possibility to extrapolate the accelerated lab-scale-tests to reality where engineering models were sought for. Other issues that were brought up in relation to steel materials was the role of impurities in the steel and welds. Finally, topics related to the changed use with higher pressures and liquified hydrogen was also brought up as well as the potential effect of vibration from, for example, a compressor.

Composite materials for various components in hydrogen systems were, however, generally seen as more unknown which was not unexpected since they have not been used as much historically. A major concern brought up was the durability and lifetime prediction of this type of materials where the opinion that polymeric materials would have too short lifetime for pipelines were brought up. Also, the temperature limits as well as a better understanding of the physics behind blistering and swelling was themes covered as well as non-destructive test methods for liner evaluation.

A topic related to both this theme and the previous two themes (gaseous and liquid), was the effect of jet flames on pipes and equipment covering both gaseous and liquid releases. Also, issues related to specific components, rather than materials, were brought up. One such issue was high-pressure-couplings where some companies argued that the leak frequency experienced was unacceptable high calling for increased attention to couplings, gaskets, and seals.

When it comes to storage methods, the most commonly mentioned method that requires additional research was underground storage. This was mostly linked to the permeation/diffusion of the hydrogen underground which is covered under the “gas phase”-topic above. Apart from that, hydrides, Liquid-Organic-Hydrogen-Carriers (LOHC) and similar novel techniques were also brought up as well as an increased attention to composite tanks for prevention of tank rupture from external fires with low and high heat fluxes.

⁶ Cryogenic hydrogen refers to gaseous hydrogen at very low temperatures, typically just evaporated from a liquid state.

Some respondents also asked for a general comparison in the level of safety for the different storage methods.

3.4 Mitigation

Several respondents stressed the importance of accurate safety distances and not least to identify relevant scenarios for deterministic distances. Also, aspects related to the influence of barriers on distances were touched upon. The design of barriers in them self were also one of the major themes in the interviews where the most common discussion was related to the required fire class – if the standard EI-system could be used, and to which rating, or if J-class should be used or maybe something new. There were also some discussions about the required pressure resistance of the walls to handle delayed ignition of releases.

Questions were also raised regarding the protection against tank rupture where the Leak-Not-Break-design⁷ was mentioned as something that was interesting and also whether this could prevent tank ruptures from jet flames. It was also some requests for more realistic test methods (i.e. development of the bonfire test) as well as assessments of optimum size of the Thermally-Activated-Pressure-Relief-Device (TPRD). Related to this, a number of respondents also talked about vent/flare design and strategy, not least the potential pressure effects originating in a delayed ignition in vent stacks and if, due to this, active ignition (i.e. flares) should be used for larger vent stacks.

Ventilation of hydrogen enclosures, to prevent the formation of a flammable mixture for smaller leaks, was another theme where several respondents wanted to know more about whether natural ventilation could be used for hydrogen or if mechanical ventilation was needed. Methods to determine the needed capacity for ventilation under different conditions were also brought up as well as ventilation for cryogenic releases.

Detection was another recurring topic with several subtopics including best practice for selection of detectors, detection limits and placement of detectors, both indoors and outdoors, as well as the use of alternative detection methods such as UV-detectors and sound detectors. There was also a perceived need related to understanding the variability of performance between commercial detectors and different detection technologies as well as the long-term stability of detectors. It was also judged to be a need to develop new technologies with better performance and also methods to detect underground releases. A somewhat related topic was related to understand the time required to isolate the system after detection.

Pressure relief of enclosures was judged as an important topic by several respondents and not least the ability to relieve pressures generated by deflagrations in enclosures with mixtures approaching stoichiometric concentrations. The reason was that many of the commercially available pressure relief hatches was judged to be too inertial to provide fast enough pressure relief to prevent the destruction of realistic buildings. Therefore, the influence of available products on the pressure and impulse should be further investigated. There was an impression among some respondents that there are “more claims than validated solutions” in the industry and that improved test protocols are needed.

Sprinkler systems was also mentioned on some occasions, mostly related to the possibility that the droplets might accelerate the flame, potentially triggering a detonation. Another question for sprinklers was whether a sprinkler system could cause ignition for liquid hydrogen similar to what have been observed for release of liquid hydrogen on water.

Apart from the mitigation methods mentioned above, there were also methods mentioned by single respondents such as foam for explosion prevention, inerting of hydrogen/air-mixtures by gas or

⁷ LNB-design refers to a technique where the design of the pressure container is such that no pressure relief device is needed since the container will allow the hydrogen to permeate through the material in case of external fire.

aerosols, odorization, recombiners for liquid hydrogen and, finally, the use of glow plugs to induce ignition at lean concentrations.

3.5 Risk analysis

Most topics related to risk analysis was about the need for improved data where the dominant area was failure frequencies for use in risk analysis, mostly related to leaks both in general and for specific components (e.g. TPRD), as well as for systems with liquid hydrogen. On some occasions, it was also mentioned a need to understand the failure modes of specific components such as composite tanks.

Apart for the leak frequencies, an improvement of the quantification of uncertainty and improved data on human reliability (i.e. error rates) was mentioned. An additional topic was data on the reliability of mitigation measures and ignition probability.

3.6 Consequence model development

A commonly espoused need for model development was in the area of gas explosion and specifically regarding models for transition into detonation that are useful for engineering (i.e. relatively short runtime for realistic domain sizes). An improved coupling of CFD and FEM⁸ was also mentioned as well as the need to model the pressure wave from delayed ignition of a jet with and without congestion.

Some respondents also mentioned models for liquid hydrogen and particularly the interaction between the release and its immediate surroundings such as the ground or water.

Another phenomenon, where further model development was seen as needed, was flame radiation where some respondent stressed the importance of the influence of environmental condition on the emission spectra as well as atmospheric absorption, while other mentioned a need to model radiation from a hydrogen flame ball⁹. The need to model the hot combustion products were also seen as an important topic by several respondents.

Some additional topics were more general for modeling such as a need to be able to visualize the uncertainty in consequence models as well as blind round-robin validation¹⁰ of different codes and scenarios.

3.7 Rescue service intervention

Some respondents expressed that the rescue service had a relatively limited role for hydrogen leaks/fires, while other expressed a need to develop tactics for specific situations such as vehicles with large H₂-inventories (e.g. trucks and rails), unmanned sites and underground structures (e.g. tunnels).

Other needs expressed were related to methods to locate leaks to complement the common methods of infrared (IR) camera and brooms, including acoustic methods. Also, safety aspects such as stand-back-distances for the rescue service as well as methods to determine if a tank already vented when arriving to scene was mentioned together with gunshot depressurization of tanks and alternatives to this technique.

⁸ CFD (Computational Fluid Dynamics) and FEM (Finite Element Modeling) are two related modeling approaches where the volume (for CFD) and structures (for FEM) are divided into small cells and the fundamental equations are solved for each cell. An appropriate coupling between the two can help to account for possible interactions between the gas and solid phase phenomenon as well as more precise consequences of over pressures on structures.

⁹ A flame ball is a diffusion flame (i.e. the fuel and air are not mixed before combustion) following a full loss of containment and thereby rapid gas expansion. Common examples are related to a tank rupture scenario.

¹⁰ Blind round robin refers to that a number of independent groups simulate the same case without knowing the results. The simulation results and the experimental results are then compared by an independent actor.

3.8 Applications

A recurring topic in the interviews regarding applications was pipelines where some respondent talked about the use of the current pipe network for blends of natural gas and hydrogen and possibly for pure H_2 in those pipes. However, a more common theme was relating to new pipelines for pure H_2 and the various safety aspects of this, some of which are described in chapter 3.1. A related topic was underground storage regarding possibility of leaks, ground diffusion and microbiological activity.

Apart from that, most applications were related to transport including safe bunkering of ships and vehicles with large H_2 -inventory such as trucks, aviation, and rail. Some also mentioned the importance of understanding safety during service of vehicles in repair shops as well as crash requirements on tanks. Also, underground structure such as tunnels and garages were mentioned as well as road transport of liquid hydrogen. Some informants also mentioned electrolyzers with the risk of oxygen and hydrogen mixing in the electrolyzer which has led to accidents before.

Finally, some questions were related to specific situations such as ignition and flame propagation in environments with low pressure and temperature relevant for the aerospace industry as well as the effect of high voltage systems on hydrogen facilities.

3.9 Non-technical

Non-technical aspects related to hydrogen safety was mentioned in some interviews, mostly related to safety culture and how a safety culture can be fostered in the new companies with no prior experience with combustible gases. Also, social acceptance was brought up, and the question if hydrogen had more or less problem with social acceptance was raised.

