MASTER THESIS

Management of safety hazards in residential buildings with multiple electrical energy storage systems

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CHAIR:

Dr. Ir. Leo van Dongen

EXAMINATION COMMITTEE:

Dr. Mohammad Rajabali Nejad
Dr. Yashar.Hajimolana
Drs. Mariëlle Winkler
Dr. Ir. Gerwin Hoogsteen

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Abstract

Electrical energy storage (EES) systems can make the business case for renewable energy generation more appealing, ultimately paving the way to a future with a lower carbon footprint. The application of EES technology in residential buildings is relatively new. Like all new technology, the concerns around its safety hazards need to be addressed before EES systems can gain a wider public acceptance and adoption. The LIFE project at the University of Twente is an opportunity to increase the understanding of the safety hazards of multiple energy storage systems, namely a hydrogen system, lithium-ion (Li-ion) and vanadium redox flow (VRB) battery systems.

This thesis analyses the associated safety hazards and proposes recommendations for delivering a safe product, especially in the operate and maintain asset lifecycle phases. The research questions are:

1. What could be the LIFE project's possible safety goals according to applicable regulations, codes, and standards (RCS)?
2. What approach could be used to identify all the hazards in an integrated EES system such as in LIFE?
3. How to demonstrate that the residual/mitigated risk is acceptable?
4. What are the top five concerns to be heeded by the fire brigade personnel when responding to safety incidences related to batteries and hydrogen system used in the LIFE project?

The thesis found that the application of safety cube theory and a structured system-safety approach is able to identify all the main hazards. In terms of safety goals, the current RCS can be either overly restrictive for a hydrogen system or do not provide sufficient guidance for Li-ion or VRB battery usage in integrated EES systems for residential buildings. For hydrogen and Li-ion battery systems, the worst-case safety risks are high enough to necessitate the use of Safety-Critical Items to reduce the unmitigated risks to acceptable levels. The top five concerns for first responders are: awareness of the existence of EES systems within or in the vicinity of the building, the need for a focal-person knowledgeable about the installed EES, the determination of whether hydrogen gas is leaking indoors, the establishment of a safe distance during emergency response, and the detection of toxic gasses (HCl, CO and HF) in the battery storage room.

The thesis concludes that the management of EES safety hazards in residential buildings can be made easier for implementation by codifying the safety requirements into prescriptive regulations and standards. To achieve this, the relevant stakeholders would need to agree on a streamlined approach.

Contents

List of acronyms

ACH – air change rate per hour
ALARP – as-low-as-reasonably-possible
EES – electrical energy storage
EESS – electrical energy storage systems
IDLH – immediate danger to life and health
IEF – initiating event frequency
LOPA – Layer of Protection Analysis
LIFE - Living project for Future Innovative Environments
Li-ion – lithium-ion
PFD – the probability of failure on demand
PHA – Preliminary Hazard Analysis
PHL – Preliminary Hazard List
PPE – personnel protective equipment
PRD – pressure relief device
PV – photovoltaic
RES – renewable energy sources
RCS – regulations, codes and standards
SCI – safety-critical items
SHA – System Hazard Analysis
RES – renewable energy sources
VRB – vanadium redox flow battery

1 Introduction

The Netherlands had pledged to achieve 14% of Total Final Consumption (TFC) energy generated from renewable energy sources (RES) by 2020, following the European Union's directive 2009/28/EC. Despite the high annual growth rate of installed capacity in the last decade, as of end 2018, the Netherlands had fallen short of the aspired target, with only 7.4% achieved. Wind and solar energy's contribution was 1.6% and 0.6%, respectively [3]. Much more installed capacity is needed before the wind and solar RES make a significant impact on reducing greenhouse gas (GHG) emissions. Various challenges stand in the way of making this a reality: political, economic, logistics, environmental, technical and social factors.

Almost 60% of electricity production in the Netherlands from RES came from wind turbines, making it the largest contributors among all RES [4]. Nearly two-thirds of the total wind energy generation is from onshore wind farms. Around 50% of installed solar PV panels in the Netherlands are installed on residential roofs, and the rest from business roofs and solar parks as of 2018 [3]. In the Netherlands, the installed solar PV capacity started growing after the government introduced a net-metering policy since 2004, enabling owners of PV panels to get favourable rates for selling surplus electricity back to the utility supplier. The take-up grew even faster after 2011, as more incentives were introduced [5, 6].

The generation of electricity from wind energy and solar by itself is only part of the renewable energy solution. These RES suffer from intermittent production when there is insufficient wind or sunlight. Furthermore, the hourly energy usage pattern of consumers is also not always in synchronisation with energy generation. For example, in the case of solar power, electricity generation happens typically during the daytime when own-consumption is low. The electrical grid infrastructure also needs to grow to cope with increased generation from RES.

Electrical energy storage (EES) technologies can be a solution to the aforementioned issues. Energy storage technology thus has the benefit of providing a means of load-levelling, in conjunction with the traditional electricity generation sourced from fossil fuels [7]. Storage systems become a backup power supply if there are interruptions from the grid-supply. They act as buffers to store surplus electricity (i.e. charging) and then supplies electricity when the user demands it (i.e. discharging), effectively overcoming the issue of intermittency and potentially unfavourable feed-in tariffs, as illustrated in Figure 1.

EES also helps in power system planning, operation and frequency regulation [8]. The availability of localised electrical energy storage will also alleviate the grid congestion problem, thereby allowing grid owners to postpone costly grid-upgrading projects.

In the Netherlands, the current drivers increasing the usage of the various form of energy storage technology come from [9]:

- The ending of the net-metering scheme in 2021 for homeowners with PV-electricity generation systems. The 'prosumers' could begin to benefit from energy storage solutions especially if the utility company starts paying a lower price for electricity purchased from the prosumer compared to what it charges for the use of grid-supplied electricity [6].

- Stricter requirements for energy efficiency labelling of homes from 2023 and the introduction of an obligation to construct newly built homes without a connection to the gas network. These measures are expected to trigger additional demand for domestic self-supply and storage of electricity.
- The approval by the Dutch parliament in 2018 of a motion to end the 'double' taxation charge for the consumption of electricity. A considerable improvement on the business case for energy storage projects is to be expected.

In short, efforts to decarbonise electricity generation requires the advancement of better energy storage technology. A better understanding of its advantages, disadvantages and safety aspects can help increase the public adoption of EES.

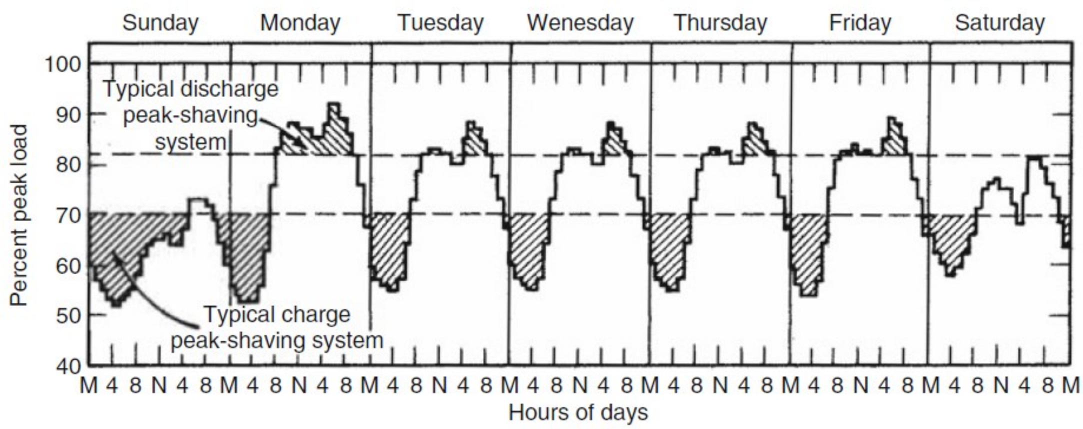


Figure 1 Hourly data on electricity usage in a full week. Load shifting and storage technology can be used to achieve load-levelling. From [7].

1.1 Background of the LIFE project

In 2019, the University of Twente initiated the 'Living project for Future Innovative Environments' programme or more conveniently referred to with its acronym, the 'LIFE project'. The project aimed to research the interplay between the trio of technology, human and the infrastructure system in supporting society's transition towards a future of low carbon footprint, climate-friendly living, and a circular economy.

The LIFE project is expected to span over ten years, with six units built initially as a pilot. The houses would be designed respectively for the occupancy of one, two and three persons. These houses would function as 'living labs', enabling researchers to monitor and evaluate the residents' interaction and smart water-energy systems. Ten small-and-medium enterprises around the Twente region, known as the LIFE Project Partners, are expected to be involved. These Partners contribute to the project's conceptual design, equipment supply, installation, support and maintenance.

Figure 2: Conceptual presentation of the first phase of the field lab. Source: LIFE project documents.

Figure 2 shows a conceptual presentation of the systems meant to be delivered in the LIFE project's original scope. The residential building will be equipped with systems that can generate electricity from renewable sources such as wind and solar. Wind-generation has been dropped from the subsequent project scope. The surplus generated electricity would be accumulated into one of the three types of energy storage technology - lithium-ion batteries and a redox-flow batter, shown in Figure 3 and a hydrogen system - and then utilised again whenever the electricity demand exceeds the generation capacity.   Hydrogen will be generated via electrolysis of water, using the surplus electricity from PV solar panels. Besides, the buildings will also have systems installed to collect, store and process rainwater, and recycle and reuse the water.

The aspiration is that the residential buildings would become autarkic, meaning that they are self-sufficient in water and energy. Nonetheless, the buildings would be connected to the grid electricity and water supply to ensure that the residents have continuous availability to these resources should any water or energy systems malfunction or fail to deliver the expected outputs.

Construction was initially meant to begin in February 2020, and residents would live in these tiny houses in May 2020. As of October 2020, however, the LIFE project's progress has been delayed and remains in the conceptual design discussion phases.

Figure 3 A unit of SuperB's SB12V100E-ZC Li-ion battery. Source: SuperB; (bottom) A unit of Volterion's powerRFB vanadium redox flow battery. Source: Volterion.

1.2 Research objectives and questions

Not surprisingly, given the immense potential upsides, there has been a lot of interest in energy storage technology. Much research efforts have been expended, currently still ongoing, improving the storage density, energy conversion efficiency and lowering the costs of production and adoption of energy storage technology.

Incidences of Li-ion battery fires and hydrogen explosion have been widely reported [10, 11], likely to raise apprehensions about their safety to use in homes. A number of past and on-going research on the safety of EESS is focused at the detailed level of material sciences, electrochemistry and the physics of storage technology design. At a broader level, stakeholders in the residential building industry such as installers, building companies, homeowners, and residents to the municipal councils would be more interested in the aggregate EESS safety aspects. The safety hazards management should span the entire lifecycle starting from the design, construction, use, and maintain until the product disposal.

Regulations can have positive and negative effects on the innovation process [12]. The adoption rate of EES is affected by electricity and energy market regulations [9, 13]. Technological advancements, such as in the field of energy generation and storage, requires governments to maintain a balance between fostering innovation, protecting consumers and addressing the potential unintended consequences of disruption [14]. Understanding the applicable regulations, codes, and standards that relate to safe and reliable EESS can reduce the overall risk of accidents.

Should EESS be more widely adopted, it is equally essential to improve public perception and acceptance of new technologies, as seen from the earlier debates over nuclear power and genetically-modified food crops [15]. As part of the municipal permitting application process, the Fire Brigade of the Twente region requested the LIFE project team a guideline consisting of 'top five need-to-know' information for a first responder when dealing with a safety-incident related to the EES systems in a LIFE building.

This thesis intends to contribute to the LIFE project by analysing the safety hazards and making suitable proposals for delivering a safe product. The study will focus on the use of three energy storage technologies, namely the hydrogen system, the lithium-ion and vanadium redox flow batteries with an emphasis on the operate and maintain asset lifecycle phase. Therefore, this thesis attempts to achieve the research objective by answering four of the following questions:

1. What could be the LIFE project's possible safety goals according to applicable regulations, codes, and standards (RCS)?
2. What approach could be used to identify all the hazards in an integrated EES system such as in LIFE?
3. How to demonstrate that the residual/mitigated risk is acceptable?
4. What are the top five concerns to be heeded by the fire brigade personnel when responding to safety incidences related to batteries and hydrogen system used in the LIFE project?

1.3 Structure of the thesis

Chapter 2 contains relevant information gleaned from literature review efforts. It introduces system safety concepts, followed by a section describing the applicable regulations, codes and standards for EESS used in the LIFE project. The chapter's final sections describe the safety hazards of hydrogen, Li-ion battery and VRB systems, and the existing methods for mitigation.

Chapter 3 contains the proposed approach to managing the EES system safety, describes its application in the LIFE project and the application outcome. Chapter 4 presents a discussion of the proposed approach and the outcome. Chapter 5 provides a conclusion to the research while also making recommendations for the LIFE project.

The appendices contain the safety analysis worksheets, and additional information gleaned from literature reviews, detailed calculations, and supporting data used in the safety analysis.

2 Literature review

2.1 System safety

System safety is the formal name for a comprehensive and systematic examination of engineering design or mature operation and control of any particular hazards that could injure people or damage equipment [16]. Having a good understanding of the system safety concept is essential to ensure safety in a product's design. Firstly, the definitions of commonly-used terms in system safety are given, followed by an explanation of key concepts.

2.1.1 Definitions of terminology used in system safety

Product: ISO 9000 defines a product as an output produced by an organisation, which could be tangible or intangible. Examples of the first are such as goods and services, while examples of the latter are such as information and software [17].

System: Blanchard and Fabrycky, in their textbook 'Systems Engineering and Analysis', defined a system as 'a set of interrelated components functioning together toward some common objective or purpose'. Randomly found items or products in a room does not constitute a system if these items lack any functional relationships with each other [18].

Safety: The Online Cambridge dictionary defines 'safety' as 'a state in which or a place where you are safe and not in danger or at risk' [19]. In contrast, Aven in his paper on safety-science, mentioned that even some safety professionals defines a 'safety' with something that is entirely risk-free [20], whereas another perpective is that safety is a subjective judgement. The ISO/IEC Guide 51 further stresses that 'safety' is a 'freedom from risk which is not tolerable' [21], thus explicitly recognising that there is always some level of risk present in products or systems.

Hazard: The ISO/IEC Guide 51 defines a hazard as a 'potential source of harm', while 'harm' is defined as 'injury or damage to the health of people, or damage to property or the environment' [21]. This definition implies that hazards are pre-existing situations which can potentially lead to unsafe events.

Risk: That safety and risk are inter-related is broadly agreed upon by safety professionals and researchers [20]. ISO 31000 defines risk as 'effect of uncertainty on objectives' [22]. This is a broad definition and is typically used at the corporate level of an organisation and can be categorised broadly into financial and non-financial risks. Safety risks belong to the latter category. From a safety standpoint, ISO/IEC Guide 51 defines risk as to the 'combination of the probability of occurrence of harm and the severity of that harm', that is, risk = probability x severity [21]. This definition is widely used when assessing safety risks brought about by a hazard.

Hazards Theory: The hazard theory is explained by Ericson [23], in his textbook 'Hazard Analysis Techniques for System Safety'. Three elements must be present to define a hazard accurately: firstly the existence of a hazardous source; secondly an initiating mechanism or a trigger; thirdly a target or thing that is vulnerable to injury or damage. Ericson refers to these as components of the hazard triangle. Events that can cause harm are sometimes called a mishap or an accident. Hazards can transit into mishaps/accidents due to a confluence of factors. The hazard-mishap relationship is depicted in Figure 4. The calculation of the risk of an unsafe event is similar to how it is described in ISO/IEC Guide 51.

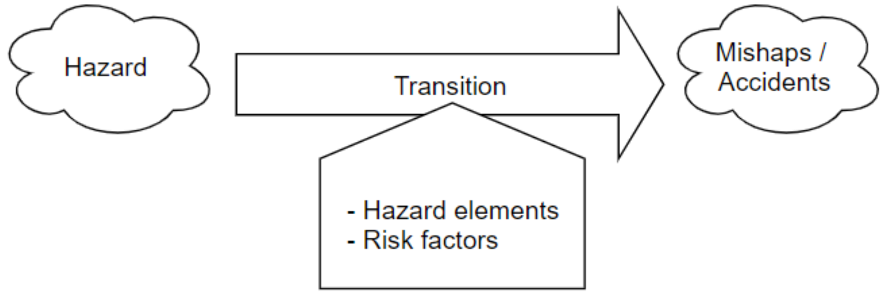


Figure 4: Hazard-mishap relationship, adapted from [23].

Both Bahr and Ericson state that mishaps/accidents do not just occur as random events. Rather, they are a result of a process with many steps, but are controllable and predictable provided that the safety hazards are correctly analysed [16, 23]. This premise forms the philosophical basis for system safety, whereby the safety hazards need to be firstly identified, followed by efforts to mitigate the risks they bring. The overall purpose of the system safety process is to identify hazards, eliminate or control them, and mitigate the residual risks.

The system safety process has been established for many years and is currently applied in many industries and organisations. Various variations of the system safety process exist, but the general theme and steps are consistent. Bahr, in his textbook 'System Safety Engineering and Risk', detailed the ten steps in to manage system safety [16]. ISO/IEC Guide 51 has a flow-chart describing the iterative process of risk assessment and risk reduction for safety hazards. Quite similar in concept is the eight sequential elements described in the United States Department of Defence (DoD) standard MIL-STD-882E: System Safety [24]. For comparison, all three variations are shown in Figure 5 and Figure 6.

As can be observed, the three versions have principally similar structure to describe the system safety process. The eight elements from [24] are elaborated below.

In Element 1, the system safety approach is formally documented by describing the system under analysis and the objectives of the analysis efforts. The document should also detail out the risk management efforts, the overall programme management structure and how the hazards and associated risks are to be formally accepted [24]. In Element 2, hazards are identified using systematic analyses on the hardware, software, system interfaces, operation and the operating environment. All hazards shall be documented in a closed-loop hazard tracking system. Element 3 is achieved by ascertaining the occurrence probability and severity of the safety mishaps for each identified hazard. Some of the hazard assessment techniques are discussed further in a later section.