4 Research needs for battery safety

This chapter briefly describes the nine different areas identified for battery safety and the subtopics within each area. The large number of identified subtopics prevents a detailed description of the areas and a certain background knowledge of the reader is assumed. At least, the reader should be familiar with the concepts introduced in chapter 1.3. The presentation is based on the information provided by the respondents and the reports analyzed and the author has tried to limit any own evaluation of the suggestions.

4.1 Thermal runaway

The topics covered in this area were related to processes within the module/pack, including individual cells, and covered several different parts in the process from underlying causes to gassing. A general interest was to understand the causes of thermal runaway better and how to avoid it in practice. There was also an interest in understanding the specific influence of small variations in the electrolyte composition to optimize safety, together with electrical performance, as well as the influence of SOC on TR-probability. A related topic was how to trigger a thermal runaway in tests in an appropriate, realistic and reliable way.

The next step in the process, after the thermal runaway has been established in the first cell, is the potential propagation of thermal runaway inside the module or pack where both the influence of aspects such as cell configuration, form factor, insulation and casing, as well as differences due to type of chemistry, was discussed together with passive mitigation such as barrier within the module/pack. Design to prevent cell ruptures was also mentioned.

Some respondents also talked about the importance of using modeling to extrapolate from cell-level-tests to module-level-behavior which was called “virtual testing”.

4.2 Gas release

In this theme, various aspects related to both the composition and rate of battery vent gas production was considered. When it comes to the composition, a high interest was put in the influence of battery chemistry on the gas composition and the question if it is possible to generate generalizable knowledge for specific chemistries rather than relying on battery specific tests. Some respondents also pointed to the effect of the mode of TR-initiation on the gas composition and that this should be investigated further. Several respondents also pointed to that no consensus has been reached among researchers on appropriate ways to measure the gas composition. There are some generic recommendations in, for example, UL9540A, but more specific guidance is needed.

For the rate of gas production, it was stressed that not only the total volume of gases produced is important, but also the rate over time which differs between batteries and is relevant, for example, for ventilation sizing. It was also mentioned that different pressure relief designs of modules and packs might influence the size of the potential flammable clouds. Some respondents also pointed to the relevance of understanding which ignition sources that are capable of igniting different mixtures. Similar to for the gas composition above, there was a perceived need to develop more accurate methods to measure the production rate.

The main issue discussed for battery vent gases was related to the combustibility of the gas mixture even if some mentioned the production of toxic gases and even the potential tradeoff between toxicity and other safety related properties (e.g. for Lithium Iron Phosphate, LiFePO_4 – having a higher thermal stability, but producing more HF in case of a thermal runaway).

A further question covered was related to aged batteries and whether the gas composition might change when a battery has been exposed to a large number of cycles since some gases are formed and dissolved in the electrolyte even during normal operations.

4.3 Scenario

The scenario mostly discussed during the interviews was fires following thermal runaway and specifically appropriate design-fires for Li-ion-battery fires. Similar to hydrogen, the respondents contemplated whether the typical EI-classifications for fire compartments were appropriate for Li-ion-batteries. There was also a perceived need for large-scale explorative fire testing to understand the phenomena better. The standard method of measuring heat release rate by oxygen consumption calorimetry was also questioned by some respondents.

Several respondents also talked about delayed ignition, and the associated gas explosion, of battery vent gases and described this as the most important scenario for safety. At the same time, others were unsure whether this was a credible scenario to be used for design purposes or just a worst case scenario. On some occasions, the respondent contemplated whether the requirement on fire barriers might actually increase the risk in some situations since it might restrict the dispersion of gases, thereby increasing the concentration to potentially flammable concentrations.

Finally, additional hazards related to the environmental impact from released metals (based on Ni, Co, Li and Mg) from a fire were considered as well as electrical hazards.

4.4 Statistics

The discussions on to this theme mostly related to the need to derive appropriate frequencies for thermal runaway, and related scenarios, for various applications such as electrical vehicles, small devices (e.g. cell phones), small vehicles and Battery-Energy-Storage-Systems (BESS). It was argued that this information was needed both for risk analysis of specific facilities and for a better understanding of the problem. It was also seen as useful to be able to perform cost-benefit analyses of measures stipulated in standards and legislation.

As described by the respondents, there are generally statistics collected by the rescue service, even though it seems like this is not readily available in all countries, but the level of details available as well as quality is generally low, and often it is even difficult to understand whether the fire originated in the battery or not. This might require increased attention to fire investigation of battery fires, which are either not performed today, or the result of such investigations are proprietary for the company or insurance agency. To improve the design of batteries, it was seen as useful to investigate the specifics linked to thermal runaway in different actual cases and improve data sharing between industries.

4.5 Mitigation

This theme covered a broad range of various techniques for mitigation, but also the general question regarding what should determine the level of protection needed. A common method today in many standards and guidance documents is to link the need for mitigation to the electrical storage capacity of the batteries. Some respondents argued that this was not a relevant quantity and that it should rather be linked to battery chemistry or other more relevant aspects.

Most respondents brought up detection as an important area, especially early detection using the BMS¹¹, where different algorithms to detect potentially hazardous situations in the battery could be identified and mitigated before a major thermal runaway was established. There was also discussion on various gas detector options and how an optimum detection strategy could be implemented.

The respondents also talked about ventilation needs. There is guidance for ventilation rates in various standards, such as NFPA 855, but the basis for the stipulated values is generally unknown. However, it is clear that it does not account for important aspects such as gas production rate or vent gas composition, which indicates that it is either over-conservative for some batteries and/or under-conservative for others. A related topic is also gas stratification, covering both whether the vent gases

¹¹ The Battery Management System (BMS) is the integrated processing capability in the battery pack monitoring aspects such as temperature and voltage and controlling the rate of charge and discharge.

will accumulate as a layer close to the ceiling (or floor) or if it might even be layers of different compositions since the composition is likely to change during the venting phase and thereby possibly have significantly different densities preventing mixing. The performance criteria for the ventilation system are also generally unknown. For traditional combustible gases, the ventilation is typically designed for minor leaks, but not for major leaks. It is not known how this translates to battery energy storage systems.

The question of pressure relief was also raised, which is related to the question of gas explosions described in chapter 4.2. As mentioned in that chapter, some respondents argued that it is not known if this is a credible scenario for design or just a worst-case scenario. According to some respondents from the industry, pressure relief is not currently used for batteries. If this should be used as a design scenario for batteries, some respondents pointed to that more research is needed to provide guidance on how to design the pressure relief hatches and translate the experience from the combustible gas industry.

Fire barriers were also one of the major topics where a lot of discussion was around the need rating for barriers and the appropriate rating, see also discussion in chapter 4.3.

Also similar to hydrogen, placement was another central topic discussed regarding both distances outdoors (commonly referred to as safety distance), for example, between containers, and placement indoors, for example, in homes. How different mitigation measures could influence the possibility of placing battery storage close to vulnerable targets was also touched upon.

Apart from this, most of the discussion was focused on different suppression techniques and agents. Several mentioned that there are a lot of comparisons between different suppression agents in the literature. Although there still is some need for experiments on full-scale systems, since it has been found that the possibility of the suppression to reach the cells often is more important than the specific type of agent, the perceived need is now more to translate this into engineering principles and guidelines. There could also be some need for more fundamental studies for specific suppressants such as aerosols and gas suppression (e.g. CO₂ for maritime).

Finally, one respondent pointed to that electrical hazards have not been enough investigated since batteries can give very high short-circuit currents and that direct current (DC) allows for electric arcs with a long duration.

4.6 Rescue service intervention

Development of appropriate tactics, especially for BESS and heavy vehicles, was mentioned as important even if some respondents argued that there are guidelines in other countries that could, more or less, be directly implemented in the Nordic countries. In what situation the fire service simply should let the object burn to completion was also discussed, not least given the issues with the transport of damaged batteries discussed in chapter 4.9. Some specific suppression techniques, such as direct water injection, were also mentioned.

Special attention was also put on toxic compounds released into the run-off water from suppression activities and safety for firefighters regarding electric shocks and gas explosions. It was argued that these factors should be accounted for when developing new tactics rather than exclusively focusing on what is most efficient to put the flames out.

4.7 New battery technologies

The product development in the battery area is very rapid, and, for Li-ion batteries, the chemistry in the batteries is constantly undergoing development requiring additional safety research. Batteries where the lithium has been replaced by sodium, consequently called Sodium-ion-batteries, are already on the market. Even though they currently seem to be safer, since they have a lower tendency to trigger thermal runaway, they still contain a flammable electrolyte and, thereby, the possibility of causing similar scenarios. There is also a need for safety research to be integrated into battery

development to, for example, reduce the flammability of solvents and add flame retardants where possible. Also, research on the safety implications of new battery designs (e.g. cell-to-pack) was seen as important as well as potential implications of batteries becoming a structural part of new vehicles. Finally, there is also a research need on new cooling technologies which might be flammable and cause thermal runaway in case of a leak.

Apart from the continuous improvement of the already widely implemented Li-ion-technology, there are also more disruptive changes in the battery technology close to, or already on, the market – not least the solid-state batteries, which do not have a liquid electrolyte. This will eliminate the type of scenario with a thermal runaway followed by gassing, but potentially introduce new risks, which was not least illustrated by the well-known “blue bus” fire in Paris in 2022, where the lithium-metal battery was seen generating a very large amount of glowing metal particles. Among the respondents, some argued that it is important to research solid-state batteries already now, while others argued that safety research should wait until it has been proven to be a viable alternative although the research methods developed should be applicable also to new technologies.

It was also mentioned that “hybrid batteries”, with packs including both solid-state and liquid electrolyte batteries, should be investigated from a safety perspective.

4.8 Applications

Many respondents described that battery safety research, up until recently, almost exclusively focused on automotive applications, particularly passenger cars. However, recently, the focus has shifted more towards stationary energy storage, which respondents saw as very different.

Besides solving the issues related to stationary energy storage, identified important areas of future safety research were focused mainly on other modes of transportation. Many respondents pointed to the risks of smaller vehicles, such as scooters and electric mopeds, potentially charged inside residential buildings. Also, modes of transportation where the possibility of evacuation was limited, particularly ships, aviation, and submarines, were seen as important.

Other topics covered by some respondents were structures containing electric vehicles, particularly car parks, and workshops, co-storage with other fuels, as well as battery swapping. Also, safe warehouse storage of batteries was mentioned.

4.9 End-of-life

The area “end-of-life” refers to the end of the lifetime of a battery in a specific product. A topic that has received some attention in later years, but still, according to respondents, requires additional research, was second-life, which means that the battery is integrated into a new product, commonly stationary energy storage where the requirement on energy density is less. A major issue in the area was the ability to determine whether a battery was safe enough to be integrated into a new product, commonly referred to as “State-of-Health” or “State-of-Safety”, since, for example, dendrites can grow over time, making a battery less safe. The research needs included both a shared definition of the concept as well as the development of appropriate tests.

In case the battery is not suitable for reuse, it is sent for recycling, which also introduces safety-related challenges. This includes safe temporary storage of batteries as well as safe discharge of batteries before recycling.

A final theme in this topic is the transport and storage of damaged batteries after both fires and other events. Since it is known that thermal runaway can be reinitiated after quite some time, this is a major practical problem. There are also risks related to stranded energy in partly damaged batteries, introducing both fire and electrical risks.

5 Prioritization of research needs

In this chapter, the results of the quantitative survey can be found starting from a description of the background of the respondents (chapter 5.1) and then on to the rating of research needs for hydrogen safety (chapter 5.2) and battery safety (chapter 5.3), respectively.

5.1 Background of respondents

In total, 114 surveys were filled out, with 53 replies for hydrogen and 61 for batteries. To prevent excessive length of the survey, only a limited number of background variables were collected. The most important was probably the type of organization found in Figure 5.

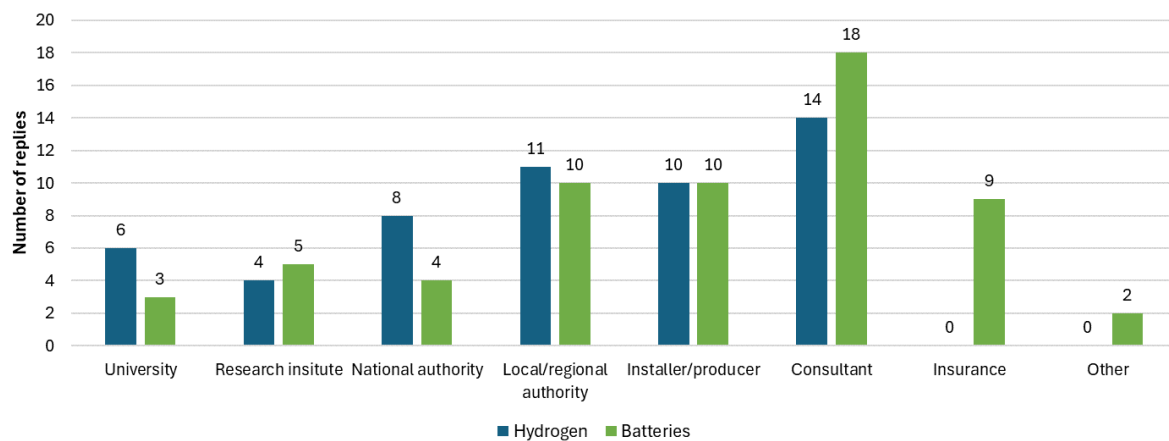


Figure 5 – Distribution of organization types among respondents.

A clear conclusion from the figure above is that the respondents have a clear overweight towards non-research organizations, where the research organization only makes up 19 % and 13 % of the replies for hydrogen and batteries, respectively. This needs to be acknowledged when assessing the priorities in chapters 5.2 and 5.3.

Apart from the organization type, the remaining background questions were about experience and, self-judged, level of knowledge, which can be found in Figure 6.

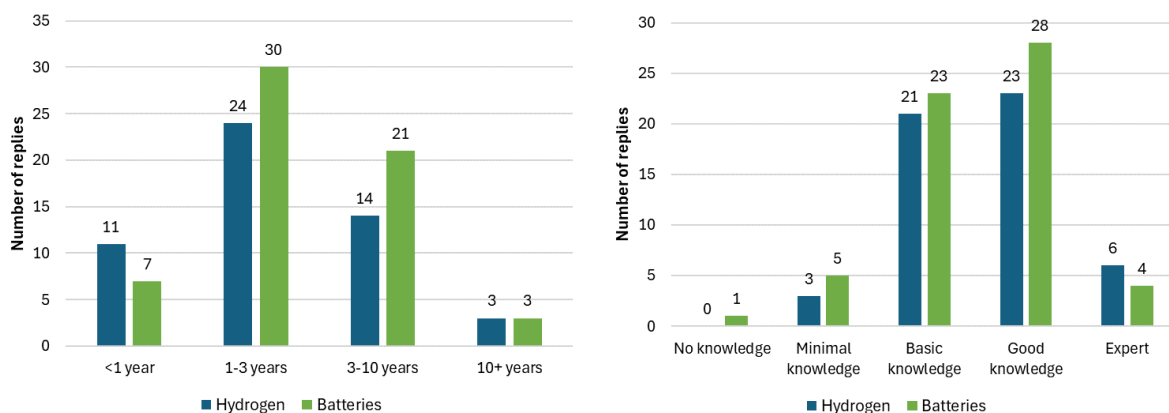


Figure 6 – Distribution of experience (left) and self-assessed level of knowledge (right) among the respondents.

It can be seen that the distribution is relatively similar between hydrogen and batteries, with approximately equal numbers with basic knowledge and good knowledge.

5.2 Hydrogen safety priorities

In Figure 8, the area prioritization among researchers (i.e. universities and research institutes) and non-researchers can be found. The result reveals a good agreement in the rating between the two groups, except that researchers tend to rate every area slightly higher. An obvious interpretation of the difference is that it might be due to that researchers think that research is more important in general, thereby their career choice. One interesting exception to the agreement is liquid hydrogen, which researchers tend to rate higher than non-researchers. This might be due to the fact that many research gaps exist in the area, since it has been less investigated than gaseous, while the number of projects involving liquid hydrogen in the Nordic countries is still relatively small.

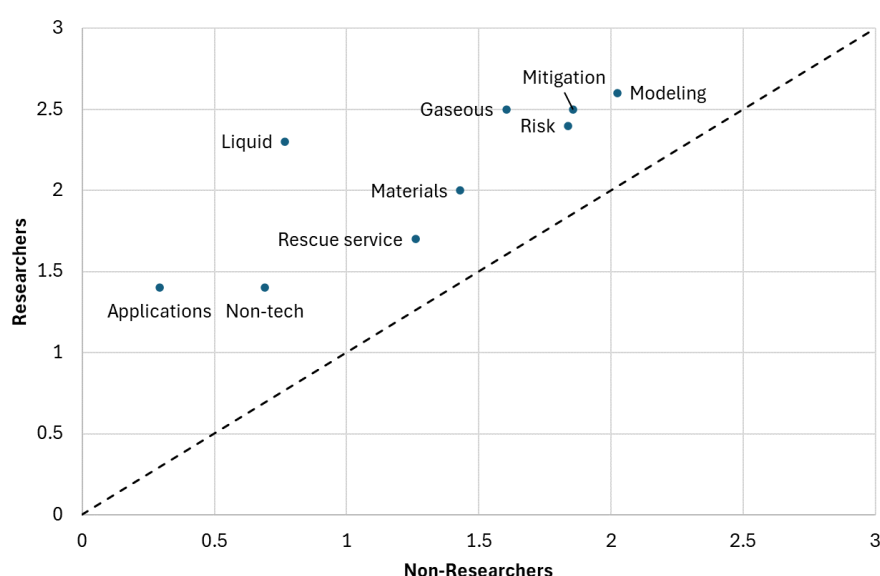


Figure 7 – Prioritization of the nine research areas for hydrogen safety among researchers and non-researchers. In the figure, 0 refers to “Neutral” and 3 refers to “Very important”.