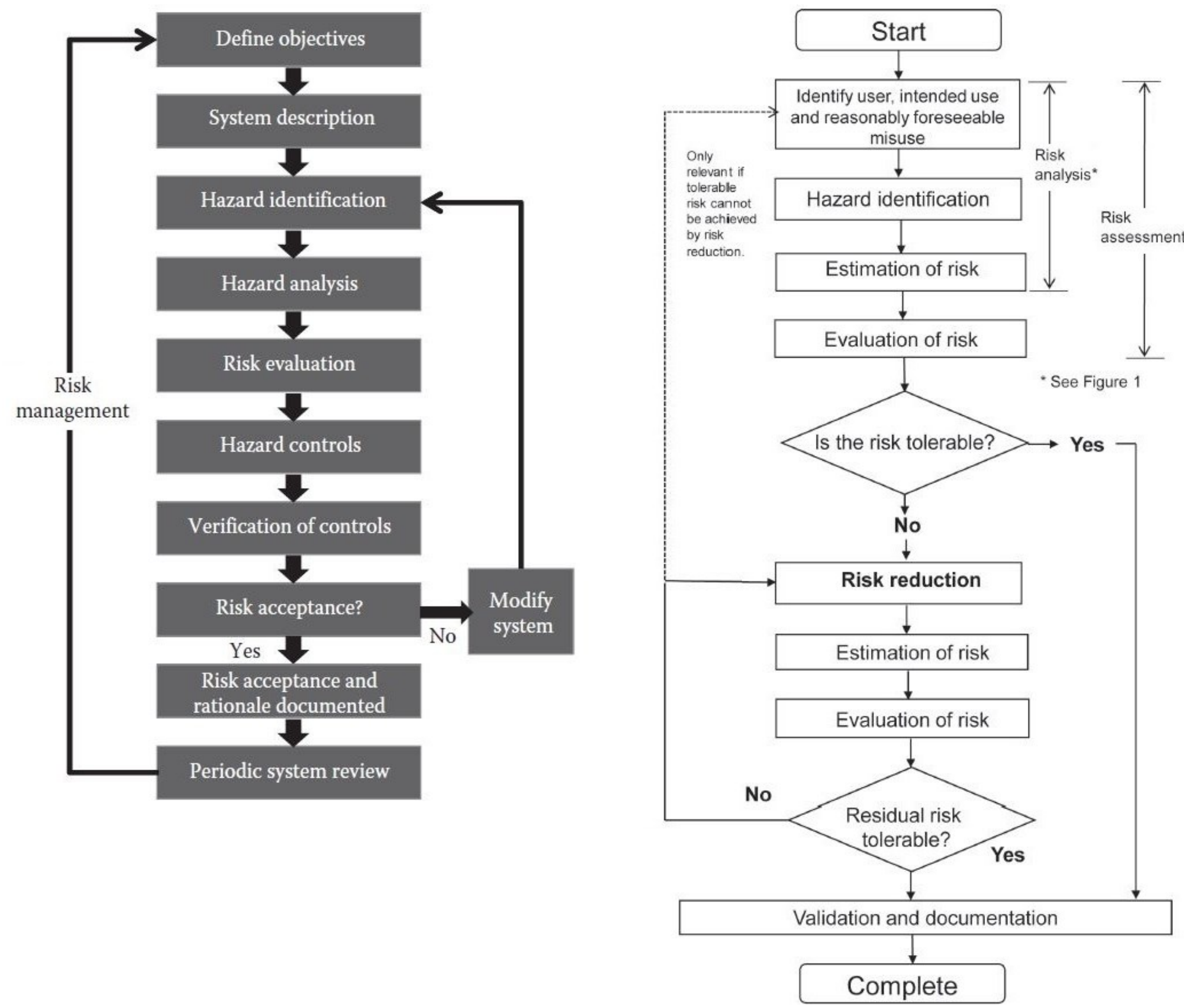


Figure 5 (left) System safety process described by Bahr [16]; (right) risk assessment and risk reduction process for safety hazards described in ISO/IEC Guide 51 [21].

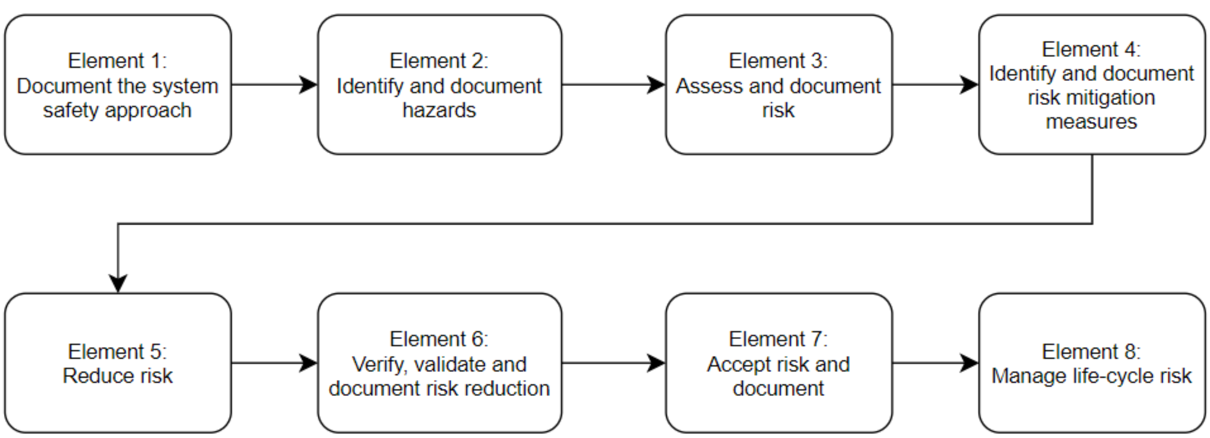


Figure 6 Eight elements of the system safety process from MIL-STD-882E [24].

In Element 4, the potential risk mitigations are identified, and the expected risk-reduction achieved are to be estimated and documented. Hazards are eliminated whenever possible, but if this is not achievable, then the associated risk should be reduced to the lowest acceptable level, or what is also commonly known as As-low-as-reasonably-possible (ALARP). The concept of ALARP and risk mitigation is also discussed further in a later section.

In Element 5, the appropriate mitigation measures are selected to achieve ALARP. Factors taken into consideration are such as mitigation cost, feasibility and effectiveness. In Element 6, the effectiveness of the risk-reduction efforts is checked via proper analysis, testing, demonstration and inspection. In Element 7, the residual risks need to be agreed upon and accepted by the appropriate stakeholders, typically the authority bodies. The combined activities from Elements 5 through 7 is called 'risk evaluation' in [16]. Finally, in Element 8, the hazards and associated risks are managed throughout the entire asset lifecycle phases. Re-evaluation of risk can be brought about by newly-identified hazards or hazards that have a higher level of risk than what was initially thought. Besides, according to ISO/IEC Guide 51, future developments in technology and knowledge could also lead to more economically feasible improvements to attain the minimum level of risk for a system or product [21].

2.1.2 Hazard Analysis Types and Techniques

According to Bahr [16], hazard analysis should be systematic and comprehensive, and the failure delve into the details to discover any hidden interactions is akin to relying on luck for safe outcomes. Ericson [23] makes a distinction between hazard analysis types and hazard analysis techniques. The analysis type, of which he established seven types, defines the analysis timing, depth of detail and system coverage. The analysis technique, on the other hand, refers to a particular methodology that yields specific results.

Analysis types: Ericson states that there are seven basic analysis types [23]. He recommends that all seven basic analysis types be performed over the entire asset-life cycle phases, as a means of ensuring that all hazards and its associated risk has been identified, analysed and mitigated. The reason for this is because one particular hazard analysis type does not necessarily identify all the hazards within a system. Each analysis type acts like a filter, in which certain types of hazards are identified. After applying all the seven filter 'types', the known remaining hazards would have been reduced to an acceptable level of risk. This is depicted in Figure 7. Tailoring for conducting lesser types is possible, but this needs to be reasoned and justified in the system safety management plan of a project [23].

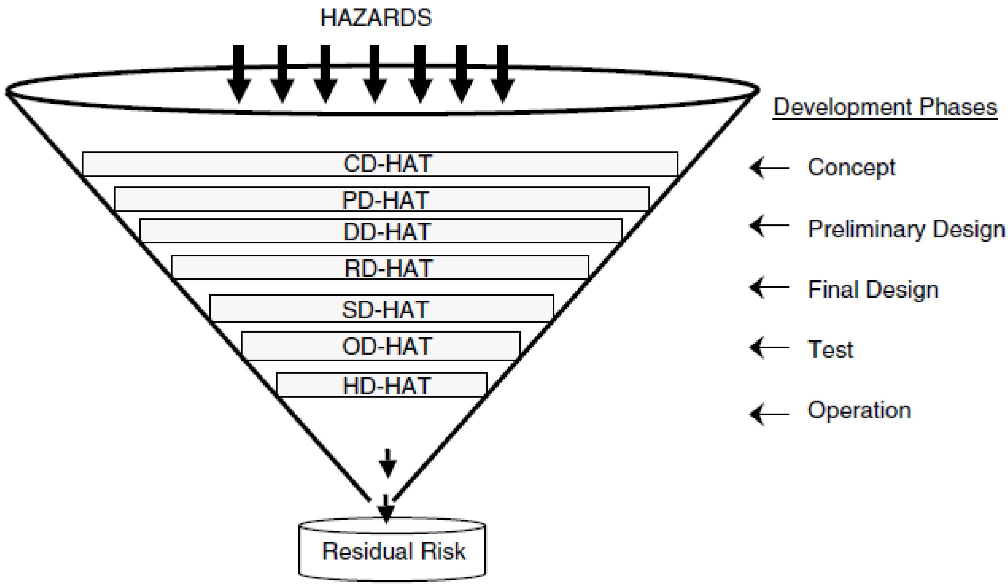


Figure 7 The seven hazard assessment types (HATs). The seven hazard assessment types (HATs). CD: Conceptual-design; PD: Preliminary-design; DD: Detailed-design; RD: Requirements-design; SD: System-design; OD: Operations-design; HD: Health-design. From [23].

Analysis techniques: Numerous techniques currently exist. Some were developed for use in particular industries, for example in commercial nuclear power, transportation, chemical process, oil and gas, food processing, military, aerospace and consumer products. Some techniques originated in one industry but have become popular in other industry sectors [16]. Table 1 shows some of the commonly-applied techniques, while a more detailed description of these techniques can be found in Appendix 1. The techniques are differentiated by aspects such as suitability with analysis technique type, phase in the asset's lifecycle, quantitative or qualitative assessment, application efforts, and if these techniques are of inductive or deductive nature. A brief explanation of these aspects is given next.

Table 1 Examples of some commonly-applied safety hazard analysis techniques

• Preliminary hazard list	• Fault tree analysis
• Preliminary hazard analysis	• Event tree analysis
• Subsystem hazard analysis	• Failure mode and effects analysis
• System hazard analysis	• Barrier analysis
• Operating and support hazard analysis	• Hazard and Operability analysis
• Health hazard assessment	• Bowtie diagramme
• Safety requirements/ criteria analysis	• Layer of protection analysis

Asset Lifecycle: A system typically goes through several phases of life, called the system lifecycle. Each industry may have its unique lifecycle phase defined differently, but generically there are five phases, as shown in Table 2 [16, 18]. Activities in the context of the LIFE project is also shown. The distinction of each lifecycle phase makes it easier to focus on the required activities and targets. At the end of each phase, an evaluation is typically conducted to decide if a project should proceed further, with resource and cost implications.

Table 2 Five lifecycle phases of a system or a product

Lifecycle phase	Commonly used terms	Primary activities	Examples in the LIFE project context
1	Concept definition	The ideation of the system. The system requirements are defined. After a trade-off analysis is conducted, a concept is selected.	Evaluate EESS and technology options to install. Survey the market for potential project partners. Estimate costs. Identify project risks.
2	Development	The preliminary design is established. Further on, the detailed design is accomplished where the detailed engineering drawings and calculations are produced. After some iterative activities, the design is matured, and the product is ready for production. Prototypes models are created at this phase.	*During preliminary design:* Evaluate design possibilities. Conduct a preliminary safety hazard analysis. *During detailed design:* Develop detailed design Conduct detailed-design and interface hazard analysis
3	Production; Construction	Manufacturing of the system.	Install EESS. Construct LIFE facilities. Handover to the university.
4	Operation and Maintenance; Utilisation	The system enters service, which then requires support and maintenance.	Collect and analyse energy usage. Maintain LIFE facilities.
5	Disposal; Retirement; Phase-out	The system is decommissioned from use and disposed-off.	Dismantle EESS and sell or dispose of properly.

Quantitative vs Qualitative: This attribute distinguishes the characterisation of risk [23]. The quantitative approach calculates the risk to a numerical value, using quantitative or numerical data. The derived risk value is unambiguous, but its accuracy and validity have to be evaluated based on the input data quality and uncertainty factors. The qualitative approach categorises the risk into groups that represent a range of risk values. This approach makes it more flexible and less restricting. Despite being comparatively less detailed that the qualitative approach, the qualitative approach can still yield useful insights with less effort and time [23, 25], or when quantitative methods are not practical or possible due to the lack of credible data. A semi-quantitative method, essentially a combination of attributes from the two methods, can be used when a degree of risk calculations are required. Table 3 highlights the main differences between qualitative and quantitative methods.

Table 3 Key attribute differences between qualitative and quantitative risk assessments. Adapted from [23].

Attribute	Qualitative	Quantitative
Numerical outcomes	No	Yes
Cost	Lower	Higher
Difficulty	Lower	Higher
Complexity	Lower	Higher
Required data	Less detailed; more general	More detailed, depth and quantity
Technical expertise	Lower	Higher
Time required	Lower	Higher
Tools required	Seldom	Usually
Accuracy	Lower	Higher

Application efforts: The application effort is influenced by factors such as the technique's methodology complexity, the required time to perform the analysis, the level of depth of analysis, the requirement for an understanding of advanced mathematics, specialised software tools and an experienced facilitator. Some techniques can be quickly learned from practical step-by-step guides, do not require prior application experiences, and be conducted using widely-available spreadsheet tools. Other techniques require a sound grasp of boolean algebra, statistical theory and mathematical modelling skills, and detailed knowledge of the modelled process [23].

Inductive vs Deductive: These are forms of logic reasoning. Inductive reasoning, sometimes called 'bottom-up' reasoning, is based on evidential support to draw a broader conclusion [26]. With inductive reasoning, the conclusion arrived at is general and more than suggested than the given data. Ericson states that it is advantageous to use inductive reasoning when trying to identifying safety hazards. Inductive reasoning helps to find potential failures ("what can go wrong") and the possible effects of each failure ("what happens if it goes wrong") without already having the details of the system specifics. Techniques with inductive characteristics are Preliminary Hazards Analysis (PHA) and Failure Mode and Effect Analysis (FMEA).

Deductive reasoning is the reverse of inductive reasoning. The specific conclusion is arrived at from a set of premises, and supported by observation and data. The conclusion does not exceed or imply more than the premises upon which it was based. Ericson recommends that deductive reasoning be used to find the causes of a failure, by asking the question "how can it go wrong" [23]. Techniques that use deductive reasoning are like Fault Tree Analysis (FTA) and Event Tree Analysis (ETA).

2.1.3 Risk analysis

Risk analysis is the determination of risk levels, an essential aspect when analysing safety hazards. As explained in the previous section, risks can be characterised either qualitatively or quantitatively. Risk matrix has been used for a long time and is popular in various industries to help determine the level of risks and help prioritise decisions for actions. According to Peace, its advantages, among other factors, are its relatively quick and straightforward application, promotes discussions in risk workshops, enables a graphical representation of risk and enables some level of consistency in decision making [27].

An example of a risk matrix is found in the MIL-STD-882E standard, where the combination of probability (Table 4) and severity (Table 5) classifications which then allows the user to designate a risk score using a risk assessment matrix (Table 6). The use of the risk-matrix simplifies risk-scoring, by assuming that all risks within the same category (e.g. High, Serious, etc.) carries the same weight regardless of the distinction between the probability and severity.

Table 4 Probability levels for risk assessment. From MIL-STD-882E [24].

Probability Levels				
Description	**Level**	**Individual Item**	**Fleet/Inventory***	**Quantitative**
Frequent	**A**	Likely to occur often in the life of an item	Continuously experienced.	Probability of occurrence greater than or equal to 10^{-1}.
Probable	**B**	Will occur several times in the life of an item	Will occur frequently.	Probability of occurrence less than 10^{-1} but greater than or equal to 10^{-2}.
Occasional	**C**	Likely to occur sometime in the life of an item	Will occur several times.	Probability of occurrence less than 10^{-2} but greater than or equal to 10^{-3}.
Remote	**D**	Unlikely, but possible to occur in the life of an item	Unlikely but can reasonably be expected to occur.	Probability of occurrence less than 10^{-3} but greater than or equal to 10^{-6}.
Improbable	**E**	So unlikely, it can be assumed occurrence may not be experienced in the life of an item	Unlikely to occur, but possible.	Probability of occurrence less than 10^{-6}.
Eliminated	**F**	Incapable of occurrence within the life of an item. This category is used when potential hazards are identified and later eliminated.		

* The size of the fleet or inventory should be defined.

Table 5 Severity levels for risk assessment. From MIL-STD-882E [24].

SEVERITY CATEGORIES		
Description	**Severity Category**	**Mishap Result Criteria**
Catastrophic	**1**	Could result in one or more of the following: death, permanent total disability, irreversible significant environmental impact, or monetary loss equal to or exceeding $10M.
Critical	**2**	Could result in one or more of the following: permanent partial disability,injuries or occupational illness that may result in hospitalization of at least three personnel, reversible significant environmental impact, or monetary loss equal to or exceeding $1M but less than $10M.
Marginal	**3**	Could result in one or more of the following: injury or occupational illness resulting in one or more lost work day(s), reversible moderate environmental impact, or monetary loss equal to or exceeding $100K but less than $1M.
Negligible	**4**	Could result in one or more of the following: injury or occupational illness not resulting in a lost work day, minimal environmental impact, or monetary loss less than $100K.

Table 6 Risk assessment matrix. From MIL-STD-882E [24].

RISK ASSESSMENT MATRIX				
SEVERITY / PROBABILITY	**Catastrophic (1)**	**Critical (2)**	**Marginal (3)**	**Negligible (4)**
Frequent (A)	High	High	Serious	Medium
Probable (B)	High	High	Serious	Medium
Occasional (C)	High	Serious	Medium	Low
Remote (D)	Serious	Medium	Medium	Low
Improbable (E)	Medium	Medium	Medium	Low
Eliminated (F)	Eliminated			

The University of Twente uses Fine & Kinney method to measure risks related to workplace safety. This method is commonly used in the construction and cement industries [28]. The user needs to evaluate three parameters for a given workplace hazard. The parameters are the severity of injury linked to hazard (S), the exposure to the hazard (E) and the probability of the hazard occurring (P). These parameters are assigned numerical values, and the risk-index R is obtained by multiplying all three parameters, i.e. R = S x E x P. Five categories exist for the risk-index. Table 7 summarises the parameters and the representative values of each parameter.

Table 7 Parameters for Fine & Kinney risk analysis method. Adopted from [29].

Severity (S)		**Exposure (E)**		**Probability (P)**	
Scale	*Value*	*Scale*	*Value*	*Scale*	*Value*
Slight effect; injury without absence through illness	1	Very rarely (less than 1x a year	0.5	Next to impossible/unthinkable	0.1
Important, injury with absence	3	Rarely (approx. 1x a year)	1	Almost unimaginable	0.2
Severe, lasting injury with absence	7	Sometimes (monthly)	2	Highly unlikely, but conceivable	0.5
Very severe, a fatal casualty	15	Occasionally (weekly)	3	Unlikely, but possible in the long term	1
Disaster, multiple fatal casualties	40	Frequently (daily)	6	Unusual (but possible)	3
		Constantly (multiple times a day)	10	Possible	6
				To be expected	10

Risk Index (R)	
Risk class	*Value (R = S x E x P)*
Slight risk; acceptable	21
Little risk; attention required	$21 < R \leq 71$
Moderate risk; apply simple measures	$71 < R \leq 201$
High risk; apply large measures immediately	$201 < R \leq 401$
Risk is too high; stop activities / operations	$R > 401$

Despite some apparent difference between the risk matrix and Fine & Kinney's (F&N) method adopted by the University of Twente, both matrices' closer examination reveals some overlapping areas. For example:

- The probability levels in the MIL-STD-882E has six scales, compared to F&N's seven-scale probability levels. The highest probability value on the MIL-STD-882E scale (i.e. 'frequent') could represent the top-two most probable levels on the F&N scale (i.e. 'To be expected' and 'Possible').
- The severity levels in MIL-STD-882E has only four scales, whereas the F&N has five scales. The highest severity value on the MIL-STD-882E (i.e. 'catastrophic – one or more deaths') can represent the top-two most severe levels on the F&N scale (i.e. 'disaster, multiple fatal casualties' and 'very severe, a fatal casualty'). Other than that, the different severity categories are an exact match with each other.

Developing risk matrices is not a trivial matter. Peace also cautioned about the pitfalls of using risk matrices [27]. He noted that the matrix designer needs to have the necessary competency to consider issues such as the organisation's risk criteria, cognitive bias, adequacy and reliability of information and data to structure the matrix and alignment with regulations and national data. When a risk matrix is taken from another organisation, it should be tailored or adapted for the user's organisation. Risk criteria are defined by ISO Guide 73 as the 'terms of reference against which the significance of a risk is evaluated' and are based on 'organisational objectives, internal and external contexts'. They can be derived from standards, laws, policies and other requirements [30].

2.1.4 Risk mitigation

In some system safety literature, the term 'controls' or 'reduction' is used in place of 'mitigation'. When incorporating risk-mitigation measures, not every mitigative measure provides the same level of effectiveness. Accordingly, a key risk-reduction principle in system safety is that there exists an order in which the preference of mitigative measure types should be undertaken [16, 21, 23].

ISO/IEC Guide 51 mentions the risk-reduction principle following the "three-step method" which emphasises the bulk of risk-reduction measures is done during the design phase [21]. In this phase, the order of priority being first, by using inherently safe design; second, by the installation of guards and protective devices; and third for the designer to provide adequate information for use to the end-user. In contrast, the remaining risk can be further mitigated during the use phase, which consists of installing additional protective devices, providing training, the proper organisation of work, supervision and equipment application, and the use of personal protective equipment. MIL-STD-882E's hierarchy of precedence essentially states the same principle, where the first order of preference is the removal of the hazard in the design.

2.1.5 Safety-critical items

Risk-reduction for systems can be achieved from the use of safety-mechanisms. These are sometimes called 'safety-critical items' (SCI), safety-critical systems (SCS) or safety-critical functions (SCF). These terminology can carry precise meanings, depending on the referencing context. In some standards and legal definition, SCI, SCF, or SCS may be subjected to stringent requirements on the engineering and management process, testing, and target-risk criteria [31]. The terminology is used in the IEC 61508 series on functional safety, one of the most widely used standard today, focusing on electronics and related software. In this standard, functional safety are the active safety functions that relies on electronics and software working correctly and reliably to reduce the safety risk to a tolerable level. Passive safety systems, such as a fire-resistant door, is not considered as part of functional safety [32].

In contrast, the MIL-STD-882E standard defines SCI as 'hardware or software items that have been determined through analysis to potentially contribute to a hazard with Catastrophic or Critical mishap potential, or that may be implemented to mitigate a hazard with Catastrophic or Critical mishap potential.' The definition does not distinguish between electronics/software, mechanical or structural types of safety mechanism.

2.1.6 System integration

Systems, even simple standalone machinery, do not exist in isolation. Systems always interface with some other elements. In their paper, Rajabalinejad et al. assert that there are three building blocks for integration: the system, human and the environment [33]. The interactions between these three blocks result in relationships that have physical or non-physical, logical or emotional, psychological or physiological, environmental, organisational and even political influences. The successful integration of a system in a real-world application then lies in the ability of all elements in the three building blocks to exist harmoniously, and not to function independently.

Rajabalinejad et al. further demonstrated how the Safety Cube theory could be used in system safety analysis to generate multiple interface-related views. The purpose is to unearth as much as possible safety hazards that could arise from the integration of systems.

2.1.7 Safety criteria

In the opening section, it was explained that safety could be defined in relative rather than absolute terms. According to Bahr, the risk appetite, or the answer to the question 'how safe is safe enough?' can be established by defining the safety criteria. The definition of the acceptability or 'tolerability' criteria requires careful thought by an organisation's management. Critical go/no-go decisions are made from these established criteria [16].

ISO/IEC Guide 51 states that the tolerable (or acceptable) risk can be determined by firstly the current values of society. Secondly, the search for an optimal balance between the ideal of absolute safety and what is achievable. Thirdly, the demand to be met by a product or system. And finally, factors such as suitability for purpose and cost-effectiveness. The risk acceptability threshold can be subject to national regulations and standards, especially for inherently high-risk hazards [21]. Ale stresses that risk decisions are essentially political and driven by legal and cultural histories [34], and is likely to be different across the industrial sectors.

For example, the practice of defining an acceptable level of safety is used in the aviation industry. The International Civil Aviation Organization (ICAO) states that the acceptable level of safety is defined individually for each operator/service provider based on the regulator's target level of safety, typically translated from society's expectations and perception of safety. Generally, the acceptable level is defined in terms of the probability of an aircraft accident occurring [35].

When using the qualitative risk assessment approach, some organisations use the hazard risk index to denote the level of risk that is considered acceptable. For example, referring to Table 6, an organisation might designate that risks assessed as high/red be unacceptable; the medium/yellow risks might require the management's oversight for the ultimate determination of acceptability; only the low/green risks be regarded as acceptable.

With the quantitative risk assessment approach, the acceptability criteria can be less ambiguous. The safety authorities in some countries like the United Kingdom and the Netherlands had done studies on the risks of major hazards. Subsequently, risk acceptance criteria were defined for individual risk and society/groups of people [34]. In the Netherlands, the results of the calculated individual and society risks are used in land planning, and environment permits approval [36]. The Public Safety Establishments Decree (or, in its commonly-used Dutch acronym BEVI) defines the individual risk as the risk of an unprotected individual dying as a direct result of an on-site accident involving dangerous substances. The individual risk is visualised by risk contours on a map, with a limit 1×10^{-6} per year for vulnerable objects, such as housing and schools [36].

FN curves can represent societal risks. Figure 8 shows an example of FN curves adopted by three countries [37]. The LIFE project could also adopt the FN curve for the Netherlands as a society, that is using the shaded area in the FN curve as the acceptability criteria. The maximum cumulative probability of the deaths of members of the public, who could be in the vicinity of the house containing EES systems during a safety incident, occurring should not exceed the line with a negative-two gradient. This line is equivalent to the probability of a death occurring at 1×10^{-3} per year, or ten deaths occurring at the probability of 1×10^{-5}per year, and so forth.

A 2009 report by UK's HSE states that the calculation of FN curves is very resource-intensive and hence can be expensive [38]. These curves are the cumulative frequency (F) of accident scenarios are plotted against the number of casualties (N) in an incident scenario. Criterion lines can be drawn on the FN curves as a means to define risk zones or categories, which is then used for comparison with the calculated curve for a particular major hazard location. If any point of the location's curve sits above the criterion line, this would indicate unacceptability. Ale, in his paper, mentioned that the FN curves are used as guide values as a matter for discussion, but after adoption, it becomes the official acceptability criteria [34].

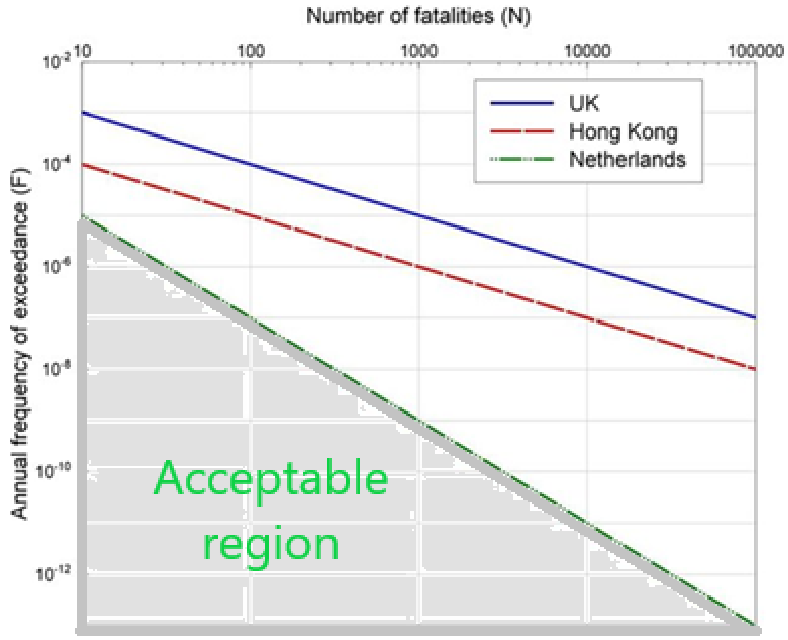


Figure 8 Societal risk in FN curves. Adapted from [37].

2.1.8 The ALARP principle

In the opening section, it was mentioned that there is no such thing as absolute safety. The ALARP principle, originating from the United Kingdom's Health and Safety Executive (HSE), is used in many industries to guide safety risk-reduction, that cannot be eliminated entirely, to 'tolerable' levels. The UK's Health and Safety Act 1974 states that risks need to be reduced to ALARP [38]. The UK's HSE defined three regions of risk within the risk framework of major accidents, namely intolerable, tolerable if ALARP and broadly acceptable [38]. Risk falling under the 'acceptable' category usually mean that no further action is needed. In contrast, 'unacceptable' risks, (sometimes termed 'intolerable' [39]), need to be mitigated until it achieves at least 'tolerable' levels (sometimes termed 'undesirable'), which falls within the region between 'acceptable' and 'unacceptable'.

The amount of effort required to reduce the risk further beyond 'tolerable' levels would typically depend on a cost-benefit study [16, 40]. According to Bahr, for risk to be considered ALARP, it must be demonstrated that the cost in reducing the residual risk further is grossly disproportionate to the risk-reduction gained. The unmitigated/inherent risk levels are first ascertained, followed by an estimation of the risk-reduction benefits gained by adding additional mitigation measures. The demonstration of ALARP can also be accomplished by predefining the acceptability levels as part of the safety objectives [16]. Figure 9 illustrates the ALARP principle with some statistical examples [38, 41].

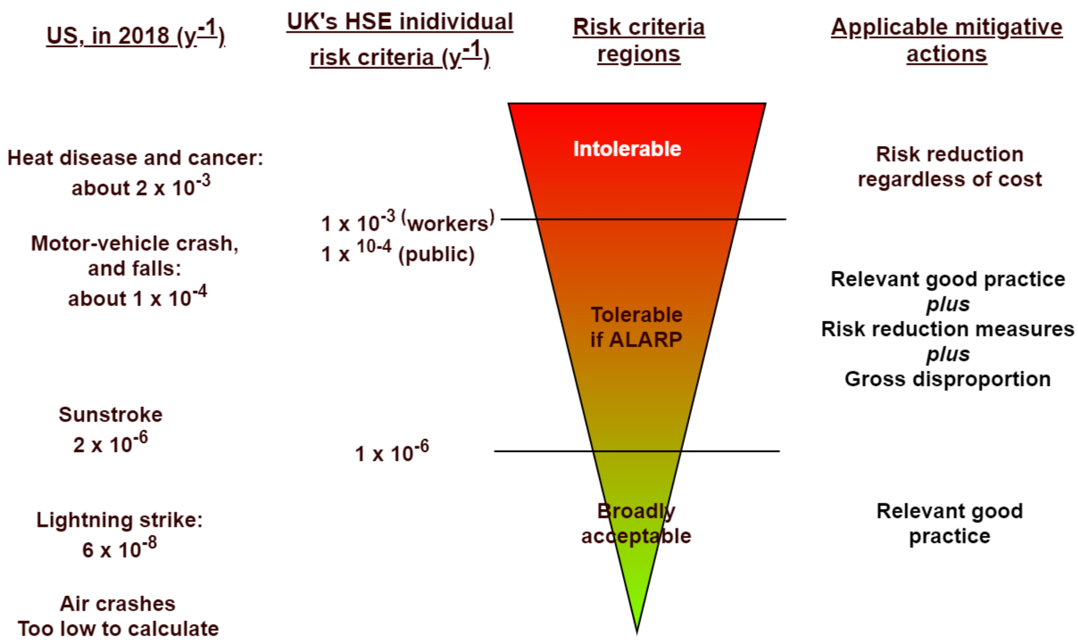


Figure 9 Illustration of the ALARP principle. Modified from [38], and additional data from [41].

TÜV Rheinland mentioned several tools that can help demonstrate risk-reduction to ALARP levels [42]. Within this range of options, the easiest and most practicable involves only referencing codes and standards which capture past experiences and current understanding of a problem or the use of current technology. At the other end of the spectrum are more challenging tools to use, which introduces a large amount of uncertainty. These more sophisticated tools are typically used in more complex projects involving more complex decisions.

Some organisations establish guidelines to assist in the decision-making on effort and resources to allocate for risk-reduction efforts. This is sometimes called the concept of proportionality, whereby the higher the risk, the more likely additional risk reduction measures will be adopted [29]. The cost-benefit study becomes more transparent and reviewable if information regarding the cost, time and effort to implement the mitigation measure is available.

An example of a decision-making tool based on proportionality is shown in Figure 10. The dimensions of risk-reduction benefits and the investment of resources (money, time and effort) have been combined into a matrix to aid the decision-making process to achieve acceptable risk levels. When the evaluated mitigation has high risk-reduction benefits, it is worth investing the resources to reduce the risk further, except for when the unmitigated/inherent risk is already low, and the required resources are high.

Another variation of the cost-benefit analysis to demonstrate ALARP is to use the Implied Cost of Averting a Fatality formula [42]. The ICAF is simply

$$ICAF, \text{€ } or\ \$ = \frac{Net\ cost\ of\ option}{Potential\ saving\ of\ life}$$

$$= \frac{Cost\ of\ option - Reduction\ in\ loss\ of\ assets\ \&\ production}{Potential\ saving\ of\ life}$$

	Sacrifice (time, money, trouble)								
	Low			Med			High		
Risk reduction	High risk	Med risk	Low risk	High risk	Med risk	Low risk	High risk	Med risk	Low risk
High	Go	Go	Go	Go	Go	Go	Go	Go	Stop
Med	Go	Go	Go	Go	Go	Stop	Go	Stop	Stop
Low	Go	Go	Stop	Go	Stop	Stop	Stop	Stop	Stop

Figure 10 An example of a decision-making tool based on the principle of proportionality, from BowtieXP's Methodology Manual [40].

The ICAF is then tabulated to aid the decision-making process, as shown in Table 8:

Table 8 Decision-making table based on the Implied Cost of Averting a Fatality. Adapted from [42].

ICAF (€/fatality avoided)	**Guidance**
< €1 000	Always implement
€1 000 - €10 000	Always implement, unless the risk is low
€10 000 - €100 000	Consider, if the risk levels are high or if there are other benefits
> €100 000	Cost is grossly disproportionate

Developing the cut-off points can be a sensitive subject and requires careful consultation with stakeholders affected by the decisions. Whichever tool is used, the demonstration of ALARP requires defensible documentation the selected and discounted options, at a level of details that commensurate with the equipment lifecycle and the magnitude of risk [42].

It should be noted that the concept of ALARP is not adopted in the Netherlands. The acceptability criteria of risks for the individual and society are explicitly specified by law, without allowing for a further argument of ALARP [34]. These values were mentioned in the preceding section. Nonetheless, ALARP is a concept that is worth keeping in mind when managing risks.

2.1.9 Safety case

The term 'safety case' can be defined as a 'structured argument, supported by a body of evidence that provides a compelling, comprehensible and valid case that a system is safe for a given application in a given operating environment [43]'. Different definition exists, depending on the industry and country. Safety cases have become popular across the industry such as nuclear, railway, chemical and off-shore oil and gas. Safety cases use argument and compilation of evidence to demonstrate that all credible hazards have been suitably managed, and its risk reduced to acceptable and ALARP levels.

The use of safety cases should come with some precautions. Leveson argued that safety cases are prone to confirmation bias. Confirmation bias is the tendency to favour information that confirms a hypothesis. Furthermore, there is a tendency of not using the worst-case scenario in favour of focusing on the most likely events [44].

To conclude the section on system safety, it is reiterated that system safety concepts are important during a product's development phases to assure a safe product. System safety is typically embedded in an organisation's management systems as a subset of safety management systems (SMSs), which refers to the enterprise-level management structure [16].

2.2 Regulations, Codes and Standards (RCS)

In trying to achieve the thesis objective, this section discusses the key regulations, codes and standards (abbreviated to 'RCS') related to safety for installing EESS in residential buildings in the Dutch context. The 'CE' marking is obligatory for products for which EU specifications exist. These products require the affixing of CE marking to indicate that the product is deemed to meet EU safety, health and environmental protection requirements [45]. An essential step towards achieving a 'CE' mark is to determine the applicable directives and standards.

RCS provide guidance and requirements during the entire asset lifecycle phases, especially on safety aspects. The adherence to RCS per se does not guarantee absolute safety. Nonetheless, compliance with RCS support the development and usage of safe and reliable products and reduces the overall risk of accidents.

Hagen and Whitlock's book on fire-safety [25], written based on the Dutch situation, argued that a risk-based approach does not make a rule-based method redundant. Their book explained that rules from regulations and standards already contain a general risk-approach that would cater to non-complex and low-risk buildings. 75% of the total buildings would fall in this category. For complex and high-risk buildings, fire-safety engineering would need to be applied, relying on specialist knowledge of fire, building, human, environmental and intervention characteristics.

Saffers and Molkov cautioned against the over-reliance on RCS, advocating instead to use RCS to complement fire-safety engineering methodology and engineers and technicians to be highly trained in using state-of-the-art tools for fire-safety engineering design [46]. They also argue that safety engineering cannot be substituted by risk-informed and quantitative risk assessment approaches because there is insufficient statistical data, especially for emerging technologies such as hydrogen systems.

2.2.1 Definitions

A "regulation" is a binding legislative act. A "directive" is a legislative act that sets out a goal that all EU countries must achieve [47].

The term ‘codes and standards’ are used frequently in the United States. The United States’ National Fire Protection Agency (NFPA) defines a code as “a model, a set of rules that knowledgeable people recommend for others to follow. It is not a law but can be adopted into law. A code tells you what you need to do. On the other hand, a standard ‘tends to be a more detailed elaboration, the nuts and bolts of meeting a code. A standard you how to do it” [48].

Within the European Union, the terminology ‘standards’ or ‘norms’ are more frequently used than ‘codes’. `Standards' or `Norms' are defined as documents that provide rules, guidelines or characteristics for activities or their results, for common and repeated use [49, 50]. European Standards (ENs – ‘*European Norms*’) are documents that have been ratified by one of the three European Standardization Organizations (ESOs): CEN (European Committee for Standardization), CENELEC (European Committee for Electrotechnical Standardization or ETSI (European Telecommunications Standards Institute). Other well-known international standardisation bodies include the International Standards Organisation (ISO) and the International Electrotechnical Commission's (IEC).

‘Guidance’ documents are occasionally published by regulatory bodies to help companies and individuals understand and implement specific laws and regulations. In the Netherlands, the Dutch Standardisation Body (NEN) manages the standardisation process. When EU standards accepted in the domestic laws in the Netherlands, it would have the words ‘NEN’ affixed to the standard’s name or title. Guidelines would be attached with ‘NPR’ in the title.

Standards are voluntary, which means that there is no automatic legal obligation to apply them. However, standards can be used to achieve the objectives of laws and regulation. In many cases, EN standards are written to help achieve compliance with specific European directives. Adherence to a specific EU directive is more likely if a product complies with a harmonised European standard. Harmonised European Standards mean that standards developed by different bodies on the same subject have been ratified by one of the three ESOs and published in the Official Journal of EU [49]. An example prefix of a harmonised European standard that has been adopted in the Netherlands would be ‘NEN-EN-ISO’.

When referring to machinery safety standards, the ISO’s definition of types is commonly used and is explained below [51].

- Type-A standards (basic safety standards) give basic concepts, principles for design, and general aspects applied to machinery.

- Type-B standards (generic safety standards) deals with one safety aspect or one type of safeguard used across a wide range of machinery.
- Type-C standards (machine safety standards) deals with detailed safety requirements for a particular machine or group of machines.