In Figure 8 below, the top 20 specific research needs for hydrogen safety can be found. It can be seen that topics relating to mitigation seem to be rated as most important, occupying six of the places in the top-10-list. Safety distances seem to be seen as much more important than the other items, while the difference below that is small and might well be influenced by random variation¹².

The ranking is not very surprising since the mitigation measures in the list are the ones employed at almost all hydrogen facilities, and therefore, it can be expected that they are seen as important, at least by non-researchers making up the great majority of respondents (see chapter 5.1). One interesting finding was that the reliability of mitigation methods (#2) scored much higher than improved leak frequencies (#16). This could potentially reflect that considerable efforts have been put into deriving leak frequencies over the years and that, despite the inherent uncertainty, the possibility of reducing this uncertainty might be seen as low.

The physical phenomenon scoring highest is DDT in inhomogeneous clouds (#5) and, further down the list, the related topic of pressure from delayed ignition of jets (#15) can be found. This indicates that

¹² A formal statistical test is however difficult since the distribution cannot be assumed to be normal and the number respondents are too low for non-parametric tests.

this should be the topic of future research. Interestingly, jet flames at very high pressures (#14) scored relatively high despite the fact that there is a significant amount of research indicating that the notational nozzle approach, coupled with established jet flame models, give accurate results (see, for example, Kotchourko & Jordan (2022) and Molkov (2012)). This can be interpreted as a need to improve research communication.

Given the low area rating of liquid hydrogen (especially among non-researchers who were, as previously mentioned, a great majority of raters), it was surprising to find five topics in this area on the top 20-list. One possible interpretation of this is that liquid hydrogen is not seen as very important as an application, but the raters acknowledge that there are many unknown topics in the area that still merits investigation.

Apart from this, there is one application, Underground storage (#18), and tactics for vehicles with larger H₂-inventory (#20) on the top-20-list.

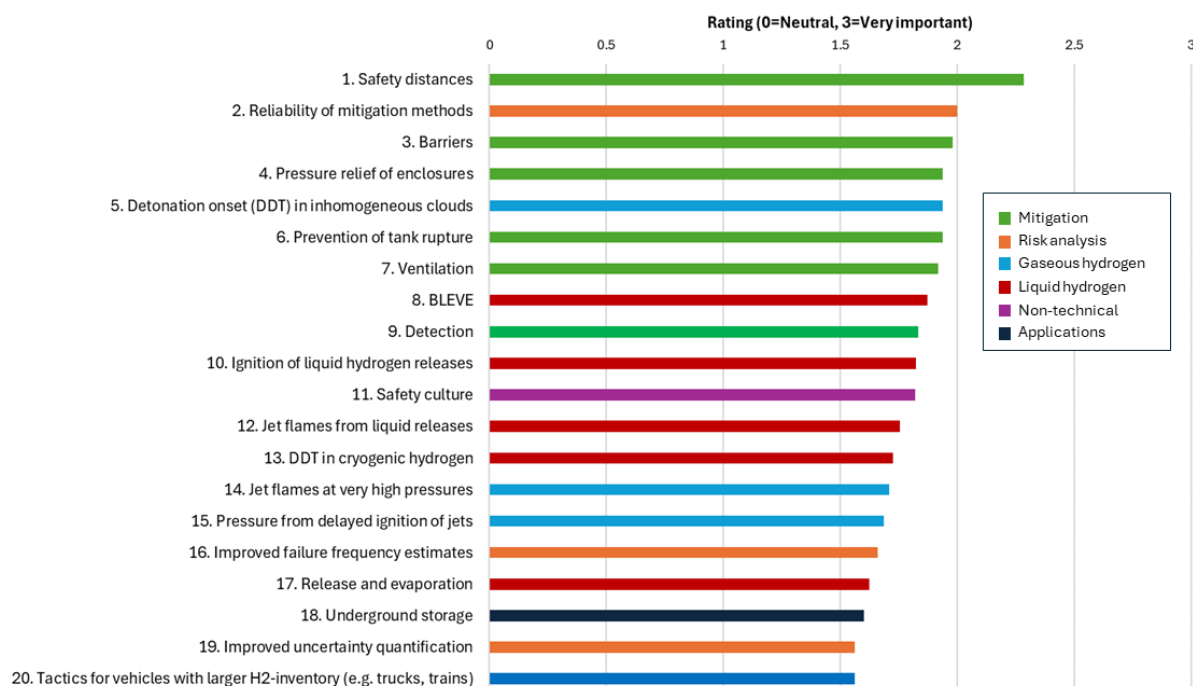


Figure 8 – Top 20 research needs for hydrogen safety.

A comprehensive list of all ratings, per area, is presented in Appendix A.

5.3 Battery safety priorities

For battery safety, the agreement among researchers and non-researchers seems to be less than for hydrogen safety, although the ranking seems to be similar. Gas release and consequences are both rated as important, indicating a higher need to understand the physical phenomena involved rather than, as for hydrogen, to investigate specific mitigation methods.

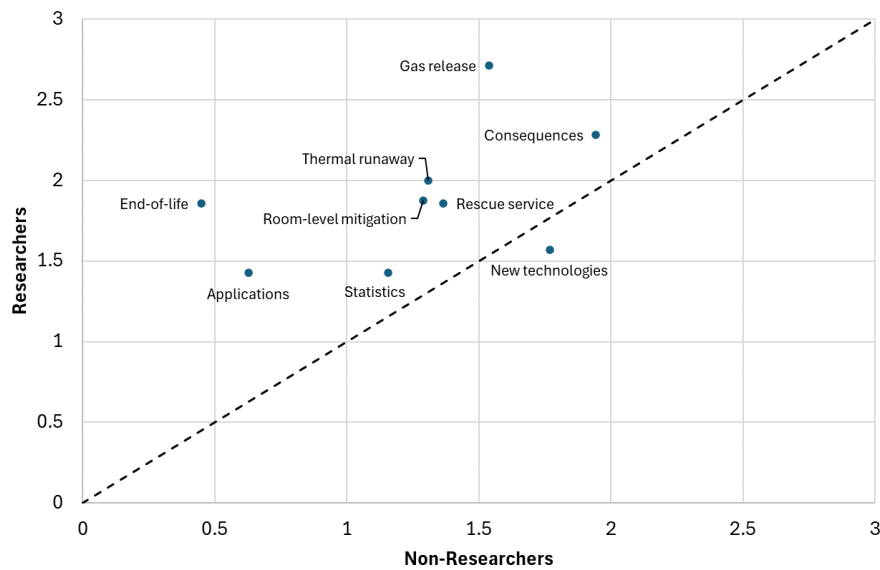


Figure 9 – Prioritization of the nine research areas for battery safety among researchers and non-researchers. In the figure, 0 refers to “Neutral” and 3 refers to “Very important”.

Despite the relatively low rating of room-level mitigation in Figure 9, three mitigation measures can be found in the top 10 for specific topics and an additional two for the 11-20 rating. The highest rating was given to the placement inside buildings (#1) followed by measures to prevent the propagation of thermal runaway between cells (#2). On third place, the potential influence of battery size (i.e. capacity) on the consequences (#3), and thereby likely on required mitigation. This was interesting, indicating a need to better understand the rate of vent gas generation on full-size systems (see chapter 4.2), which also relates to the fourth topic on ventilation (#4). The remaining mitigation methods, located slightly lower in the list, are safety distance outdoors (#12) and pressure relief of enclosures (#14).

Stationary energy storage seems to be of general interest constituting the highest scoring application (#18) and also the most important for rescue service tactic development (#9) and for accident statistics (#5). This application probably also influences the high interest in fire barriers (#6) as a method for mitigation. The transport and storage of damaged batteries (#7) was also seen as important despite the relatively low rating of end-of-life as an area. Following this, solid-state batteries (#8), which were just recently introduced on the market, can be found.

Similar to the area rating, several topics relating to consequences can be found on the top-20-list with explorative large-scale experiments (#10), gas explosions (#11), and design-fires (#16).