2.2.2 Hydrogen systems

An attempt was made to list all the applicable key regulations and Type-A standards for the LIFE project's hydrogen system, as shown in Figure 11. Because numerous standards exist for hydrogen systems, only a sampling of some Type-B and C standards were shown. The list is discussed below.

Regulations for hydrogen systems

From a safety angle, existing regulations already adequately address the risks associated with hydrogen production, storage and usage. The 'Greenenergy Box' pilot project mentioned that the 'CE' certification is needed for the commercialisation of stationary hydrogen fuel cell installations throughout Europe [52]. The main five directives that need to be complied with are:

- Machinery Directive 2006/42/EC
- Low Voltage Directive 2014/35/EU
- Electromagnetic Compatibility Directive 2004/108/EC
- Pressure Equipment Directive (PED) 2014/68/EC
- ATEX Directive

The permitting process faces numerous legal barriers which currently impedes faster adoption of hydrogen fuel-cell application in the transportation and residential sector. HyLaw, a consortium of partners from 18 European countries, aims to boost the market uptake of hydrogen and fuel cell technologies, providing a clear view of the applicable regulations whilst proposing policy papers to partner-countries' authorities to remove legal barriers [53]. In a policy paper for the Netherlands, HyLaw identified the EU and Dutch regulations that impact the deployment of hydrogen technology.

Five directives, in particular [54],

- Major Accident Hazards Directive 2012/18/EU (popularly known as "Seveso III")
- ATEX Directive 2014/34/EU (the recast of "ATEX 95")
- Industrial Emissions Directive (IED) 2010/75/EU
- Strategic Environmental Assessment (SEA) Directive 2001/42/EC
- Environmental Impact Assessment (EIA) Directive 2011/92/EU

together with the European industry-standard classification system (NACE Classification Codes) result in a costly process to obtain a permit for localised hydrogen production, and restricts hydrogen production to zones marked for industrial and particular commercial usage.

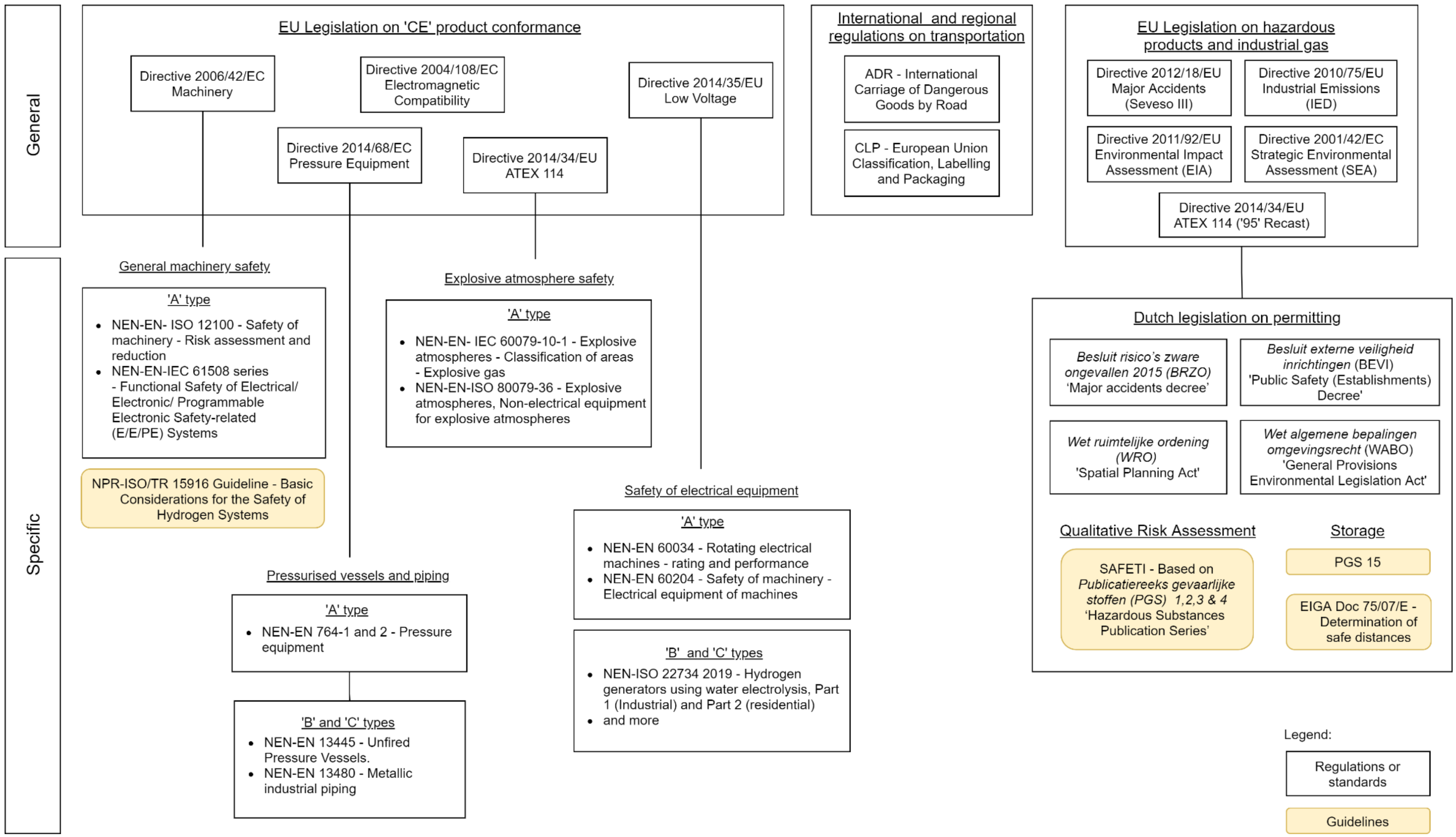


Figure 11 An overview of the applicable regulations, codes and standards for hydrogen systems for the LIFE project

Under these relevant laws, hydrogen is considered an industrial gas. There is currently no distinction made in the permitting process between high-emission production methods of hydrogen as an industry, and 'green' hydrogen produced via water electrolysis. Simplified rules currently do not exist for processing and storing small quantities of hydrogen, envisioned for hydrogen-refuelling stations and residential use. As a result, hydrogen-refuelling stations (HRS) with on-site hydrogen production facilities are relegated to industrial areas, unlike conventional refuelling stations [54].

A description of the afore-mentioned EU directives can be found in a list in Appendix 2.

Dutch laws are consistent with the afore-mentioned European directives, and place a high degree of regulation on hydrogen the production and storage. The regulations which govern the production and storage of hydrogen are [54]:

- *Besluit risico's zware ongevallen 2015*, also known as the 'BRZO' and translated as the 'Decree on the risks of serious accidents', or 'Major accidents decree'. This regulation is essentially the translation of the SEVESO III Directive into Dutch laws.
- *Besluit externe veiligheid inrichtingen* (BEVI), translated as the 'Decree on external safety of establishments' or 'Public Safety (Establishments) Decree'. This regulation is intended to protect people in the vicinity of a company with hazardous substances. When evaluating an environmental permit (*omgevingsvergunning milieu*) or when making a spatial planning decision (*ruimtelijk besluit*), the competent authority must take into account safety distances to protect individuals (location-specific risk) and groups of people (group risk). The BEVI also contains the risk criteria for the individual and groups.
- *Wet ruimtelijke ordening* (WRO), translated as the 'Spatial Planning Act', is the instrument to define the spatial needs such as space for living, working, recreation, mobility, water and nature in a coherent approach.
- *Wet algemene bepalingen omgevingsrecht* (WABO), translated as the 'General Provisions Environmental Legislation Act'. This law regulates the environmental permit, an all-in-one integrated permit for activities within a project and is granted by the municipality.

Information on the BRZO can be found on the website of the Dutch Ministry of Health, Welfare and Sports [55]. More information on BEVI, WRO and WABO regulations can be found on the relevant website for the Dutch Ministry of Infrastructure and Water Management [56].

The BEVI stipulates that all BRZO companies are subject to BEVI requirements [54]. Strictly going by BEVI requirements, if the amount of stored hydrogen is below the limits of 'low threshold' under Annex 1 of the SEVESO III directive (i.e. 5000 kg), then a company need not be registered as a BRZO company [57]. For the LIFE project, the estimated amount of hydrogen stored was around 200 kg, thus the University of Twente, as the owner of the LIFE project, need not be registered as a BRZO company. However, the BEVI requirements on the safety distances for hydrogen systems would still apply. The BEVI ultimately assigns the municipalities and provinces as the competent authorities to enforce the safety distances as stipulated under the WRO and WABO Acts.

Transportation of both hydrogen and Li-ion batteries is regulated by regional and international regulations, such as the International Carriage of Dangerous Goods by Road (ADR), United Nations and the European Union's Classification, Labelling and Packaging (CLP) Regulation. Nonetheless, the LIFE project's legal requirements are of less concern, mainly because hydrogen is produced on-site and is not required to be transported. If the situation arises and hydrogen transportation is needed, then the responsibility to comply with the regulations is on the hydrogen supplier and transporter. The hazards and safety precautions need to be communicated to all actors/stakeholders in the supply chain in the latter case.

Standards and guidelines for hydrogen systems

According to the Fuel Cell & Hydrogen Energy Association (FCHEA), there are two main Technical Committees involved developing and maintaining international standards for hydrogen and fuel cell technologies [58]:

- IEC/TC 105 is the International Electrotechnical Committee on Fuel Cell Technologies
- ISO/TC 197 is the International Organization for Standardization Technical Committee on Hydrogen Technologies

FCHEA maintains a website that compiles a list and description of standards used in hydrogen fuel-cell technology. The list of over 400 standards includes standards developed by geographic regions and also by international organisations. The main ones shown in Figure 11 is briefly described below.

General machinery safety

- NEN-EN- ISO 12100:2010 Safety of machinery — General principles for design — Risk assessment and risk reduction. Hydrogen and battery systems could also be considered a 'machinery' under this standard's definition.
- NEN-EN- IEC 61508 series on the Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related (E/E/PE) Systems. This standard would most probably apply due to the E/E/PE nature of safety devices.

Pressurised vessels and piping

- NEN-EN 764 series on pressure equipment. Parts 4,5 and 7 are referred to in the Pressure Equipment Directive.
- NEN-EN 13445 - Unfired Pressure Vessels. This standard provides rules for the design, fabrication, and inspection of pressure vessels. Its purpose is to replace all national standards in the European Union for pressure vessel design and construction codes and is harmonised with the PED.
- NEN-EN 13480 - Metallic industrial piping. This standard specifies the requirements for industrial piping systems and supports, including safety systems, made of metallic materials with a view to ensuring safe operation.

Explosive atmospheres safety

- NEN-EN-IEC 60079-10-1 - Explosive atmospheres - Classification of areas - Explosive gas atmospheres, concerning the classification of areas where flammable gas or vapour hazards may arise and may then be used as a basis to support the proper selection and installation of equipment for use in hazardous areas. It is intended to be applied where there may be an ignition hazard due to the presence of flammable gas or vapour, mixed with air. Hydrogen and Li-ion battery systems can produce such an atmosphere. This standard is the most commonly used and internationally recognised standard for electrical equipment [59]. However, it does not apply to domestic premises if a hazardous atmosphere is rarely created [60].

- NEN-EN-ISO 80079-36:2016 - Explosive atmospheres, Non-electrical equipment for explosive atmospheres — Basic method and requirements. This standard provides the basic method and requirements for the design, construction, testing and marking of non-electrical Ex-rated equipment (Ex = explosion protection), Ex-rated components, protective systems, devices and assemblies of these products that have their potential ignition sources and are intended for use in explosive atmospheres.

Electrical safety

- NEN-EN 60034 series is related to rotating electrical machines, or electrical motors.
- NEN-EN 60204 – Safety of machinery – Electrical equipment of machines. This standard applies to electrical, electronic and programmable electronic equipment and systems to machines not portable by hand while working, including a group of machines working together in a coordinated manner.

Electrolysers:

- NEN-ISO 22734:2019 Hydrogen generators using water electrolysis —Part 1 is for Industrial, commercial, and Part 2 for residential applications: construction, safety, and performance requirements of modular or factory-matched hydrogen gas generation appliances. Hydrogen generators refer to electrolysers.

Guidelines for risk assessments on hydrogen safety:

- *Publicatiereeks gevaarlijke stoffen*, or PGS – literally translated as 'Hazardous Substances Publication Series' are guidelines for companies that produce, transport, store or use hazardous substances and for authorities charged with supervising and granting permits to these companies [61]. These are published by what formerly was known as the Dutch Ministry of Housing, Spatial Planning and the Environment (VROM). The main ones used in the assessment of risk arising from the processing and storage of not only hydrogen but also Li-ion and VRB.
    - PGS 3, which is the guideline for quantitative risk assessment. The contents, together with that of PGS 1, 2 and 4, have now been migrated to the electronic software package SAFETI-NL [62].
    - PGS 15, regarding the storage of packaged hazardous substances [63], such as hydrogen.
- NPR-ISO/TR 15916 Guideline - Basic Considerations for the Safety of Hydrogen Systems
- Doc 75/07/E. Determination of safe distances. Published by the European Industrial Gas Association (EIGA), this guideline meant for industrial purposes but could have the potential to be adapted for use for hydrogen in residential homes.
- Research Report RR715 (2009) - Installation permitting guidance for hydrogen and fuel cell stationary applications, published by the United Kingdom's Health and Safety Executive.

2.2.3 Batteries in general

Figure 12 shows the RCS list that applies to both the Li-ion and VRB systems and batteries in general.

Regulations for batteries in residential buildings

Under current regulations, batteries may well be regarded as a household appliance [64]. As such, the relevant EU directives that apply are [65]:

- Machinery Directive 2006/42/EC,
- General Product Safety Directive 2001/95/EC
- Low Voltage Directive 2014/35/EU (electrical household appliances)

Also, batteries need to conform to:

- Electromagnetic Compatibility Directive 2004/108/EC
- Battery Directive 2006/66/EC
- ATEX Directive 2014/34/EU

From a permitting aspect, there currently no restrictions on installing batteries in residential buildings in the Netherlands. The PGS (Dutch acronym for 'Hazardous Substances Publication Series') guideline Li-ion batteries has not mandated many specifications on Li-ion battery storage, mainly due to the limited extent of knowledge. Each municipality could set their conditions [66]. In the meantime, work is on-going to draft the PGS 37 guide to address Li-ion battery storage hazards. The current draft version is aimed at household batteries bigger than 25 kWh capacity.

A review of several codes and guidelines suggests unclarity on the allowable limits of battery capacity in residential buildings to distinguish it from large-scale grid-level storage. For example, the 2018 edition of the International Fire Code 2018, suggests that up to 600 kWh capacity is allowed in buildings [67]. The Battery Storage Guidance published the Energy Institute suggests the minimum threshold of 500 kW or 250 kWh for a system to be considered 'mid and larger scale' [68]. Rephrasing it, anything below the suggested threshold would be regarded as 'small scale domestic battery'. The difference in treatment for small or mid-to-large scale systems seems to be the extent of recommended safety measures.

From an environmental aspect, Li-ion batteries' recycling process has a very high impact as it emits high amounts of greenhouse gases. Repurposing of lithium-ion batteries for second-life use is also energy-intensive. Lithium hexafluorophosphate ($LiPF_6$), an electrolyte used in these batteries is also suspected to be hazardous to the environment and human health [69]. The Battery Directive 2006/66/EC aims to minimise the negative impact of batteries and accumulators and waste batteries and accumulators on the environment. However, its current provisions do not ensure lithium recovery and other valuable materials such as cobalt found in Li-ion batteries.

The transportation of lithium-ion batteries and vanadium electrolyte need to comply with regional and international regulations such as the

- European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)
- International Maritime Dangerous Goods (IMDG)

- United Nations Recommendations on the Transport of Dangerous Goods
- Classification, Labelling and Packaging (CLP)
- Dangerous Goods Regulations (DGR), by the International Air Transport Association (IATA)

For the LIFE project, the need for battery transportation is only during installation and decommissioning phases; once installed, it is highly likely that the battery would remain in the same location until its end of life.

A description of the regulations above is provided in Appendix 2.

Standards and guidelines for battery systems

The standards and guidelines shown in Figure 11 are related to the batteries in general but are focused on the types used in the LIFE project.

- IEC 60364 Electrical Installations for Buildings is IEC's international standard on electrical installations of buildings. The harmonised national wiring standards published in the European Union by CENELEC is known as HD 60364.
- NEN 1010: Safety requirements for low-voltage installations. This standard implements the IEC 60364, and is not legally binding; The document is more of an agreement of best practices and minimum requirements for low-voltage installations in residential, non-residential construction [70].
- NEN 4288 *Buurtbatterijen - Bedrijfsvoering van buurtbatterijen voor lokale opslag van elektrische energie* (Neighbourhood batteries - Operation of neighbourhood batteries for local storage of electrical energy). This widely-anticipated standard is due to be published at the end of 2020, or early 2021 and would provide guidelines for installing batteries in residential homes.
- NEN-EN- IEC 62933-5-2:2020 Electrical energy storage (EES) systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical-based systems. This standard focuses on overall system safety when it is connected to the grid supply.

Specifically on Li-ion batteries:

- IEC 62485 - Safety requirements for secondary batteries and battery installations; Part 5: Safe operation of stationary lithium-ion batteries, is work in progress and is due to be published in 2021.

Specifically on flow batteries:

- IEC 62932-2-2:2020 Flow battery energy systems for stationary applications - Part 2-2: Safety requirements. Defines the requirements and test methods for risk reduction and protection measures against significant hazards relevant to flow battery systems
- CWA 50611:2013 (E) Workshop Agreement - Flow batteries - Guidance on the specification, installation and operation. This is not an official European standard but represents the consensus of interested parties. This document can serve as a guideline and tool for achieving a technical agreement where there is no prevailing desire or support for a developed standard.

The technology of electrochemical storage systems (i.e. batteries) is continuously evolving and improving, as evidenced by the introduction of new standards such as NEN 4288 and IEC 62485.

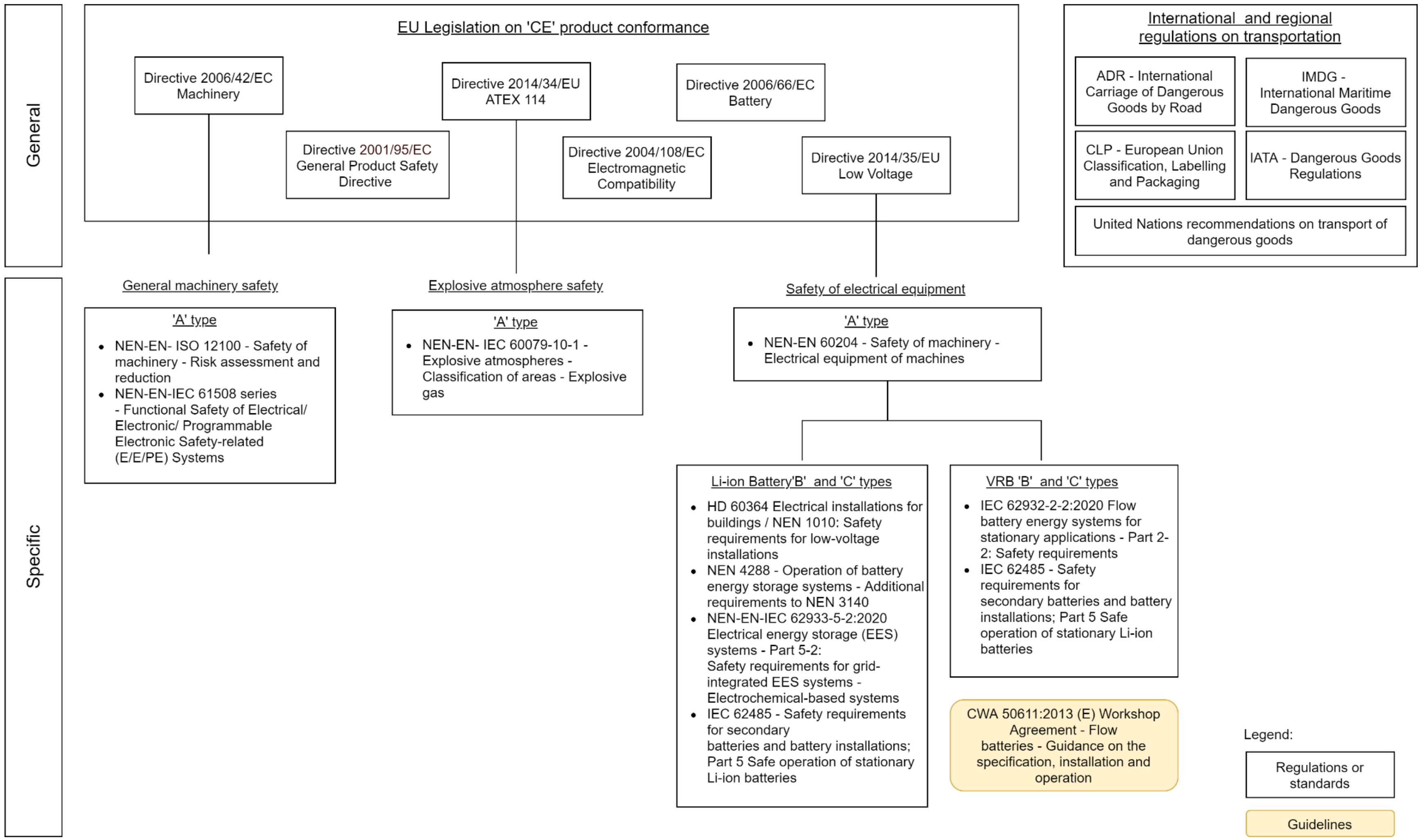


Figure 12 An overview of the applicable regulations, codes and standards for battery systems for the LIFE project

2.2.4 Other related RCS

Although the hydrogen and battery systems occupy the core focus, other aspects of the LIFE project also impact the safety considerations of EESS in residential buildings. These are related to the building structure, occupational safety and health, electrical safety and emergency response.

Building structures

The *Bouwbesluit* (2012), or the Dutch 'Building Decree', lays out the safety, health, usability, energy efficiency and the environmental performance requirements for building structures. Compliance is necessary regardless of whether a permit is required for the structure [71]. If EES systems are to be fitted into homes, they would need to comply with noise generation requirements, air-ventilation and fire-safety, among others.

In 2021, stricter requirements for energy use will take effect, essentially mandating that new building would need to be more energy-efficient [72], potentially boosting EES adoption in homes.

Occupational safety and health (OSH) regulations

The OSH-related regulations are meant to promote safe working conditions. The applicability is during every phase of the EES life-cycle, but more so during the system's construction and installation. More information can be found on the website of the Dutch focal point for EU-OSHA [73]. According to the website, the principal OSH regulations in the Netherlands are:

- *Arbeidsomstandighedenwet (Arbowet)*, or the 'Working Conditions Act'. It provides general provisions for employers and employees to deal with occupational safety and health, such as having a written OSH-policy or a risk inventory.
- *Arbeidsomstandighedenbesluit (Arbobesluit)*, or the 'Working Conditions Decree' elaborates the Working Conditions Act. It covers a wide range of OSH topics such as provisions on workplaces, dangerous substances, noise, vibrations, and so on that employers must follow.
- *Arbeidsomstandighedenregeling (Arboregeling)*, or the 'Working Conditions Regulation'. It contains particular provisions that are changing relatively fast. An example is the occupational exposure limit for dangerous substances.
- *Besluit risico's zware ongevallen (BRZO)*, or the 'Major Accidents Decree'.
- *Regeling risico's zware ongevallen (RRZO)*, or the 'Major Accidents Regulation', containing specific eleborations on the BRZO

Electrical safety in general

Various codes and standards provide guidelines for electrical safety. Some of the widely-used ones are:

- IEC 60364 Electrical Installations for Buildings, which was already mentioned in section 2.2.3.
- NEN-EN-IEC 60335-1:2012 - Household and similar electrical appliances - Safety - Part 1: General requirement. This standard deals with electrical appliances' safety for household and similar purposes, their rated voltage being not more than 250 V for single-phase appliances and 480 V for other appliance. The harmonized standard is EN 60335-1 and defines how appliances may comply with European directives, such as the LVD.

- NEN-EN-IEC 62305 series - Protection against lightning. This standard series provides general principles to be followed to protect structures against lightning, installations and contents, and persons. There are four parts in the series.

Emergency response

- The University of Twente's crisis response plan for use in the event of a major disaster on the university campus, such as a fire, an explosion. This plan is integrated with Enschede's Municipal Emergency Plan [74]. When the LIFE project is completed, it is expected that the houses would also be included in the university's crisis response plan as they are considered 'laboratories'.
- *Operationele Handreiking Incidentbestrijding Gevaarlijke Stoffen (OHOGS)*, translated as 'Operational Guide - Incident Response to Hazardous Substances'. This guide is used by the fire-brigade in the Netherlands, and contain guidelines on managing various scenarios involving lithium-ion and hydrogen fires.

2.3 Safety hazards of hydrogen systems

This section and the following two consist of a review on the respective hydrogen, Li-ion, and VRB systems' safety hazards. For each EESS type, historical safety incidences and data will be mentioned, followed by a general description of the safety hazards. The sections then conclude by detailing the available mitigation measures that can be applied to manage the risks.

When discussing the safety aspects of electrical energy storage systems (EESS), it is advantageous to have some background knowledge. Appendix 14 contains an overview of EESS and more details on hydrogen, Li-ion and VRB systems based on literature reviews.

2.3.1 Safety incidences involving hydrogen systems

Society has a perception that hydrogen unsafe to use [75-77]. Safety incidences such as the Hindenburg airship disaster in 1937 [78] and recent cases involving fuel-cell vehicles and recreational balloons [79] have a long-term negative influence on hydrogen's safety risk.

An analysis of 215 hydrogen-related accidents up to July 2007, captured in the ARIA database [11], concluded over 70% of the accidents whose causes are known are due to organisational and human failure alone or coupled with an equipment failure. This implies that less than 30% is due to malfunctioning of equipment. 12% of the cases resulted in deaths, while 13% resulted in serious injury. Out of the 25 mortal accidents recorded in the ARIA database, 48% occurred during maintenance operations. In the report, maintenance or upkeep operations include hot work (e.g. welding, cutting, grinding), errors or wrong commissioning of facilities during maintenance operations, rinsing of equipment without a detailed risk analysis, poorly conducted operations, resulting in hydrogen leaks and electrical or automation failure. Organisation or process management errors involve electrolysis facilities, runaway reactions and poor waste management that culminated in hydrogen gas generation. Also, 84% of the studied events include fires or explosions, while the remaining 16% concern non-ignited hydrogen leaks. All the mortal incidences involved company employees, and none involved rescue workers and the general public. The analysed accidences were all industrial incidences, and there were no mentioning of any domestic incidences. The latter could be because there was a minimal number, if at all, of domestic hydrogen installations when the study was conducted.

The Hydrogen Incident and Accident Database, or HIAD, is a European Commission-sponsored web-based platform to record and define hydrogen-related incidences. The author analysed 447 incidences as of November 2019 and found that around 13% of the incidences resulted in deaths. Approximately 75% of the incidences involved hydrogen jet fires or explosions [80].

In both the ARIA report and HIAD, it was noted that the hydrogen-production process itself did not cause approximately 18-20% of the incidences. These include the accidental contact between water and molten metal, water gas formation, reactions involving hydrides, or acid corrosion.

Suwa et al. did a study on 195 incidences in Japan from 1949 up till early 2002. They concluded that around 68% of the accidents were due to artificial factors, such as imperfect inspections, operational errors, judging errors or incorrect usage. This is much more than incidences caused by the equipment failure itself. Their study also found that most of the accidences, at about 38%, occurred on the piping system such as flanges and valves. Approximately 40% of the incidences resulted in hydrogen fires, and 40% resulted in explosions. All the fatality cases came from the incidences with explosions [81].

2.3.2 Hazardous properties of hydrogen

The reality is that hydrogen as a flammable material is comparable with dangers that come with the usage of other flammable liquids and gas such as natural gas (methane) and automobile gasoline (petrol). Table 9 shows a comparison of some the properties of the three fuels.

When ignited, the hydrogen flame is almost invisible; thus, it is hard to avoid and fight. Although hydrogen itself and its resulting combustion are non-toxic, hydrogen can cause asphyxiation by displacing oxygen from the breathable air. Compounding this hazard is that hydrogen is odourless and cannot be picked up by humans' smelling senses. However, since hydrogen is about 14 times less dense than air, it will rise and disperse very quickly. If released in an enclosed area, it will accumulate at the highest sections.

Hydrogen is flammable in the presence of an oxidiser (such as oxygen). It only requires less than one-tenth the energy to ignite compared to gasoline vapour and methane gas. The ignition energy required by hydrogen is inversely proportional to its concentration in air. Compared to gasoline vapour and methane, hydrogen has a much wider range of flammability and explosive limits. The flame temperature is higher as those originating from gasoline vapour and methane but emits less heat radiation and thereby less likely cause secondary fires.

Table 9 Selected physical properties of hydrogen, natural gas and petrol. Data combined from [82-84].

Property	Hydrogen	Natural gas (mostly methane)	Petrol	Key to H_2 safety
Colour	No	No	Yes	Not visible to eyes
Toxicity	None	Some	High	Not toxic
Odour	Odourless	Mercaptan (stenched)	Yes (stenched)	Undetectable by the human nose
Buoyancy, relative to air	14 times lighter	2 times lighter	3.75 times heavier	Very buoyant
Energy, by weight	2.8 times more than petrol	~1.2 times more than petrol	43 MJ/kg	-
Energy, by volume	4 times less than petrol	1.5 times less than petrol	31.7 MJ/L	Danger from pressurised or liquified H_2
Flammability in air (LFL - UFL), vol. %	4.1 - 75	5.3 - 15	0.8 - 8.1	wide flammabtility range; easy to form mixture;
Detonability / Explosive limits in air (LDL - UDL), vol. %	18.3 - 59	5.7 - 14	1.4 - 3.3	Wide range
Flame temperature, ^oC	2130	1961	1977	High temperature, but not unusually so
Flame colour	Pale blue, nearly invisible in daylight	Blue-yellow-orange	yellow	Pure flame not visible to eyes
Percentage of thermal energy radiated from flame to surroundings, %	17 - 25	23 - 33	30 - 42	Physical feel of heat does not occur until direct contact is made
Coefficient of diffusion in air, cm^2/s	0.6	0.24	0.06	Highly diffusive in air: fast formation of flammable mixture
Minimum ignition energy , mJ	0.02	0.28	0.96	Easily ignited
Flash point, ^oC	-253	-188	-11 to -45	Liquid H_2 is easily flammable

Hydrogen is also highly diffusive; thus, its molecules can migrate through materials. Leakages through joints can occur as well as through hydrogen-induced cracking material failures. When cooled cryogenically into liquid phase, there is also the hazards of freeze burns, embrittlement and decarburisation of storage materials. When discharged, liquid hydrogen will form a vapour cloud that gives rise to flammability and visibility hazards [77, 84].

The following are the common hazards associated with gaseous hydrogen systems similar to that installed in the LIFE project:

Pressurised gas: Failure of containment due to high pressure can lead to direct overpressures, causing damage to pressure-sensitive organs in humans, such as the lungs and ears. Even more predominant harm is caused by indirect overpressures which can lead to fragments from the failed container or surrounding objects becoming projectiles. Pressure peaking phenomenon happens when gases that are light (lighter than air) are released at a sufficiently high rate that results in the complete displacement of the air from the enclosure. The subsequent overpressure would exceed the structural strength limit of an enclosure or a building leading to a structural collapse [85]. According to Chadwallader and Zhao, the high-pressure jet from a release can penetrate a person's clothing and skin at proximity to the point of release. Cadwallader and Zhao noted that the minimum gas pressure to penetrate the skin at a distance of 3 cm from the release point is 7 bar [86], while gaseous hydrogen is typically already at above 200 bar.

Fire and explosions: Electrolysis of water produces pure oxygen and hydrogen, of which both are flammable and can lead to explosions. The ignition of hydrogen can lead to deflagration or detonation phenomena [85]. Deflagration is the phenomenon of propagation of combustion of a flammable mixture at a sub-sonic velocity. Detonation is when the propagation occurs at supersonic velocity. Both phenomena can cause substantial injury and damage. According to Tretsiakova-McNally and Makarov, detonation is considered the worst-case scenario for hydrogen accidents. The overpressure from detonation is of many magnitudes higher than deflagration, and its propagation 2-3 times faster [85]. An environment with enriched oxygen is very volatile, burns easily, and is difficult to extinguish. Pure oxygen, at high pressure, can react violently with common materials such as oil and grease. Other materials may catch fire spontaneously. Nearly all materials, including textiles, rubber and even metals, will burn vigorously in oxygen [87].

Asphyxiation: At oxygen concentrations is diluted to below 19 volume %, there might be decreased ability to perform tasks. At lower than 12 vol. %, immediate unconsciousness may occur with no prior warning symptoms [88].

Radiant heat from hydrogen fires: This can cause secondary fires when adjacent objects are flammable and can ignite.

Acoustic hazards: The release of high-pressure gas can result in high decibel noise. Sometimes referred to as a 'blowdown', this is associated with emptying storage tank content through an orifice of a valve, or a leak [88]. Noise levels can reach up to 140 dB, depending on the pressure and the escape opening shape [86]. Noise levels of 130 dB have been achieved for 200 bar systems depressurised through a 4mm diameter valve [88].

Diffusibility and permeability: The diffusive nature of hydrogen makes certain metals susceptible to failure-modes such as hydrogen embrittlement (sometimes also known as hydrogen-induced cracking), and high-temperature hydrogen attack [89]. However, high-temperature hydrogen attack occurs at elevated temperatures, typically at above 400 ^{o}C [90]. It is less likely to occur in low-temperature hydrogen systems such as used in the LIFE project. Certain polymers suffer from swelling, blistering, and the deterioration of mechanical properties when in contact with hydrogen. Polymeric materials also ignite relatively easily, bringing a higher risk of fire [91]. The LIFE project has a design using steel storage tanks which are not susceptible to swelling concerns. Cyclic high-pressure service is of particular concern due to the potential for enhanced fatigue crack growth and hydrogen embrittlement.

There are other possible hazards but are not present in the system that is installed in the LIFE project.

Transportation of hydrogen also carries safety risk, but would not be discussed further as the LIFE project does not involve hydrogen transport.

Electrical hazards: This thesis would not discuss electrical safety in an in-depth manner as this is a vast topic with areas of specialisations. It would suffice to mention that all ESS types carry electrical hazards due to their storing electrical energy. The electrolyser, fuel-cells and other possible installed electrical equipment have sufficient voltage to cause electric shocks during operations or maintenance.

According to the UK's Health and Safety Executive, the five aspects of electrical safety need to be considered are: electrical and power safety, electrical appliances safety, electromagnetic compatibility, flammable atmospheres safety, and machinery safety [92].

IEC 60364-1 lists the electrical hazard categories such as thermal effects, over-current, fault currents, voltage disturbances, electromagnetic influences, and power supply interruptions. Also, the IET's Code of Practice for EES [93] describes some key electrical installation design considerations for low-voltage systems, such as surge and lightning protection, excessive inrush currents during switching, electrical load handling and load-shedding issues, isolation and switching off for maintenance and the selection of the residual-current device (RCD). Attention also needs to be made on the design of the battery with its auxiliary components such as the power-conditioning equipment and charge controller; and if the battery operates in parallel with the electrical grid.

[93] further mentions that electrical safety covers a range of subjects, with several recognized standards and guidelines addressing the various concerns such as safe electrical component arrangements, safe isolation for maintenance, protection against electrical shocks, short-circuiting, arc-flash and accidental contact. The mitigation for electrical-related hazards can be applied commonly across all EES types unless there is a specific system's unique requirement. For both the hydrogen and Li-ion battery systems, the hazardous zone classification needs to be considered.

Outside the immediate hazardous zones where the risk of gas-explosions is non-existent, the safety requirements of low-voltage electrical components found in residential EES are no different from that of other typical household electrical items. There is a higher assurance on safety if there is compliance with international norms and standards over the design, fabrication, installation, usage, maintenance and decommissioning of electrical and power systems and appliances. Electrical technicians who are competent and well-versed in installation and maintenance best practices can ensure good quality workmanship and a safe outcome.

2.3.3 Mitigation measures for hydrogen system hazards

In this section, much of the contents are based on the research work and findings of the HyResponse project, an EU-wide effort to provide training materials and knowledge on hydrogen emergency response for first responders [94]. The contents are supplemented by literature and guidelines from other sources and are cited accordingly on certain subject-matters.

The context of the mitigation measures is for the ‘use’ asset lifecycle phase of hydrogen systems applicable in residential buildings. All the mitigation measures can be underpinned by the hazardous event of hydrogen release from its containment to form a flammable, explosive or asphyxiating gas mixture. The mitigations listed here are non-exhaustive. Furthermore, consideration should also be given to the hazards brought about by auxiliary hardware systems such as compressors, electrolysers, electrical components, water treatment, oxygen and the fuel-cells.

The mitigation measures have been differentiated into three categories: functional, technical and operational hazard mitigations**. Functional mitigation** refers to considerations made at the conceptual design phase, typically involving understanding requirements related to the hazards, regulations and standards. **Technical mitigation** refers to the measures applied during the detailed design phase, typically involving engineering practices. **Operational mitigation** refers to measures used during operating and maintenance phase, typically involving socio-technical interactions.

Functional mitigation

Understand the requirements of regulations and industry-recognised technical standards: Safe engineering practice and design comes from adherence to mandatory machinery and pressurised equipment technical standards, some of which were shown in Figure 11. According to the best-practices guideline published by H2 Tools [95], the quality of permanent storage vessels and piping is more assured if it is designed, constructed, and tested following widely-acceptable standards such as EN 13445, or its American counterpart ASME BPVC or API Standard 620. Specific requirements may vary by type of vessel, type of service, applicable codes, and location. In the Netherlands, repair or adjustments of existing pressurised equipment would also need to comply with *Warenwetregeling Drukapparatuur* 2016 (literally translated as ‘Pressure Equipment Commodities Act 2016’). For high-pressure hydrogen storage, the maximum allowable working pressure (MAWP) should not be exceeded.

Joint integrity design. Connecting joints are the weakest link in piping systems, according to Kiwa [96], Kunte and Pareek [97]. The adherence to reputable standards such as EN 13480 - Metallic industrial piping standard, and the American counterpart ASME B31.3, would ensure adequate design, construction and testing practices of piping and piping components.

Changes in the internal piping pressures or flow rates can suggest that a leak is present in the system. Excess-flow shut-off valves, used in gaseous hydrogen refuelling stations, as described in ISO 19880-1 for gaseous hydrogen refuelling stations [98] can automatically stop or restrict the flow of fluid when the internal piping flow exceeds a preset limit. The valves prevent or minimise the amount of released gas if a pipe leak or unplanned release has occurred.

The requirement for the fire-resistance rating of hydrogen storage tanks is important, especially for tanks made of composite materials (e.g. Type III or IV). This can be achieved by the application of intumescent painting on the tank surfaces [91]. In the event of a fire due to external sources, a degree of fire-resistance can allow for a complete depressurising of the tank before the tank itself ruptures. If metallic tanks are used, then there is no requirement to have fire-proofing coating.