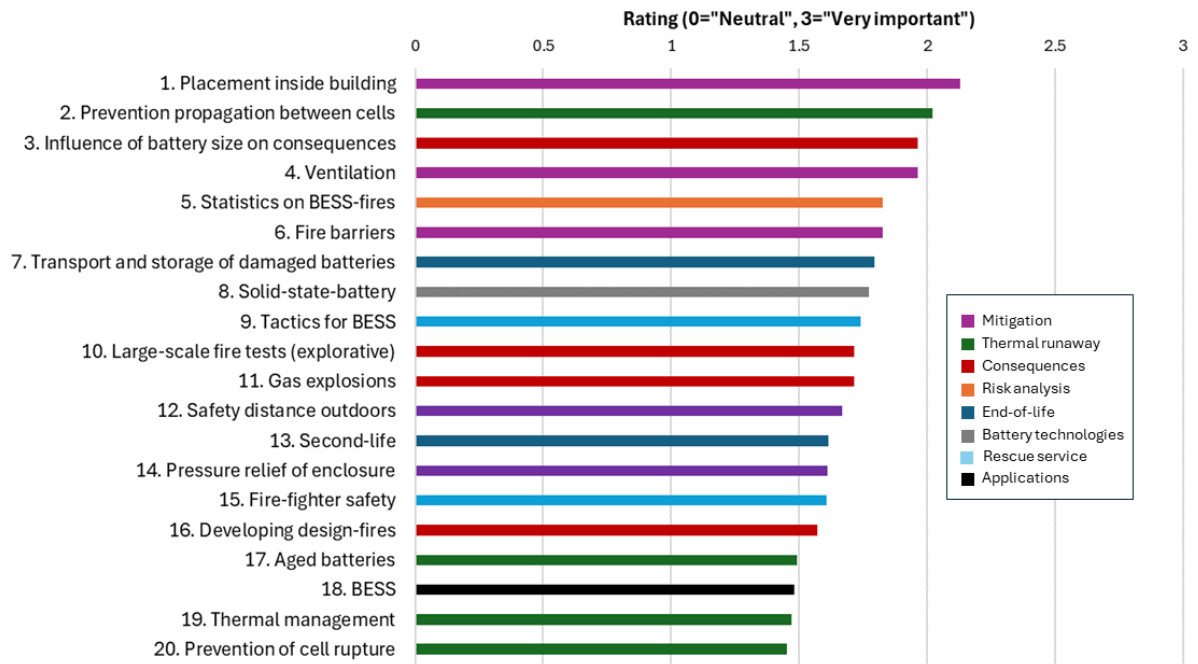


Figure 10 – Top 20 research needs for battery safety.

A comprehensive list of all ratings, per area, is presented in Appendix B.

6 Discussion on methods

The study is suffering from several limitations in the methods. The respondents for the interviews were selected based on convenience sampling, which can be criticized for several reasons. Even if a relatively broad range of respondents were sought regarding research discipline for researchers and the role for non-researchers, the results would probably have differed with a different sample. For example, no political scientists or sociologists were interviewed, which could have led to identification of more topics in the non-technical theme.

Regarding the survey, as presented in chapter 5.1, there is also a strong bias towards non-researchers and particularly to industry. This causes those actors to have a strong impact on the ranking of research needs. The high weight of industry actors in the ranking is not without merits since they represent a group which can be assumed to have deep technical knowledge about the systems and who daily struggle with implementing appropriate levels of safety in the systems. At the same time, they can be expected to have less knowledge on the state of the art of knowledge compared to researchers really stressing the need for comprehensive mappings of state of the art before initiating empirical research. Also, it can be expected that the industry has less knowledge about the most vital parts in the progression of knowledge, so they might rate the end goal (e.g. design methods for pressure relief) higher than understanding the physical processes involved (e.g. gas explosion).

As stated in the title, this report aims to give a “Nordic perspective”, but one can question whether such a thing exists – if research and research needs are not universal. The argument has some validity, but for the interviews the relatively limited sample size (20 interviews) indicates that a variation in other variables, such as research area or role in the implementation, is likely to be more important than a variation in geography. For the survey, the limitation to the Nordic countries is probably more difficult to motivate since a larger geographical area would likely give a higher number of replies and, thereby, a higher statistical power possibly allowing for non-parametric significance tests. However, to some extent, the strategy for the implementation of hydrogen and batteries in society, both from an industry and government perspective, might be dependent on geography and thereby partly motivate the applied geographical delimitation.

7 Conclusion

In the study, a total of 113 research needs for battery and hydrogen safety were identified (61 for hydrogen and 52 for batteries). The topics covered were grouped into nine areas for hydrogen and batteries, respectively, as indicated in the table below together with its average rated relevance from -3 (not important) to +3 (very important).

Table 2 – Ranking of research areas for all respondents for hydrogen and battery safety, respectively.

Rank	Hydrogen safety	Battery safety
1.	Consequence models (+2.1)	Consequences (+2.0)
2.	Mitigation techniques (+2.0)	New battery technologies (+1.7)
3.	Risk analysis (+1.9)	Gas release (+1.7)
4.	Gaseous hydrogen (+1.7)	Rescue service intervention (+1.4)
5.	Materials and storage methods (+1.5)	Room-level mitigation (+1.4)
6.	Rescue service intervention (+1.3)	Thermal runaway (+1.3)
7.	Liquid hydrogen (+1.1)	Statistics (+1.2)
8.	Non-technical aspects (+0.8)	Applications (+0.7)
9.	Applications (+0.5)	End-of-life (+0.6)

Within these areas, the three most important topics for hydrogen safety were the following based on a quantitative survey.

1. Safety distance
2. Reliability of mitigation methods
3. Barriers

Similarly, for battery safety the following topics was rated as most important.

1. Placement in buildings
2. Prevention of thermal runaway between cells
3. Influence of battery size on consequences

As no systematic analysis of the published literature has been performed within this project, several of the identified research needs are likely already investigated to an appropriate level. Hence, the list of priorities is as much about the need for research communication as for empirical research. Therefore, funding agencies must fund projects on literature reviews on specific topics to complement funding of new empirical studies.

Hopefully, the comprehensive list of research needs, and their rating, for both battery and hydrogen safety in this report can be useful for both funding agencies developing their research program and for researchers for their continued development of their field of research.

It should however be noted that the priorities presented in the interviews as well as the surveys are highly subjective. It should therefore not be seen as an ultimate truth, but rather an additional input for the development in the field. It should also be contemplated if an improved process of research prioritization can be developed in the future.

8 References

Feng, X., Oyang, M., Liu, X., Lu, L., Xia, Y, & He., X. (2018) "*Thermal runaway mechanism of lithium ion battery for electric vehicles: A review*", Energy Storage Materials, Vol 10, pp. 246-267, doi: 10.1016/j.ensm.2017.05.013.

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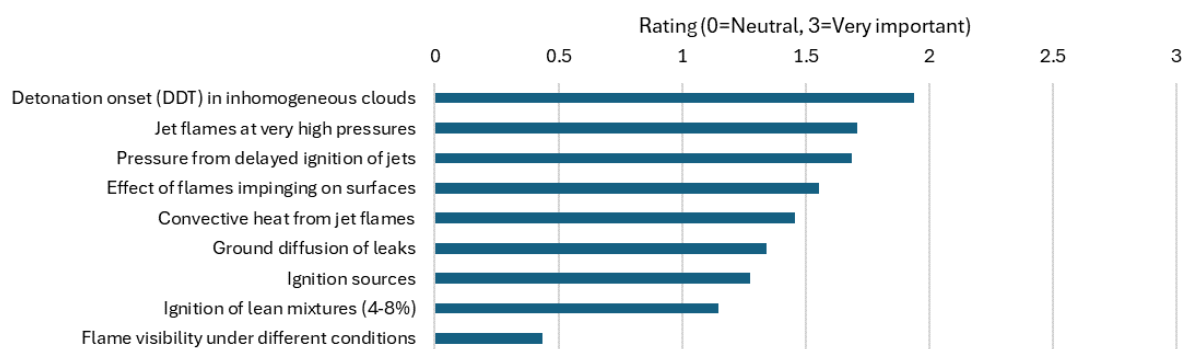
Kotchourko, A. & Jordan, T. (eds.) (2022) "*Hydrogen Safety for Energy Applications – Engineering Design, Risk Assessment, and Codes and Standards*", International Association for Hydrogen Safety (HySafe)

Molkov, V. (2012) "*Fundamentals of Hydrogen Safety Engineering*", BookBoon

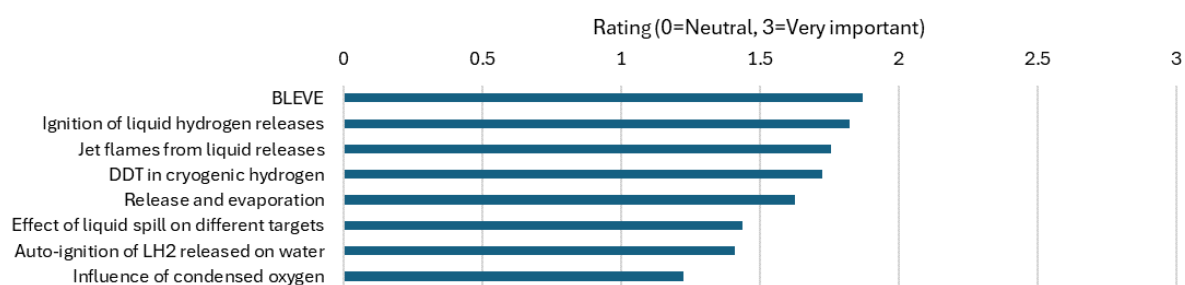
Appendix A – All priorities for hydrogen safety

In this appendix, the prioritization of all the research needs in each area for hydrogen safety can be found.