Use of appropriate construction materials and fabrication procedures: The most vulnerable metals to hydrogen embrittlement are high-strength steels, titanium alloys and aluminium alloys [89]. Preventive measures include selecting correct materials, outgassing, preheating, and temperature control during welding and post-weld heat treatment (PWHT) to reduce hardness and restore the mechanical properties [99, 100].

If a polymer material is used in hydrogen service, the effects of hydrogen on polymers' property need to be studied. High-Density Poly Ethylene (HDPE) is used as liners for hydrogen storage tanks, and along with Polyphenylene Sulphide (PPS) as pipeline liners in high-pressure hydrogen distribution systems, Polytetrafluoroethylene (PTFE) is used for seals in mechanical compressors, Viton A and Nitrile Butadiene (NBR) rubbers as seals and gaskets in valves [101]. Polyethene (PE) is not expected to react with hydrogen and is commonly used for medium and low-pressure distribution systems [102].

Use of pressure-relieving devices: Tanks need to be installed with pressure-relieving devices. At a pre-determined pressure, these devices vent off the gas to a safe location to prevent overpressure [77]. In the event of a fire, a thermally-activated pressure relief valve is a device that vents the entire contents of the container rapidly. These valves do not reseal or allow re-pressurisation of the container for hydrogen systems and are mandated for on-board hydrogen storage under European Commission Regulation (EU) 406/2010 [91].

The reliability of electrolyser membrane: According to Millet et al., within a PEM water electrolyser, the major risk is due to the possible catalytic recombination of hydrogen and oxygen stored inside the electrolysis compartments, leading to an explosive atmosphere and internal combustion within the electrolyser itself [103, 104]. Suggested mitigation includes selecting suitable or better membrane material, monitoring hydrogen content in the oxygen stream and vice-versa, and monitoring the membrane's condition for signs of degradation. In the event of a malfunction, the electrolyser should shut-off safely. This could take the form of closing the isolation electro-valves connected to the storage tanks and the system's depressurisation through the normally opened electro-valves [104].

Assess the hazardous area classification: The European ATEX 'workplace 137' directive defines the zones where potentially explosive environments could occur, based on the frequency and duration. A distinction is made between flammable gasses and dust. Table 10 shows the zone classifications for flammable gasses.

Table 10 Explosive atmosphere zoning for flammable gasses as per ATEX 137 directive.

Zone	Description
0	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour or mist is present continuously or for long periods or frequently
1	A place in which an explosive atmosphere consisting of a mixture with air or flammable substances in the form of gas, vapour or mist is likely to occur in normal operation occasionally.
2	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only.

Use of equipment rated for the relevant zones: After identifying the appropriate hazardous zones, electrical and non-electrical equipment used in each zone must be manufactured to meet a specific requirement for safety purposes. The NEN-EN-IEC 60079-10 and NEN-EN-ISO 80079-36 standards provide relevant guidelines for electrical and non-electrical equipment and contain the ATEX 137 directive requirement.

Figure 13 illustrates the possible zoning for equipment containing the source of explosive gas or vapour [60]. To determine the appropriate rating of suitable equipment, the explosion parameters – such as the ignition temperatures (i.e. the Temperature Class) and the minimum ignition energy (i.e. the Equipment Group and Sub-group) - of gasses or vapours must be known and specified to the equipment manufacturer. Hydrogen belongs to temperature group T1 and is part of gas sub-group IIC, as shown in Table 11. A solution with the appropriate explosion mark ('EX') can then be found for a required equipment safety category or protection level matching the hazardous zone classification [105].

The requirements specified by the ATEX 214 "equipment" Directive 2014/34/EU must also be complied with.

Determination of hazard distances for facilities: According to Tretsiakova-McNally and Makarov, the draft ISO/TC 197 Hydrogen Technologies document defines the **hazard distance** as the 'distance from the source of hazard to a determined (by physical or numerical modelling, or by a regulation) physical effect value (normally, thermal or pressure) that may lead to a harm condition (ranging from "no harm" to "max harm") to people, equipment or environment [106]'.

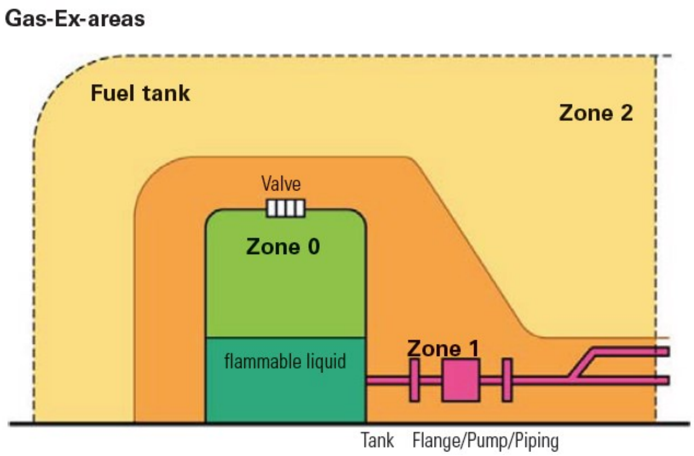


Figure 13 Equipment zone according to EN 60079-10-1. Picture from Crouse-Hinds [60].

Table 11 (left) Table showing temperature class of gas and vapours based on ignition temperature; (right) the minimum ignition energy (MIE) groups. Tables from Bartec [105]

Temperature classes	Ignition temperature range of the mixture	Permissible surface temperature of the electrical equipment
T1	> 450 °C	450 °C
T2	> 300 °C ... ≤ 450 °C	300 °C
T3	> 200 °C ... ≤ 300 °C	200 °C
T4	> 135 °C ... ≤ 200 °C	135 °C
T5	> 100 °C ... ≤ 135 °C	100 °C
T6	> 85 °C ... ≤ 100 °C	85 °C

IIA	approx.	300 µWs
IIB	approx.	150 µWs
IIC	<	50 µWs

On the other hand, the **separation distance (SD),** also known as the safety distance, or setback distance, is not universally defined and has a few interpretations. For example, the European Industrial Gas Association (EIGA) defines the SD as 'a minimum separation between a hazard source and an object (human, equipment or environment) which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident [106].' LaChance describes SD as a minimum distance 'to protect the public and other facilities from the consequences of potential accidents related to a facility's operation [107]'. For clarity, the terminology 'safe distance' would be used interchangeably with 'hazard distance' throughout this report, without explicitly referring to the defining source.

According to Tretsiakova-McNally and Makarov, the SD is affected by the following [106]:

- **the nature of the hazard**: hydrogen releases can either immediately ignite or remains un-ignited with the potential to ignite after some time. The fire type could be either micro flames, jet fires or fireballs.

- **The operating conditions and the design of the analysed equipment/facility**: the operating system's pressure, the pipe diameter, and the thermal-activated pressure relieve valve's placement location can affect the flame length of ensuing jet fire or hydrogen cloud.
- **The type of target, consisting of people, structures or equipment**: the harm or damage tolerance and criteria need to be determined as the basis for safety requirements.
- **The environment between the target and the source of the hazard**: the placement of equipment indoors or outdoors has implications for hazard scenarios.

Saffers and Molkov, in their paper [46], mentioned that the application of fire-safety engineering principles is key to the determination of hazard distances, by modelling gas plumes and explosion scenarios. The outcome can help determine the appropriate siting of the hydrogen system, the locating of safety devices such as hydrogen gas detectors, and help emergency responders plan and execute mitigative actions. An alternative method is to use guidance from regulations, codes and standards (RCS) such as NFPA 55, the International Fire Code, and EIGA's Document 75/07.

That view seems to be aligned with those of Pritchard and Rattigan. They did a study to identify and address bulk hydrogen transportation and storage issues for hydrogen refuelling station facilities. In that study, it was stated that most RCS's safe distances are derived from industrial practices and would likely to put severe limitations on where hydrogen refuelling stations (HRS) could be located in urban areas. The study suggested a reassessment of the recommended distances' scientific basis to see if they can be safely reduced for HRS purposes [108]. A similar approach might also be applicable for hydrogen use in residential areas, such as in the LIFE project.

In the Netherlands, the SAFETI software is mandatory to be used to calculate the safe distance when dangerous substances – such as hydrogen - are used, stored, processed or transported via pipelines. The calculation is essentially a quantitative risk analysis (QRA) that conforms to the Public Safety Establishments Decree (Dutch acronym BEVI) requirements.

Technical mitigation

Siting of system equipment: Outdoor storage takes advantage of hydrogen's buoyant properties as any leaks are dispersed into the atmosphere due to the relative lightness of hydrogen molecules. If the facilities are housed in enclosed spaces, then natural/passive or forced/active ventilation should prevent flammable gas mixtures from forming. The ventilation rate should ensure that the hydrogen concentration is kept below 10% of LEL (i.e. 0.4% volume of hydrogen in air) with an alarm triggered at 25% of LEL (i.e. 1% volume of hydrogen in air), which is the recommended limit for fuel-cell vehicle systems to allow for evacuation and other mitigation actions to be taken [109, 110].

Natural ventilation is preferred over forced systems as it is intrinsically more reliable and safe, as it precludes the presence of mechanical and electrical ignition spark sources. If active ventilation is to be used, the system should have the ability to indicate abnormal functioning [109]. Well-designed ventilation systems for indoor hydrogen systems can be effective barriers against the prevention of explosive and asphyxiating conditions. It is also a major defence against pressure-peaking phenomena and influences hydrogen flame type development, such as well-ventilated or under-ventilated flames [106].

Pritchard et al. mentioned that the design of the ventilation systems should then take into account the foreseeable hydrogen release rate, drawing of diluting air from a safe place, the location of low and high ventilation vents in a room, the effects of wind on the ventilation vent orientation and the existence of obstacles to airflow. Ventilation exhaust or other emission sources that may contain dangerous substances must be released to a safe place. An appropriate hazardous zone should be identified around any foreseeable release point [109].

Leak detection: Leak detection is typically separate from the hydrogen production system and can be used to enhance the overall design's safety, according to [95] and Buttner in [111]. Hydrogen sensors detect hydrogen molecules or acoustic sensors to detect the presence of pressurised gas leakages. In any case, these mechanisms allow for early warning of hydrogen release and the activation of subsequent mitigation such as automatic system shutdown.

According to Buttner, the effectiveness of hydrogen sensors is dependent on the location of placement and the selection of technology type. There is currently no validated guidance document on sensor placement. Due to the buoyant nature of hydrogen, incorrectly placed sensors will not allow for timely leak detection. Sensors placed outdoors would hardly be of use, and the application of computerised fluid dynamics (CFD) can assist in the modelling of gas flow and subsequent sensor placement [111, 112].

Hydrogen sensors are selected based on performance, lifespan, reliability and cost [113]. Decourt et al. stated that further research is needed into such sensors, testing facilities and certification [82]. They mentioned that gas chromatography and mass spectrometry techniques are widely used for hydrogen detection in laboratories. Still, these methods are bulky and expensive, rendering them impractical on an industrial scale. Buttner shared that the various sensor element platforms are commercially available, such as electrochemical, combustible gas, therm-conductivity, metal oxide, palladium-thin-film and hybrid platforms, with each platform having its advantages and drawbacks [111].

Acoustic sensors such as ultrasonic gas leak detector (UGLD) can detect leaks from pressurised sources, without being affected by background noises that generally exist in industrial environments [88]. UGLD does not identify the type of gas or the level of flammability or toxicity. However, they can provide rapid warnings in response to leaks making them good complements to the installed gas sensors since the instruments respond to the release of gas rather than the presence of gas itself.

Flame detection: The invisibility of hydrogen flames poses a danger and can be installed near or at sites where potential hydrogen fires can occur [95]. Optical (infrared or ultraviolet) or thermal (heat) types are commercially available.

Gas odourant: The use of gas odourant to give a distinctive smell detectable by the human senses has been successfully applied for natural gas and propane, which are also odourless. An example of this is the sulphur-containing odorant Mercaptan [114]. However, due to hydrogen's relatively small atomic size and high diffusiveness, odourants are not sufficiently light enough to be dispersed or carried by the hydrogen ow, thus rendering odourants ineffective as a presence indicator. Furthermore, the sulphur in the odourant can be detrimental to the life of some hydrogen fuel cells' catalytic components, thereby excluding the usage of sulphur-based odorant. According to Hodges et al., acrylate-based odourants can be alternative forms of odourants for hydrogen service and have been used in Germany [102]. This alternative form's advantages and disadvantages and how this can be introduced in distributed hydrogen production are not discussed further and warrant further research.

Blast walls: In the event of an explosion, blast-mitigating walls made of reinforced concrete can reduce the effect of overpressures and impulse, to the point that it reaches the meets the harm criteria limits. In experiments conducted by Suwa et al.[81], blast walls could reduce the overpressure by half. The report also stated that higher walls were more effective in reducing blast effects but needed higher strength since it also faces higher impulse and will incur damage. Computational Fluid Dynamics (CFD) simulation also showed that T and Y-shaped walls, when viewed from the side profile, are more effective than a conventional vertical wall in mitigating blast pressures. This is because the blast wave is diffracted twice at the wall's top edge [115].

Protection against accidental vehicle collision: The scenario of vehicle mis-starting and reckless driving has been considered at hydrogen refuelling stations. According to Suwa et al., properly designed guard rails can also protect hydrogen systems from vehicle crashes [81]. This concept can also be extended to residential systems.

Operational mitigation

Preventive maintenance: The equipment and components undergo degradation and is subjected to failure modes during its usage. Safety-related systems are only effective if it is functioning correctly. Appropriately planned and executed maintenance of the system equipment can help preserve its safety functionality. Blanchard and Fabryky explained that preventive maintenance aims to retain a system at a specified level of performance by providing systematic inspection, detection, servicing, or the prevention of impending failures through periodic item replacements [18]. In general, preventive maintenance is preferred over corrective/reactive maintenance. During the development phase, design for maintainability should be taken into account to ensure that the system can be repaired effectively, efficiently and safely. Techniques such as Reliability Centered Maintenance can systematically develop preventive maintenance programmes and control plans for the entire system.

Maintenance activity precautions: Where possible, adjustments, repairs, cleaning and service operations should occur in non-hazardous areas [109]. Where this is not possible, precautions need to be taken to ensure that these activities can be carried out safely. Maintenance personnel should have adequately trained to perform such activities, and are equipped with suitable personnel-protective equipment such as ear-plugs and safety eye-wear. Due to its inert properties, the use of nitrogen to purge a hydrogen system to be free from flammable mixtures is quite common during system commissioning and as a preparation for maintenance activities [109, 116]. Energy sources of equipment should be isolated to prevent operator safety. Ignition sparks from electrical and non-electrical sources need to be avoided, using proper procedures and tools. After a system is maintained, joints should be checked for leak-tightness.

Respect for safety zones: Warning signage, labels and placards serve as a visual reminder to personnel in the proximity of highly explosive and flammable liquid or gas so that precautions are taken. Activities that can generate sparks such as smoking or hot work should be disallowed within the zone. Signage indicating the existence of hydrogen systems is also important to first responders, such as fire-fighters, to enable the adoption of suitable response tactics. In many cases, the correct labels and placards usage is mandatory under transport and storage regulations. These symbols can also be used for process and storage areas. Several standardized pictograms are available and are shown in Appendix 11.

Safety data sheets should accompany the carriage of hydrogen so that actors/stakeholders who handle it are aware of the safety and environmental hazards and can take precautionary measures. An example of the safety data sheet (SDS) for compressed hydrogen gas is from Air Liquide [117] is found in Appendix 12.

Emergency response planning: An appropriate plan is required for on-scene actions when faced with unsafe events related to hydrogen systems. According to Tretsiakova-McNally and Makarov, the possible scenarios that need to be considered are if the release is indoors or outdoors, and the situation of immediate ignition or delayed ignition [110]. In particular the fire-brigade, emergency responders should have an approximation of the hazard distance to minimise the harm to themselves, people, and surrounding objects. The hazard distance of unignited release is directly influenced by hydrogen density (linked to the gas pressure) and the leak diameter. The hazard distance can be quickly approximated by using nomograms developed by some studies, such as [109] and [118]. Appendix 13 has an example of such a nomogram to determine the safe distance for an ignited jet and some emergency response guidelines for first responders when dealing with hydrogen unsafe events.

2.4 Safety hazards of lithium-ion battery systems

2.4.1 Safety incidences involving lithium-ion battery systems

There have been fire incidences involving lithium and lithium-ion batteries. The United State's Federal Aviation Administration (FAA) reports that from January 2006 to August 2020, there have been 290 air or airport incidents involving lithium batteries carried as cargo or baggage, averaging one incident every 20 days [119]. Out of these incidences, half of them occurred in the last three years, from 2017-2019, due to the increasing popularity of lithium-ion batteries in power banks, mobile phones and laptops. In the first year of its operations in 2013, the Boeing 787 Dreamliner was grounded after several incidences of its lithium-ion battery overheating and catching fire [120].

Large grid-scale storage systems have not been spared, for example, fires in involving a 6 MW storage facility in Belgium in 2017 [121], a second incident experienced by an established lithium-ion storage facility operator APS in the USA in 2018 [122], and twenty-three fires at lithium-ion ESS facilities in South Korea throughout 2018 till mid-2019 [123]. Out of these twenty-three first, seventeen involved installations to store electrical energy generated from renewable wind and solar sources, similar in concept to the LIFE project but probably much more massive in storage capacity.

Fires involving Tesla cars, a well-known vehicle powered by lithium-ion batteries, usually attracts attention. Yet, according to Tesla, from 2012 – 2019, there has been approximately one Tesla vehicle fire for every 175 million miles travelled. By comparison, data from the National Fire Protection Association (NFPA) and U.S. Department of Transportation shows that in the United States there is a vehicle fire for every 19 million miles travelled [124], making Tesla vehicles almost ten times safer than an average car.

An article in the NFPA Journal reported that lithium-ion batteries' estimated failure rate to be between 1 in 10 million cells to 1 in 40 million cells, depending on the cell manufacturing quality. Big ESS installations may have up to 100 000 cells in each facility, making it likely that 1 in 100 of such storage facilities could fail [125].

The properties of Li-ion batteries that give rise to safety concerns is discussed next.

2.4.2 Hazardous properties of lithium-ion battery systems

Of all the metals, lithium is the lightest, has the greatest electrochemical potential and provides the largest energy density per unit weight [7, 126]. Elemental lithium belongs to group 1 Alkali metals, which are very reactive. Pure lithium is relatively reactive, reacting with water to produce hydrogen, and will combust when heated up in the presence of oxygen [127].

Problems in rechargeable lithium batteries are related to the micro-and-macrostructural instability during the charging and recharging process and safety concerns around thermal runaway. This led to the development of lithium-ion systems to replace the use of elemental lithium batteries. Li-ion batteries use lithium carbon alloys on the negative electrode, instead of metal lithium in lithium batteries [7].

Lithium-ion batteries are safer than elemental lithium batteries, but the primary safety concern is the phenomenon called '**thermal runaway**'. Some literature explains the phenomenon in three stages [128, 129]. Stage one is the onset of overheating, which can be caused by several factors. Stage two is the heat accumulation and gas release. The electrolyte in lithium-ion batteries contains organic carbonates that will chemically react with each other during cell usage. The process, called 'cell formation', is exothermic and will produce flammable gases such as hydrocarbons, carbon monoxide, hydrogen, oxygen and especially organic electrolytes. The unmitigated increase of temperature within the cell will further increase the release of stored chemical energy. Stage three is the combustion and explosion. The availability of all three components of the 'fire triangle' (oxygen, fuel and heat) will eventually result in the combustion of flammable gases built up. During lab tests on a range of lithium-ion battery types, the batteries themselves did not explode. Still, tests by DNV-GL revealed that the flammable gases that were generated are sources for potential explosions [130].

The uncontrolled fire can propagate to adjacent cells, potentially setting off a cascading reaction and a **major fire** and the subsequent thermal effects. DNV-GL observed that a single cell fire would propagate at a rate of 1 additional cell every 60 seconds [131].

In many occasions, after the fire has been put out and no more visible flames are seen, the burnt lithium-ion battery has re-ignited due to the exothermic reactions that continue to occur within the cell. The peak room temperatures in a fire are directly correlated to the mass of the battery. In any case, DNV-GL reported that after the battery fire has been extinguished, continuous off-gassing of CO and hydrogen has been observed, potentially creating a flammable atmosphere at the battery storage area [130].

DNV-GL also noted that while some types of Li-ion batteries such as lithium titanate and lithium iron phosphate do not undergo thermal runaway, they have been observed to emit flammable gasses when exposed to external heat.

The **toxic emissions** of a battery fire can be compared to burning plastics [130, 131]. The release of toxic gases have also been observed regardless of lithium-ion battery type, the major emissions being hydrogen fluoride (HF), hydrogen chloride (HCl), hydrogen cyanide (HCN), carbon monoxide (CO) and sulphur dioxide (SO_2). The total gas production volume was observed to be proportional to the ampere-hour (Ah) size of the battery. CO, HCl and NO_2 will be the first to reach the immediate danger to life and health (IDLH) threshold levels. The highest emission was observed for CO, at around 1 litre/Ah battery energy. HCL and NO_2 levels were observed to be lower at about 0.25 litre/Ah. The emission rate during a fire is lower per kilogram of material than a plastic fire. However, the peak emission rate is higher when the fire is at its most intense moment.

Electric shocks are a possibility anytime during the entire battery lifecycle. When extinguishing lithium-ion battery fires, shock hazards are present as stranded energy in the damaged or adjacent cells, which could still hold DC voltage and the associated electrical components.

The electrolyte brings about non-energetic hazards such as **chemical hazards**. Electrolyte leakage can cause health hazards for human contact or cause short-circuiting to adjacent electronic systems [129]. The water used during fire-fighting can be highly basic (alkaline) and is detrimental to the environment [130].

Batteries are typically heavy devices, and provisions must be made for load-supporting surfaces. Ease of lifting and removal during maintenance should be considered in the maintainability study [93].

Also, the **electrical hazards** present during the operations and maintenance of EES, briefly described under hydrogen system hazards, are applicable.

2.4.3 Mitigation of safety hazards in lithium-ion batteries

Functional mitigation

Understand the requirements of regulations and industry-recognised technical standards: Engineering design and practices that adhere to applicable regulations and standards, some of which were shown in Figure 12, provide a minimum safety level.

Understand the causes of thermal runaway phenomenon: The key to effective mitigation measures of thermal runaway is to understand the causes of thermal runaway initiation. The UN 38.3 test standard implicitly refer to possible root causes of general lithium and lithium-ion battery thermal runaway. Eight separate tests - overheating, vibration, shock, impact, low-pressure environment, overcharge, external short-circuit and forced discharge - cover all possible battery abuses during transportation [130].

A report by the NFPA's Fire Protection Research Foundation [129] categorizes the five types of abuses a Li-ion battery can be subjected to, resulting in the thermal runaway phenomenon.

- **Thermal abuse:** Intense exposure of a cell to high temperatures (e.g., due to flame attack, exposure to hot combustion gases from a nearby fire, or contact with adjacent cells undergoing thermal runaway reactions) will readily induce thermal runaway in a cell.
- **Mechanical abuse:** Internal short-circuiting has been identified as a predominant cause for li-ion battery thermal runaway. This happens if an internal circuit path is formed between the anode and cathode electrodes. Mechanical effects such as vibration, shock, impact or piercing by a foreign object can damage the electrolyte separator or bring the anode and cathode electrodes together. The Li-ion batteries encased in soft-pouches can rupture in a low-pressure environment, leading to electrolyte leakages which can subsequently cause external-short circuiting between cell electrodes.
- **Electrical abuse:** Lithium plating is the phenomenon of lithium ions being deposited on the anode, instead of intercalating. Plating leads to the growth of dendrites on the anode, which degrades battery performance. Over time, the dendrites grow to the extent that it punctures the electrolyte separator leading to an internal short-circuit condition. The propensity for internal plating to occur is when the lithium-ion battery is charged in low temperature (at around $0^{o}C$), fast charging rate and battery overcharging. Factors such as cell design, electrode material and manufacturing defects have an influence.

  High discharging and charging rate can cause resistive heating within cells at points of high impedance, leading to internal heating to the point of exceeding the thermal stability limits. External short-circuiting and forced-discharging at maximum rated current can cause these condition. External short-circuiting can be caused by leaked aqueous electrolyte from the battery itself, improper packaging or a sudden external voltage surge, such as that caused by lightning strikes.
- **Cell electrochemical design** involves the selection of materials in the battery components such as the electrodes separator or the electrolyte, taking into consideration the field usage conditions that can cause thermal runaway failures.
- **Manufacturing defects** are attributed as the leading cause of thermal runaway failures in the field, in cases where mature protection electronics are already present to protect against electrical abuses. Flaws during manufacturing processes lead to defect the raw materials, electrode coatings, contaminants introduced in the assembly process, and misplaced, misapplied or damaged components.

Use Li-ion battery from manufacturers with good quality assurance and control systems: Many lithium-ion battery original equipment manufacturers (OEM) source their cells from manufacturers in other lower-cost countries due to economics and production flexibility [132]. In this situation, the OEM needs to have a good quality audit programme to allow them to assess and ensure the delivery of safe and quality batteries. Manufacturers should have a sound quality management system, such as Six-Sigma process, ISO/TS 16949. Pitorac mentioned that at the point of final assembly, OEMs also conduct tests on the complete battery package to test its functionality, safety systems, communication with the BMS, voltage balancing, and setting the state-of-charge to an appropriate level for safe delivery and storage [133].

Pitorac adds that Li-ion battery cells' production is a complicated process that requires a large number of quality measurements. For example, the electrode production stage itself involves 70 measurements and 25 tests [133]. The lithium-ion battery production chain consists of three main stages: electrode production, cell assembly and cell formation. The third and last stage is the most crucial step when the cell is charged for the first time, forming the solid-electrolyte interface (SEI), critical for its later operational performance [134]. After that, the cell would undergo intensive testing and ageing procedures. Good quality assurance, control and testing plan during the lithium-ion cell manufacturing stages can reduce the possibility of defective cells being shipped to battery and system assemblers, ensuring good reliability and safety performance

Locating or siting the battery: The limitation of a holding room for Li-ion battery systems depends on the energy the battery contains, which is translatable to the battery mass. DNV-GL's experiments showed that the battery mass is correlated to the quantity of toxic emissions from burning batteries and the peak room temperatures in a fire [130]. The International Fire Code [67] proposed 20 kWh as the limit for a single Li-ion unit, up to 600 kWh for the maximum allowable quantities. The basis for these limits was not explained.

The IET's Code of Practice [93] lists several considerations when determining the location of batteries in general. In residential dwellings, batteries and its power-conditioning equipment (PCE)/charge controller may be located in the attic/loft, in the kitchen/utility-room cabinets, under the stairs, in the garage, or outdoors. Each possible location requires some careful considerations and is shown in Table 12. Appendix 10 contains a list from the Code of Practice which includes safety and operating efficiency considerations when locating battery systems in some specific areas in a house.

Air ventilation, fire-suppression requirements, CO, HCl and NO_2 gas detection, are the main concerns at the battery location. Influencing factors include the battery capacity, consideration if an occupied or non-occupied space is to be used, and the applicable codes and regulations [130]. Large systems may have stand-alone ventilation and fire suppression systems, but small systems are dependent on the existing systems already in place. The current infrastructure should be checked for adequateness. Non-occupied space may have less restrictive codes for ventilation requirements.

Operational factors such as allowing only access for authorised personnel have to be also considered.

Table 12 Key considerations for the siting of the battery room in a residential building. Adapted from [93].

House location	Considerations
Attic/loft	• Ambient temperature range throughout the year, especially in the summer and winter • Fire detection capability, since this is a low human-traffic area • Access for installation and maintenance • Weight of battery systems • Fire-rating
Kitchen or utility-room cabinets	• Heating sources from appliances such as the oven and fridge • Protection against effects of liquid spills
Under stairs cabinet	• Does the location compromise fire escape routes
Garage	• Fire detection capability, since this is a low human-traffic area
Outdoors	• Ambient temperature range throughout the year, especially in the summer and winter • Environmental aspects against the ingress protection (IP), against solid and liquid elements

Fire rating of battery room. DNV-GL recommends a minimum 1-hour fire rating for residential buildings or 2-hour fire rating in high population density areas. This fire rating can be considered as part of a mitigation barrier to avoid the fire from cascading. The recommendation is based on the existing building fire and building codes used in the United States [130]. According to the Bouwbesluit 2012, fire-compartments' fire resistance requirements can range from 20 minutes to 1 hour, depending on the building layout and if it is a new or existing building [71].

Ambient temperature controls may be required for optimal battery performance and safety. Li-ion batteries perform best from 15-35 °C. However, Li-ion battery manufacturers usually give the operating temperature of Li-ion battery to range from 0 to 45°C for charging operations and – 20 to 60°C for discharging operations [135]. At lower temperature, batteries experience sluggish electrochemistry and hence contain lower energy and power. Besides, it was mentioned that lithium plating starts to occur during charging at low temperatures at around 0°C, which can eventually lead to dendritic growth and subsequently thermal runaway conditions. In contrast, operating the Li-ion battery at temperatures higher than the recommended range does not lead to thermal runaway but reduces battery life [136].

Use of explosion-proof equipment: While the batteries themselves are not explosion-proof, the off-gasses from burning Li-ion batteries have been assessed to T2 temperature class, and IIC gas group, as per IEC 60079 [131]. Therefore, the equipment and ventilation systems used in the battery room need to be EX-rated accordingly to prevent the risk of explosions.

Technical Mitigation

Cell design considerations: Design of the battery cells plays a significant role in preventing and mitigating thermal runaway phenomenon. Factors that influence cell failure are the cell electrochemistry, the cell's state of charge, and the heat transfer environment [129]. Design features that reduce the effect of battery abuses can be incorporated to improve its safety.

Cell chemistry determines the amount of stored energy density and the severity of the thermal runaway reaction. The state-of-charge (SOC), one of the important parameters of a battery's health, refers to the amount of stored energy in the battery relative to its nominal capacity [137, 138]. A lower SOC was found to increase the onset temperature of thermal runaway and reduce the maximum cell temperature in an internal short-circuiting [129].

According to Mikolajczak et al., the cell's heat transfer environment refers to how heat can be transferred into the cell, or out of the cell [129]. Self-heating of lithium-ion anodes in the presence of electrolyte starts in the 70-90^{o}C range. If this takes place in an adiabatic environment, it will eventually self-heat to the point of thermal-runaway initiation. The heat that can be transferred from external sources can increase the reactivity within the cell. Kai Liu et al. noted that the thermal runaway process could be contained if the internal heat generated within the cells can be released sufficiently to maintain cell temperatures at the threshold for thermal instability [128].

Materials in a cell design play a significant role in improving lithium-ion battery safety, affecting all three stages of the thermal runaway phenomenon. Kai Liu et al., in their technical review, explained for some possible approaches. For example, the initiation of the first stage of the thermal runaway can be prevented by using more reliable anode materials or trilayer separators to retard dendrites' growth. The use of liquid electrolytes that undergo shear thickening can provide added protection against mechanical crushing; separators that detect dendrite growth and provide early warning [128].

In the second stage, at internal cell temperatures above 90^{o}C, the metastable elements of the solid-electrolyte interface (SEI) can decompose, producing oxygen and flammable organic electrolyte gases. The SEI provides a passivation layer on the anode surface, which inhibits electrolyte decomposition and affords the battery a longer calendar life [139]. Besides, the lithium metal oxide at the cathode decomposes at elevated temperatures to release oxygen. Possible mitigation measures in the product design include regulating the internal cell temperature, using more stable cathode materials, for example, lithium iron phosphate, and the venting of flammable gas to external of the cell to prevent accumulation within the cell.

Lithium iron phosphate ($LiFePO_4$) is stable up to 400^{o}C compared to Lithium Cobalt Oxide (LCO), which starts its decomposition at a much lower temperature at 250^{o}C. Furthermore, $LiFePO_4$ has all the oxygen ions form strong covalent bonds with P^{5+} ions, which provide improved stability compared to other cathode materials.

In the third and final stage of the thermal runaway process, possible ways to prevent combustion are the use of flame-retardant additives in the electrolyte and also the use of non-flammable electrolytes. Many of these approaches have not yet been commercially adopted as these involve a trade-off in cell lifetime, performance, elevated toxicity hazards, and a more delicate design [128, 129].

Utilise battery cell protection systems: A battery management system, commonly known as the BMS, performs some functions that are aimed at preventing some electrical abuses, and to improve the lifetime and performance of the battery. It can monitor the voltage, current and temperature across the cells. It can be linked to other electrical and electronics system such as the battery inverter, or sensors to regulate the charging and discharging process within safe parameters. It can indicate the state-of-charge (SOC), with most BMS limiting the SOC to 80-90% for safety reasons [129].

The limitations of BMS should be recognized. The BMS itself does not stop a thermal runaway process once it has begun, and not all BMS incorporates the same features. The BMS also does not directly protect against certain abuses such as external short-circuiting, internal cell short-circuiting, mechanical impact/deformation, and external heating/fire and internal cell defects [140]. Because BMS monitors individuals cells, when large arrays of batteries are used, running into thousands of cells, having BMS for each cell is an expensive option [10].

A robust battery **enclosure** can increase the resistance to crushing, piercing and penetration, especially during packing and transportation.

Proper packaging design and materials can help prevent the occurrence of thermal runaway and subsequent fires during transportation of bulk-volume lithium-ion batteries, according to Pan et al. [141]. Lithium and lithium-ion are classified as dangerous goods under the United Nations Economic and Social Council (ECOSOC). Provisions and specific rules are covered by regulations such as the International Carriage of Dangerous Goods by Road (ADR) and the International Maritime Dangerous Goods (IMDG) and the International Air Transport Association (IATA) Dangerous Goods Regulations. The regulations require the li-ion cells to be adequately packaged for protection against short-circuiting and mechanical damage, such as vibration or piercing; proper labelling, documentation and permitting, and a qualified ADR driver for road transportation. An example of a safety data sheet for lithium iron phosphate battery can be found at [142].

Table 13 shows some of the lithium-ion battery design considerations that could be applied to mitigate thermal runaway hazard.

Adequate air ventilation is essential to primarily mitigate the threats toxic gasses formed during a battery fire as a priority. It also prevents the formation of a flammable air mixture during a battery out-gassing and removes hazardous fire gases from an enclosed area. Air changes per hour (ACH) is the measure of fresh air replacement for a particular room volume and will vary based on the room's purpose and the number of expected people in the room.

DNV-GL, in a 2017 study, used a probabilistic model to estimate the required ACH for carbon monoxide (CO), hydrogen fluoride (HF) and hydrogen cyanide (HCN) gasses emitted by a range of burning batteries, which includes Li-ion batteries [130]. Experiments were conducted on battery modules (ranging from 7.5 up to 55 kWh per module) up to a limit of 1.5 modules. The study recommended an ACH of 0.25 for the most likely scenario and up to 14.5 ACH for the worst-case scenario.

Table 13 Design considerations that can mitigate thermal runaway hazard. Adapted from [128, 129].

#	Causes	Possible 'inherently safe design' features for Li-ion battery
1	Thermal abuse	• Good thermal isolation/separation between cells to impede heat propagation. • Capability to vent oxygen and flammable gas mixture within cells, in the event of an overheating - only for cylindrical (18650 design), prismatic and pouch cell types.
2	Mechanical abuse	• Robust casing to minimise the risk of electrolyte separator damage due to external mechanical impact, shocks and high vibrations. • Some type of liquid electrolytes can also act as shock-absorbent to mechanical impact using shear-thickening properties. • Battery management system (BMS) should monitor for signs of internal cell shorting, e.g. noisy voltage signals and extended charging times, and excessive self-discharge rates.
3	Electrical abuse	• Overcharging: Charging system to incorporate safe charging current limits and voltage envelopes. • External short-circuiting: have a minimum external circuit short-circuit resistance; good packaging • Over-discharge: set specific discharge voltage limits for the battery pack; have a minimum requirement for resistance to forced over-discharge for cells used in multi-cell pack; have the capability to detect damaged cells and subsequently avoid re-charging it. • The battery packs should incorporate a Battery Monitoring System (BMS) that can monitor charging/discharging, temperature, battery shutdown to reduces the likelihood of excessive charging or discharging, which can initiate a thermal runaway. For example, by limiting the maximum state-of-charge (SOC) to 80-90%, the severity of consequences in the event of thermal runaway phenomenon is reduced.
4	Cell electrochemistry	• Use of more stable cathode materials (e.g. Lithium Iron Phosphate) • Use of more reliable anode materials to reduce lithium dendrite formation • Usage of flame-retardant additives to cell electrolytes • Usage of non-flammable electrolytes, such as solid-state or inorganic liquid solvent (still in research stages) • Reduced cell dimensions/electrolyte content to minimise the stored chemical energy

A more detailed formula for estimating the ventilation rate for lithium-ion batteries outfitted onboard ships was proposed in a separate DNV-GL study in 2019 [131]. This formula uses input variables such as the bulkhead's design pressure, vent distance from the ceiling, size of failed batteries (in Ah), and the room volume.

Recommended ACH for various buildings is prescriptively described in some industrial codes and legislated by local regulations. In the Netherlands, the ACH requirements for residential buildings are stipulated in the Bouwbesluit 2012 Section 3.6 [71], with selected figures shown in Table 14.

Table 14 ACH requirements for selected home spaces, according to [71]. The ACH is calculated based on a ceiling height of 2.6m and a floor area of 12m². The unit dm³/s per m² needs to be converted to ACH.

Space	**Minimum ventilation rate** [71]	**Calculated ACH**
Every residential space	0.9 dm^3/s per m^2 floor area or 7 dm^3/s per person, whichever is higher	1.25
Kitchen	21 dm^3/s per m^2	2.44
Gas meter room	3 dm^3/s per m^2 floor area or 2 dm^3/s, whichever is higher	4.2
Parking space less than 50m2	3 dm^3/s per m^2	4.2

Van Ginkel et al. did a study of air ventilation for certain houses designs in the Netherlands. They found that these minimum ACH rates are only achievable when a mechanically-driven ventilation system is set to the highest speed [143]. The measured ventilation rates for houses will all windows closed, and the ventilation system inactivated ranged from 0.2 to 0.3 ACH.

From these studies, it became clear that lithium-ion battery systems in homes would require installing a ventilation system to meet the necessary safety levels. The design should ensure that it is intrinsically safe, and might need an indication of normal functioning. With an ability to increase the speed, a variable speed system might be a cost-effective solution [130]. Appendix 9 contains the calculation for the approximation of minimum airflow required for the LIFE project.

Fire detection and suppression systems: The sources of thermal hazards are an external fire, an overheating battery that has the risk of propagating to adjacent cells or modules, and electrical fires originating from a BMS failure, a contactor failure, power converter failure, or aground isolation fault. Hazard from an external fire can be mitigated partly by using a designated battery room kept free from fire-risks as well as having a fire-rated boundary [131]. Fire detection and suppression systems serve to provide early intervention in absorbing heat and reducing the degree of propagation and limiting the number of batteries involved in the fire. These systems are essential for battery storage rooms with thousands of cells, typical in grid-level storage.