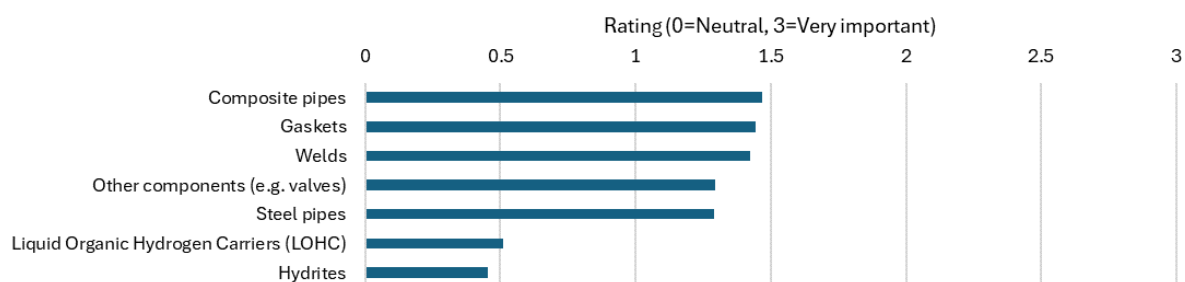
Gaseous hydrogen



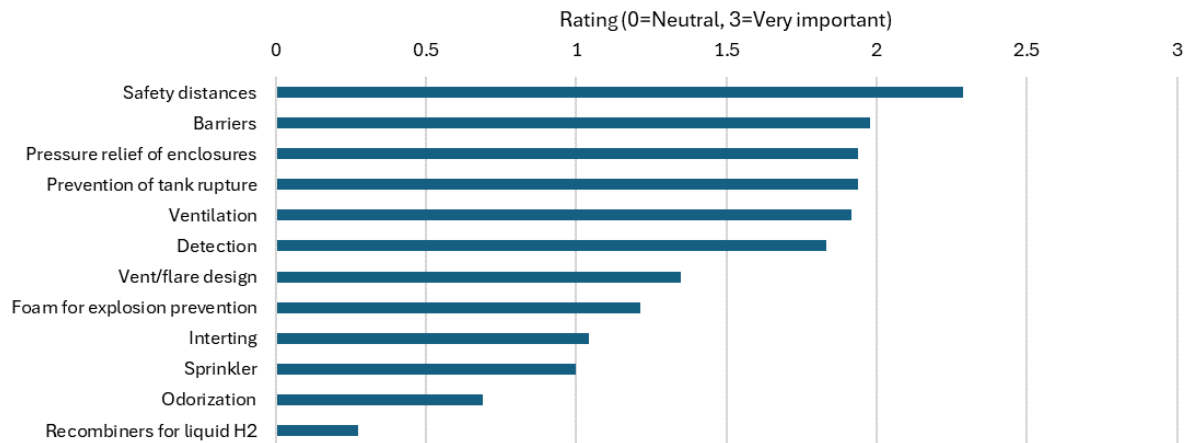
Liquid hydrogen



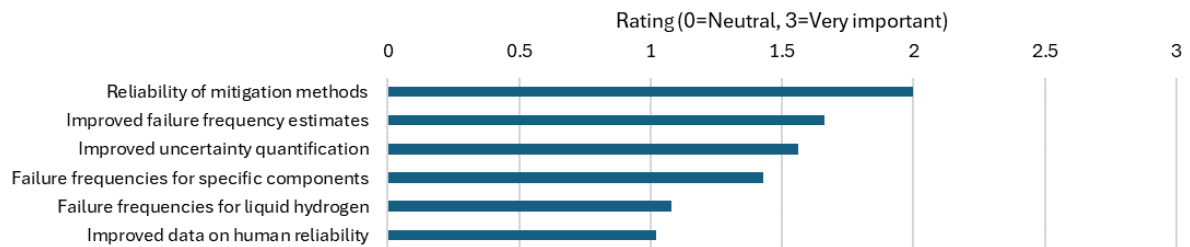
Materials and storage methods



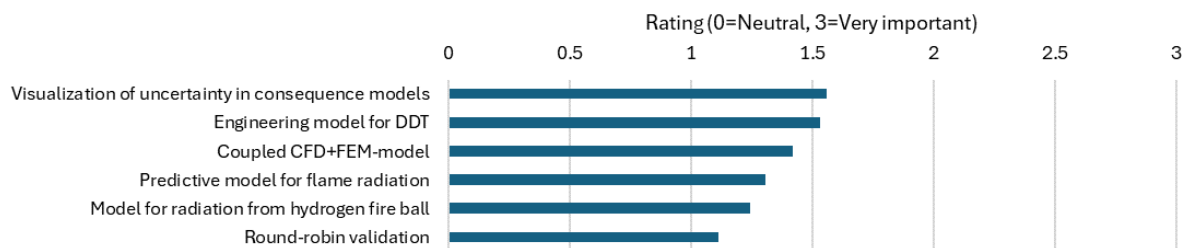
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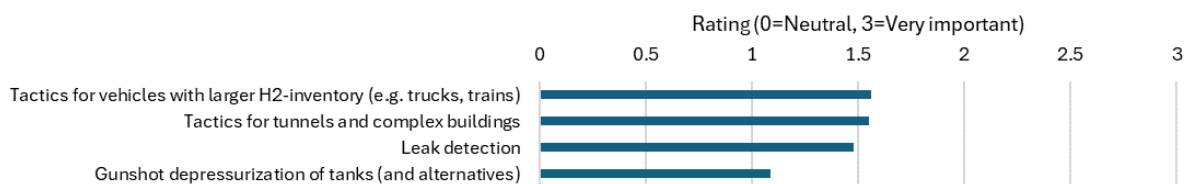
Risk analysis



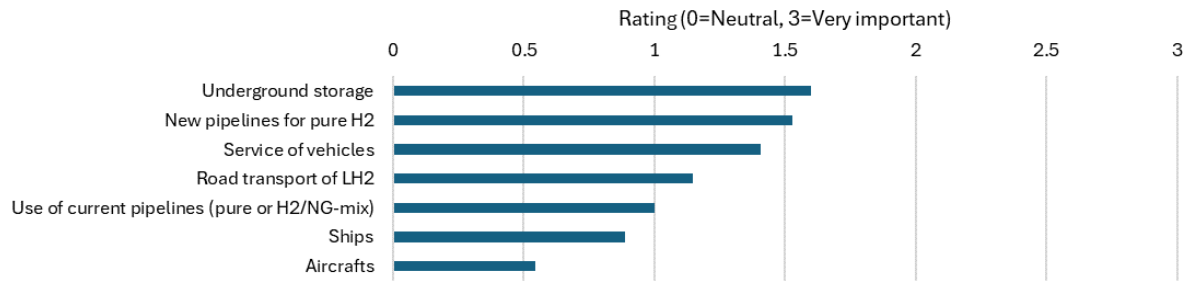
Consequence modeling



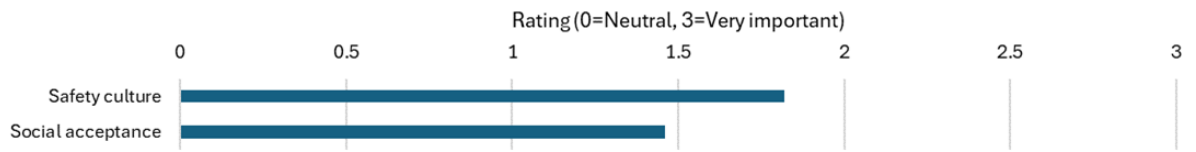
Rescue service intervention



Applications



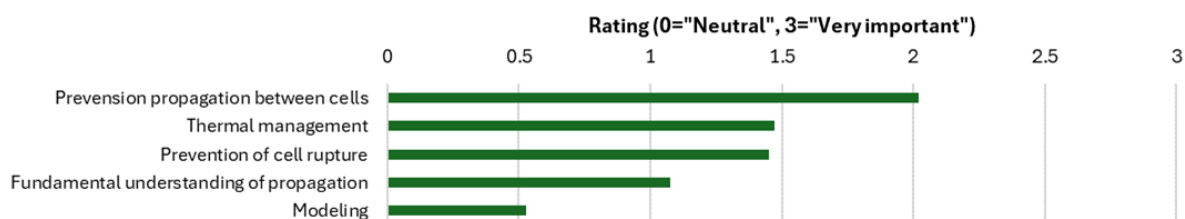
Non-technical



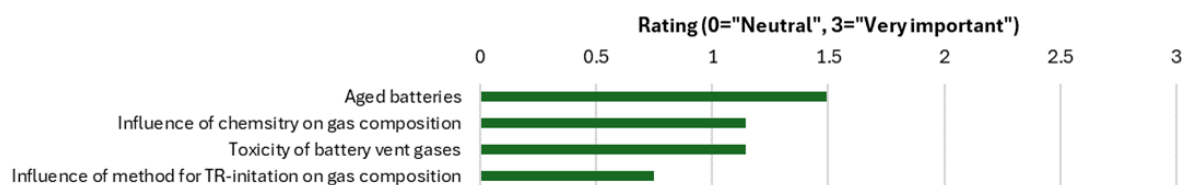
Appendix B – All priorities for battery safety

In this appendix, the prioritization of all the research needs in each area for battery safety can be found.

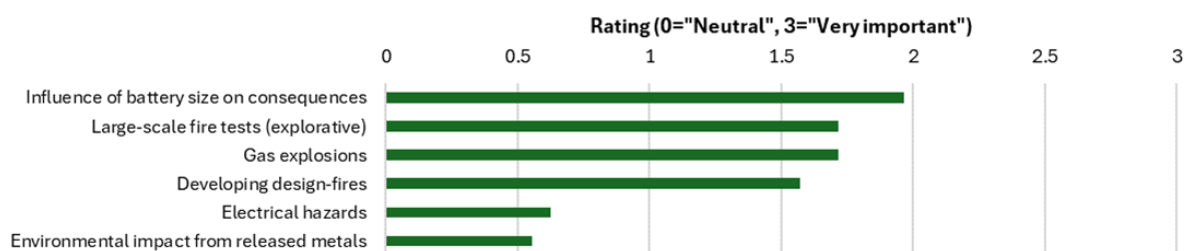
Thermal runaway



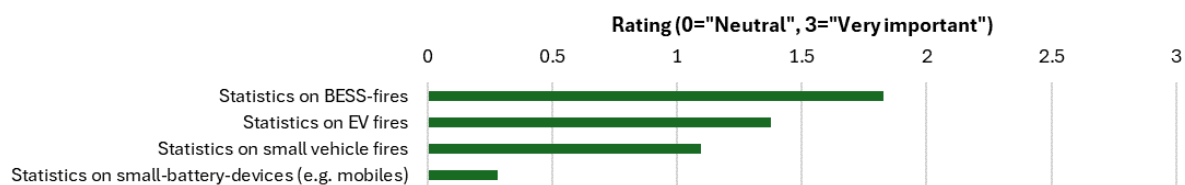
Gas release



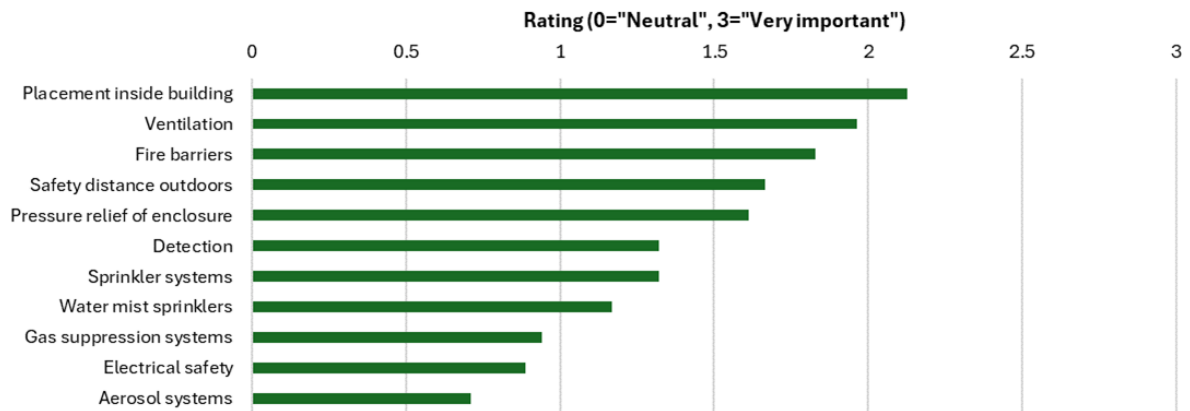
Consequences



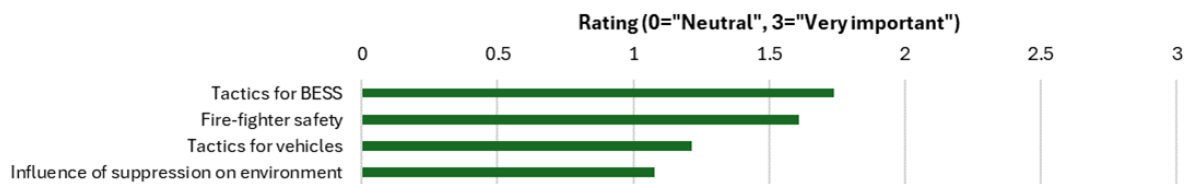
Statistics



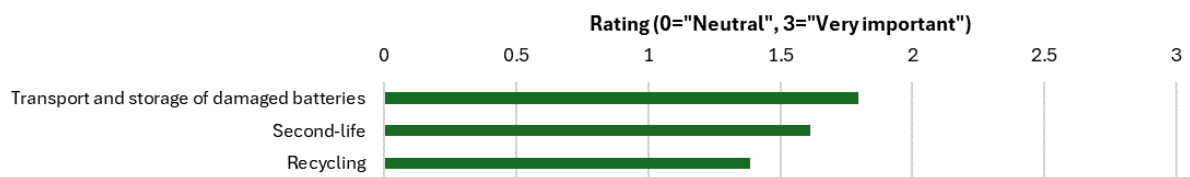
Room-level mitigation



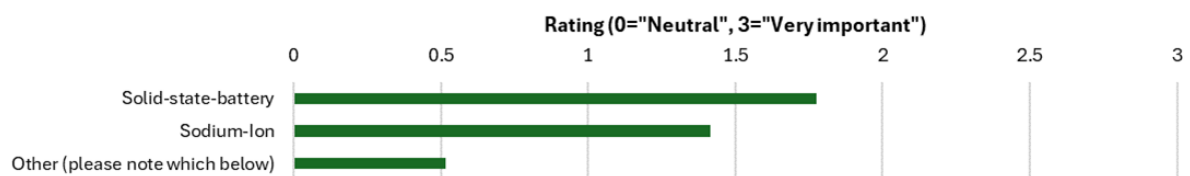
Rescue service intervention



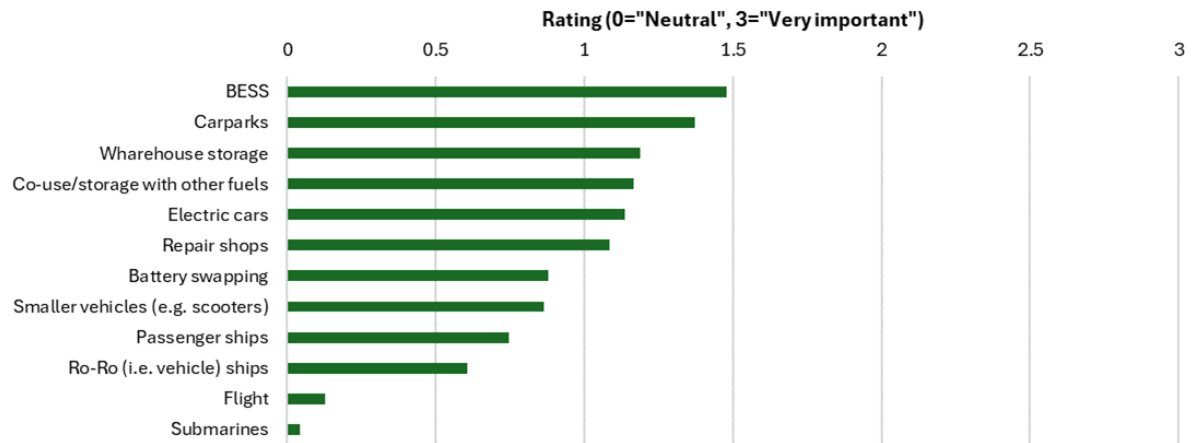
End-of-life



New battery technologies



New battery technologies



Appendix C – Research needs for hydrogen safety according to ChatGPT

Result from ChatGPT-3.5 from 2023-08-10

Prompt: “What research is needed for hydrogen safety research?”

Result:

Hydrogen safety research is essential for the successful deployment of hydrogen as a clean and sustainable energy carrier. As hydrogen technologies are being developed and integrated into various sectors, including transportation, industry, and energy storage, it's important to address safety concerns. Here are some key areas of research needed for hydrogen safety:

1. Hydrogen Behavior and Release:

- a. Study the behavior of hydrogen in different environments, including its dispersion, mixing, and diffusion characteristics.
- b. Research the mechanisms and factors influencing hydrogen release from storage, pipelines, and handling processes.

2. Hydrogen Detection and Sensing:

- a. Develop reliable and sensitive hydrogen sensors to detect leaks and concentrations in various settings.
- b. Investigate novel sensing technologies for accurate and real-time monitoring of hydrogen presence.

3. Hydrogen Storage Safety:

- a. Study the safety implications of different hydrogen storage methods, such as compressed gas, liquid, and solid-state storage.
- b. Research materials and designs that mitigate potential hazards associated with hydrogen storage, such as embrittlement and spontaneous ignition.

4. Hydrogen Infrastructure Safety:

- a. Analyze the safety of hydrogen production, transportation, and distribution systems, including pipelines, filling stations, and delivery trucks.
- b. Investigate potential risks and develop mitigation strategies for hydrogen supply chain operations.

5. Hydrogen Combustion and Ignition:

- a. Study the conditions under which hydrogen can ignite and develop improved understanding of hydrogen combustion dynamics.
- b. Research techniques to prevent and control hydrogen fires, including flame suppression and venting strategies.

6. Hydrogen Interaction with Materials:

- a. Investigate the effects of hydrogen on various materials, such as metals and polymers, to prevent degradation, embrittlement, and potential failures.

7. Hydrogen Infrastructure Standards:

- a. Contribute to the development and enhancement of safety standards and regulations specific to hydrogen technologies.
- b. Ensure that hydrogen-related equipment, processes, and facilities meet rigorous safety requirements.

8. Modeling and Simulation:

- a. Develop accurate computer models and simulations to predict hydrogen behavior, dispersion, and safety scenarios in different environments.
- b. Use simulations to test safety measures and optimize infrastructure design.

9. Emergency Response and Training:

- a. Research effective emergency response protocols and strategies for hydrogen-related incidents.

- b. Develop training programs for first responders and personnel working with hydrogen technologies.

10. Public Perception and Acceptance

- a. Investigate public perceptions and attitudes toward hydrogen safety to better understand concerns and improve communication strategies.
- b. Address public concerns and build confidence in hydrogen technologies through outreach and education.

Collaboration between researchers, industry stakeholders, regulators, and policymakers is crucial for advancing hydrogen safety research. Continued funding and support for research efforts are essential to ensure the safe and successful integration of hydrogen into our energy landscape.

Appendix D – Research needs for battery safety according to ChatGPT

Result from ChatGPT-3.5 from 2023-08-10

Prompt: What research is needed for battery safety research?

Result:

Battery safety research is a critical area of study, especially as battery technology continues to advance and find applications in various industries, including consumer electronics, electric vehicles, and renewable energy storage. To ensure the safe and reliable operation of batteries, several areas of research are needed:

1. Chemical Composition and Materials Research:

- a. Investigating new electrode materials with higher energy density, stability, and thermal resistance.
- b. Studying the interactions between different materials within the battery to prevent undesirable reactions and thermal runaway.

2. Thermal Management:

- a. Developing advanced thermal management systems to regulate battery temperature and prevent overheating.
- b. Researching innovative cooling methods and materials to dissipate heat more effectively.

3. Electrolyte Studies:

- a. Investigating new electrolyte formulations that are less flammable and have improved thermal stability.
- b. Studying the behavior of electrolytes under various conditions to better understand their impact on battery safety.

4. Electrochemical Modeling and Simulation:

- a. Creating accurate models that simulate battery behavior and predict potential safety issues under different operating conditions.
- b. Developing real-time monitoring systems that can detect deviations from normal behavior and trigger safety mechanisms.

5. Internal Short Circuit Detection and Prevention:

- a. Researching methods to detect and prevent internal short circuits, which can lead to thermal runaway.
- b. Developing self-healing materials or designs that can isolate damaged areas and prevent catastrophic failures.

6. Battery Pack Design and Engineering:

- a. Designing battery packs with built-in safety features, such as pressure relief mechanisms and physical barriers to contain thermal events.
- b. Optimizing the layout of battery cells to minimize the impact of thermal runaway within a pack.

7. Safety Testing Standards and Protocols:

- a. Establishing standardized testing methods to evaluate battery safety, including mechanical abuse, thermal stress, and electrical abuse tests.
- b. Continuously updating testing protocols to account for new battery chemistries and technologies.

8. Advanced Monitoring and Control Systems:

- a. Developing sophisticated battery management systems (BMS) that can actively monitor and control individual cells within a pack to prevent unsafe conditions.
- b. Integrating smart algorithms that can predict and mitigate safety risks.

9. Recycling and End-of-Life Considerations:

- a. Researching environmentally friendly and safe methods for recycling and disposing of batteries at the end of their lifecycle.
- b. Investigating ways to recover valuable materials from used batteries while minimizing environmental impact.

10. Public Education and Awareness:

- a. Conducting research to better understand user behaviors and attitudes toward battery safety.
- b. Developing effective strategies to educate the public about safe battery usage and handling.

Collaboration between researchers, engineers, regulators, and industry stakeholders is crucial to advance battery safety research and implement findings in practical applications. Additionally, ongoing funding and support for battery safety research are essential to address emerging challenges as battery technologies continue to evolve.

Prompt: What research is needed for the safety of BESS?

Results:

Ensuring the safety of Battery Energy Storage Systems (BESS) involves a multifaceted approach that requires research in several key areas:

1. **Battery Chemistry and Materials:** Research aimed at developing safer battery chemistries and materials is essential. This includes studying the properties of different electrode materials, electrolytes, and separators to improve thermal stability, reduce the risk of thermal runaway, and enhance overall safety.
2. **Battery Management Systems (BMS):** BMS research is crucial for monitoring and controlling various parameters of battery operation to ensure safety. Advances in BMS technology can enable better state-of-charge estimation, overcharge and over-discharge protection, thermal management, and early fault detection.
3. **Thermal Management:** Efficient thermal management is critical for preventing thermal runaway and maintaining safe operating temperatures within the battery system. Research in this area focuses on developing effective cooling systems, thermal insulation, and heat dissipation techniques to manage temperature fluctuations and mitigate the risk of thermal events.
4. **Fault Diagnosis and Prognosis:** Research into fault diagnosis and prognosis involves developing techniques and algorithms to detect, diagnose, and predict potential faults or failures within the BESS. Early detection of abnormalities allows for timely intervention and preventive measures to avoid safety hazards.
5. **Safety Standards and Regulations:** Developing and updating safety standards and regulations specific to BESS is essential for ensuring uniformity and compliance across the industry. Research in this area involves identifying potential safety hazards, establishing testing protocols, and defining safety guidelines for the design, installation, and operation of BESS.
6. **Risk Assessment and Mitigation:** Conducting comprehensive risk assessments helps identify potential hazards associated with BESS installations and develop mitigation strategies to minimize risks. This includes analyzing the consequences of failures, assessing the impact on personnel safety, property damage, and the environment, and implementing measures to enhance safety and resilience.
7. **Fire Safety and Emergency Response:** Research in fire safety focuses on understanding the behavior of lithium-ion batteries during thermal runaway and developing effective fire suppression systems and emergency response protocols. This includes studying the effectiveness of various extinguishing agents, designing fire containment systems, and training personnel in emergency procedures.

8. **Environmental Impact Assessment:** Assessing the environmental impact of BESS involves evaluating the lifecycle emissions, resource depletion, and potential hazards associated with battery production, operation, and disposal. Research in this area helps identify ways to minimize environmental impacts and promote sustainable practices throughout the lifecycle of BESS.

By addressing these research areas, stakeholders can work towards enhancing the safety, reliability, and sustainability of Battery Energy Storage Systems, thus facilitating their integration into the broader energy infrastructure and promoting the transition towards a cleaner and more resilient energy future.