Several types of fire suppression systems are available, with each having its advantages and drawbacks. There is currently no best-practice established for the most suitable fire extinguisher type [144, 145]. It is not easy to specify precisely the extinguisher class type to use as a Li-ion battery fire constitute solid materials such as separator material, construction material and electrodes (Class A-type), flammable liquid due to the aqueous electrolyte (Class B-type) and energized electrical apparatus (Class C in the

United States; unclassified in the European Union) [145]. Ghiji *et al.* mentioned that the most commonly recommended medium by Li-ion battery manufacturers is water, chemical/dry powder, CO2 and foam.

DNV-GL found that all the previously-mentioned medium will put out Li-ion battery fire, but water provided the best cooling effect [130]. Gas will knock out the flames, but may not provide adequate cooling to the battery cells. Foam was not recommended for EESS fires in general as it prevents heat from being removed as fast as possible. Water should be considered as a last-resort measure as it will destroy entire battery modules within the same enclosure, and in high-voltage systems will induce short-circuiting and hydrogen production.

For battery systems in residential buildings, these suppression systems may not be necessary if the li-ion are distributed into small cell lots, instead of located centrally. Single-cell fires are typically not of significant concern and should not the focus of fire suppression system design. DNV-GL also recommends that for single-cell fires, the best form of mitigation is 'cascading protection,' which aims to stop the fire from propagating to other cells. In the best-case scenario, the fire will consume itself and burn out.

When water is used as a cooling medium, many codes call for 'copious amount' to suppress lithium-ion fire design. It is crucial to ensure that hydrants or emergency hoses can provide the minimum required amount of water flow to suppress Li-ion fire. DNV-GL quantified the probabilistic minimum amount required through experiments, which will help in the sizing of water-based fire suppression systems and the fire-brigade guidelines [130, 131].

Toxic gas and lower explosion limit (LEL) detection: It was previously mentioned that CO, HCl and NO_2 gasses are discharged during the thermal runaway phenomenon. CO is also the primary signature of flammable. DNV-GL recommends using CO detectors in the battery room as a means of identifying the early onset of thermal runaway. HCl and NO2 detectors are recommended based on these being emitted and first achieving the immediate danger to life and health (IDLH) thresholds [130, 131].

Operational mitigation

Emergency response plan: A burning Li-ion fire is difficult to extinguish and requires a different response plan from fighting a conventional solid or liquid-based fires. DNV-GL suggests that first responders need to consider aspects such as the out-gassing of toxic fumes, the availability of onboard suppression system and ascertain if the fire is cascading to other cells or modules (indicated by rising temperatures). Other matters that should be considered too are the hazards of delayed cascading ignition and electrical shock, and the choice of extinguishing medium to be used. No users should attempt to approach the battery fire without suitable personnel-protective equipment (PPE) such as breathing apparatus, heat resistant clothing and outfit that can protect against electric shocks. The presence of a Li-ion subject expert or a person knowledgeable about the system capacity, layout and existing safety systems would assist the emergency responders [130].

Post-fire clean-up: After the fire has been put out, the battery room needs to be adequately ventilated before safe-entry is possible, as per DNV-GL's recommendations [130]. In any case, the use of proper breathing apparatus is highly recommended. Residual energy may still exist, representing an electric shock hazard. Li-ion batteries may re-ignite soon after the fire has been extinguished, or even after a few days. This is caused by heat deep within the cell, leading to the thermal runaway sequence again. The burnt batteries are submerged in water to dissipate the heat thoroughly. When submerged, the Li-ion cells' off-gassing has been observed, causing the water to be basic or acidic. The water needs to be treated and disposed of, usually by an expert handler. DNV-GL, therefore, recommends that whenever possible, the relevant subject matter expert, or battery manufacturer, should arrive on-site and take ownership of the site after the fire has been extinguished. The appointed person would then be responsible for preventing re-ignition and for disposing of the battery.

Warning signage: Proper signage may be necessary to inform the building residence, members of the public, or first-responders of the existence of Li-ion battery systems. Signage can be in the form of symbols indicating Li-ion batteries under transportation regulations, such as UN 3480 or UN3481 for shipping and the ADR symbol '9', and code M4. Hazard signage warning of electric shock and to indicate a battery charging area, from EN ISO 7010 (Graphical symbols — Safety colours and safety signs — Registered safety signs) can also be used. According to IET [93] and the NEN 1010 standard, a warning of the battery voltage should be provided at the battery room where the nominal battery voltage exceeds 60 V. Some examples of pictograms for Li-ion batteries are shown in Appendix 11.

Implement an appropriate maintenance plan: The battery system provider would typically provide, within the operations and maintenance manual, a suggested set of maintenance activities that are needed. Safety systems installed separately, such as the ventilation, detectors and ambient temperature controls, should also be periodically inspected and it's functionality verified. Contractual agreements and warranties may also affect the frequency of maintenance and a responsible party to execute the maintenance activities. The IET's Code of Practice for EESS specifies two types of proactive/preventive maintenance. The first is scheduled maintenance, including cleaning fans/ventilation in electronic components and checking for the accumulation of dust and other contaminants on the batteries. The second is periodic verification to ensure that the energy storage system and it's components remains safe and is in good operating condition. The verification regime should be similar to, or a subset of that used for initial system commissioning. Shorter interval inspections can be beneficial in identifying signs of abnormal operations and early faults signs. For more details, the reader can refer to the IET's Code of Practice for EESS [93].

2.5 Safety hazards of Vanadium redox flow battery (VRB)

2.5.1 Safety incidences involving VRB systems

VRB is claimed to be among the safest of all existing battery types [146-148], although this could not be verified with documented statistics. One possible reason could be the relatively low installed capacity, despite the mass-commercialisation of VRB for the past 20 years, with an estimated 100 VRB units installed worldwide as of 2019 [149].

The other possible reason is due to the inherently-safe features of VRBs. The electrolyte, being in an aqueous form, is not flammable and non-explosive. After the pump is turned off, and the electrolyte is drained from the cell stack, there is negligible stranded energy, thus eliminating the hazard of arc-flash and electric shock [147].

Whitehead et al. estimate the total electrolyte in a VRB stack of 8 hours of energy storage to be in the order of 1% of the total volume, an indication of the low amount of stranded energy [148]. In their experiment, they found that external short-circuiting is unlikely to occur with proper design measures but could occur during service, maintenance and decommissioning work. Internal short-circuiting could arise if the ion-exchange membrane degrades. Still, the safety risk is low, and the stack can operate normally with an increase of hydraulic mass transfer rates.

2.5.2 Hazardous properties of VRB systems

Toxicity and **corrosion** issues are the biggest concern in VRB systems. The electrolyte is around 15% vanadium, 25% sulphuric acid, 60% water by volume [147]. Some other elements, such as chloride may be present to improve the electrolyte and overall battery performance [150].

Dassisti et al. mentioned that vanadium metal is possibly carcinogenic to humans, but it is only present during the electrolyte production stage, before being mixed into vanadium sulfate solution [146]. Vanadium sulphate, used as the electrolyte of VRBs, is non-toxic. They state that the solid ion exchange cell membrane may be highly acidic or alkaline during the disposal phase and thus should be considered toxic. The electrolyte does not degrade and can be recycled in a new VRB system.

Despite this, DNV-GL discovered that when an external heat source is applied to the electrolyte, emissions of hydrogen chloride (HCl) and hydrogen fluoride (HF) have been observed, with HCl occurring in the greatest quantity [130].

Sulphuric acid (H_2SO_4) in the electrolyte is a strong acid, with a pH of less than 1. It is stable but requires proper handling during transportation and storage. The safety data sheet (pg 235)explicitly warns that direct contact with the human body should be avoided, and leakages into the ground will cause soil and water contamination.

2.5.3 Mitigation measures for VRB

Due to the relative safety of VRB, only a brief description would be given for its safety mitigation measures.

Storage conditions: The operating temperature range for VRB systems is from -20°C to 50°C and is driven by the battery's power and voltage performance rather than safety [151], a point also pointed out by Dassisti et al. [159]. Battery management systems (BMS) exist for VRB systems, but it is not used to prevent the non-existent hazard of thermal runaway such as in Li-ion battery systems. Instead, the BMS is used to monitor and intervene during abnormal operations, by measuring parameters such as voltage, ampere, pump operation and operating temperature[152]. Nevertheless, within this range, the emission of toxic fumes should be negligible. The Volterion VRB system has the option of cooling the electrolyte using external water or glycol-based systems to cater to a high-cycle operation or high ambient temperature use.

Storage room ventilation: To mitigate the effects of toxic HCL emissions when the electrolyte is heated up, the storage room should be adequately ventilated. DNV-GL suggest that an air change rate of 0.25 ACH is sufficient to maintain the HCL gas concentration below the immediate danger to life and health (IDLH) levels [130].

Containing the corrosive electrolyte: The electrolyte tanks should be constructed of corrosion-resistant materials. Stainless steel of grade 316 is commonly used for containing sulphuric acid [153, 154]. Some VRB system providers, such as Volterion's system for the LIFE project, provide a secondary electrolyte containment layer; if the primary containment develops a leak. A means to **detect the primary containment leaking** can automatically halt the VRB operation and allow for a system inspection.

Operational mitigation: The **emergency response plan** would also need to consider scenarios of electrical-induced fires, toxic gases emitting from the heated electrolyte, environmental hazards due to leaking electrolyte and the corrosive effect of electrolytes on humans. When handling VRB systems, **personnel protective equipment** (**PPE**) should be worn to avoid VRB electrolyte coming in direct contact with the skin and eyes. Thus the safety data sheet (pg. 235) advised that PPEs such as nitrile gloves, goggles, acid-resistant protective clothing are recommended. Firefighters should also use self-contained breathing apparatus (SCBA) when facing fires in the vicinity of VRB systems.

The use of **proper signage** would also warn users on the corrosive aspects of the sulphuric acid electrolyte. Appendix 11 contains examples of suitable pictograms.

The Volterion VRB system also has features to detect abnormal operation, and alarm and status-indicator to inform the user accordingly. A **preventive maintenance** and inspection regime should be implemented to ensure such safety functions' continuous proper operation.

3 System safety approach for the LIFE project

In this chapter, a proposed approach for identifying the safety hazards for the EES systems is offered. The first section describes the method in a general manner, while a further elaboration would be given in the subsequent section when discussing the outcome.

3.1 An approach to managing system safety

The system safety concepts, explained in Section 2.1.1, was used to identify and manage the EES systems' safety hazards in the LIFE project. Figure 14 summarises the approach, showing the main six-steps and the sub-activities within each step. This approach was adapted from lecture notes of Safety by Design offered at the University of Twente and [155].

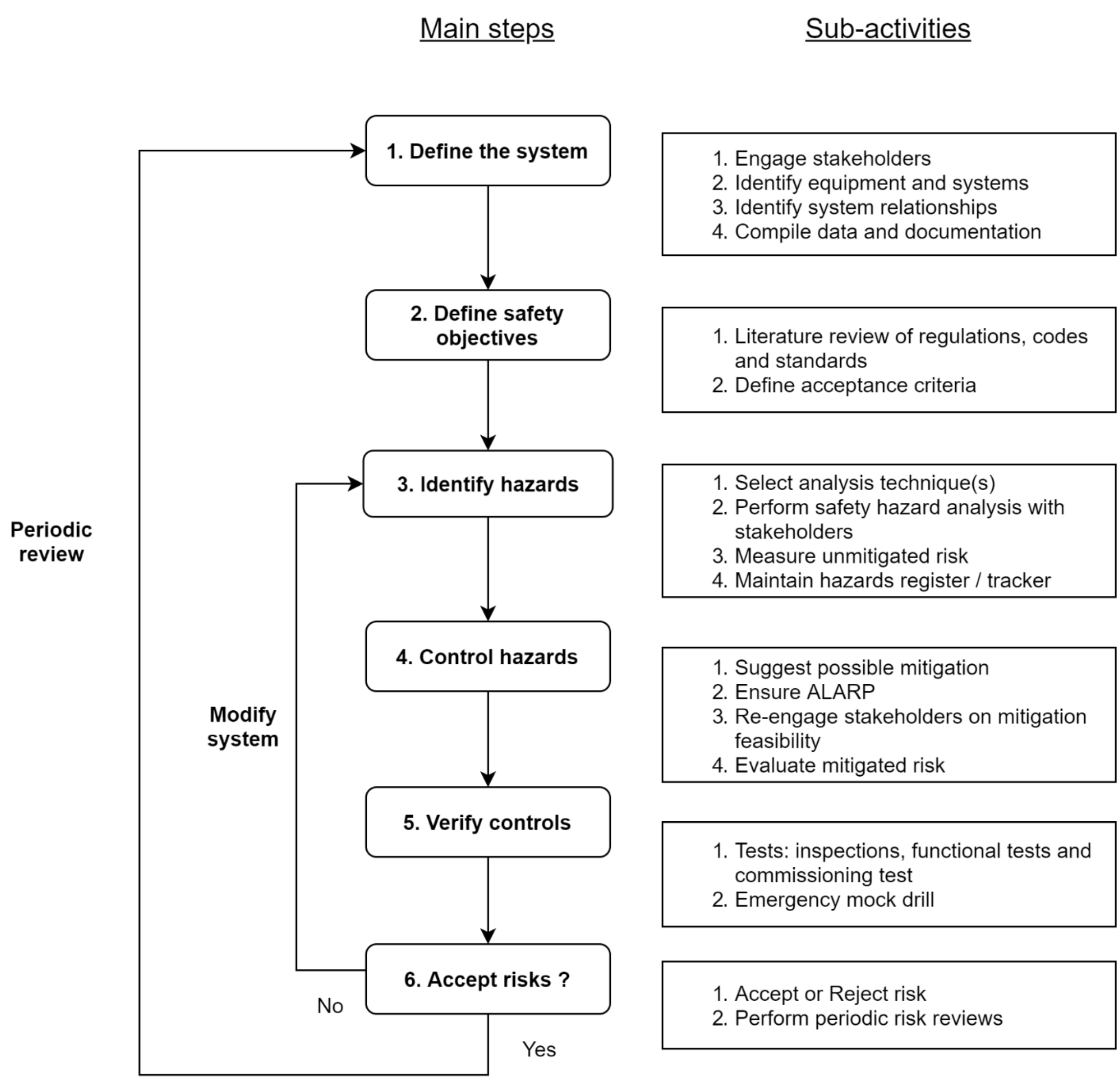


Figure 14 The proposed system safety process. Adapted from [155].

In Step 1, the system under consideration was defined to establish the scope for analysis. Stakeholders such as the LIFE project management team, project partners, and the Twente fire-brigade were engaged in obtaining their concerns and clarifying expectations on the analysis deliverables. These engagements helped formulate this thesis's research objective and research questions and established a working relationship for the planned analysis work ahead. Also, documents and data related to the LIFE systems were compiled to better understand the system and support the analysis efforts ahead.

In Step 2, the safety objectives were defined. There was a need to set some target for safety design performance, in recognition that safety is a matter of comparative perspectives. To this end, some acceptance criteria for safety were proposed based on the review of applicable regulations, codes and standards. The criteria in qualitative and quantitative terms were defined, in the anticipation that both approaches would be used for the hazards analysis.

Steps 3 and 4, although described as two separate steps, were in practice implemented together and iteratively. In Step 3, the safety hazards were identified. Several hazard assessment techniques were used to recognise that no single technique can effectively identify all possible hazards, as previously mentioned in Section 2.1.2. Further elaboration of the applied techniques is in the next section.

In Step 4, the hazards controls or safety barriers are identified and implemented to reduce the safety risks associated with each identified hazard. The controls could be in the form of engineering or management controls following the hierarchy of controls described in Section 2.1.3. The risks have to be reduced to tolerable or acceptable levels for hazards that have been assessed as having intolerable levels of risk. For risks that have been evaluated as being in the 'tolerable' range, it was demonstrated that as-low-as-reasonably-practicable (ALARP) levels had been attained. At this point, the preliminary results of the hazard assessments were shared with the LIFE Partners for the hydrogen and Li-ion battery systems to seek and obtain their feedback. Representatives from the Fire Brigade of Twente region were also re-engaged to discuss guidelines for first responders.

Step 1 up until Step 4 was done at the Conceptual design phase until the end of the Development phase. Steps 5 and 6 can only be implemented after the LIFE project has been physically constructed and assembled. When the safety analysis was conducted, the LIFE project was still transitioning from the conceptual design to the preliminary design lifecycle phase. Hence, both Steps 5 and 6 could not be demonstrated in this thesis. Step 5, had it been implemented, would encompass performing inspections, equipment functional tests, overall system commissioning test, and conducting mock-up emergency response scenarios.

In Step 6, the asset owner would need to decide on the acceptance of the mitigated or residual risk. The mitigated risk should be compared with the safety objectives, as defined in Step 2. If the mitigated risk is not acceptable, then a modification of the system may be required to bring down the risk levels further, effectively iterating the process from the third step onwards. If the residual risk is accepted, then the system can be put into use. Periodic reviews of the safety risks are recommended during the remainder of the asset lifecycle in light of possible system or process parameter changes.

The next section elaborates on the outcome of the application of the approach mentioned above.

3.2 System definition

3.2.1 Compilation of data and documentation

An inventory of systems, equipment and components was drawn up, while functional flow block diagrams were created to understand the interactions between the LIFE equipment. Appendix 12 contains the documents used to support the safety analysis.

3.2.2 Identified equipment and related systems

The pieces of equipment in the LIFE project exist as part of a broader, interacting ecosystem. The interaction was discussed by Rajabalinejad et al. in [33] and briefly described in Section 2.1.5, and is useful to visualise the inter-relationships of the systems under consideration. Six levels of system integration hierarchy were established: the integration of technical systems, the human systems, the system of systems, the sociotechnical systems, the political systems and the regional/global systems. This is shown in Figure 15 and is explained below.

The individual circles are the systems that exist in the LIFE project. At the core, the 'technical systems' layer, encapsulates all the LIFE project systems. The elements within this circle are expected to integrate well with each other to deliver the desired performance parameters, which should ideally be defined by the LIFE project owners. As indicated by the shading within each circle, the safety analysis's main focus was on the chemical storage system, i.e. the hydrogen system, and the electrochemical storage, i.e. the Li-ion battery and VRB systems. All other elements within the innermost circle, which are partially shaded, are included only in the initial analysis.

It is acknowledged that safety hazards exist in every system in the LIFE project. Typically, a system safety analysis for a product under development which would cover all possible identified elements. The failure to take into account and manage these hazards could contribute respectively to an unsuccessful integration of all the installed systems and safety incidences. Still, these hazards are arguably already familiar to the stakeholders within the residential building industry. They would probably fall under the 75% of all low-risk and non-complex building types described by Hagen and Witlok in [25] and briefly described in Section 2.2, page 23. Thus, beyond the initial hazards analysis, safety hazards related to the non-EESS were excluded on purpose.

The second layer, the 'human systems' layer, consists of the first layer and the human-elements that interfaces with the LIFE project, during its entire lifecycle phases. For brevity, elements such as 'project partners', of which several exists have been rolled into a single bubble. The third layer, the 'system of systems' layer, includes the second layer interacting with other systems. Three of these systems, namely the public spatial planning, the university's emergency response set-up, and the campus' road system, were included in the analysis as they directly related to the permitting application and the LIFE's safety aspects.

The fourth layer, the ‘socio-technical systems’, contains the third layer and system elements related to people and technology. ‘Socio-technical’ is a broad definition that refers to systems incorporating both human and technology [156]. Of these, the elements that were considered by the author to have the most significant influence on safety hazards are human resources development and the regional fire-fighting system, where the necessary knowledge and competency needs to be developed to handle novel EES systems.

The fifth layer, the ‘political systems’, include elements related to the local and national policies and laws. In particular, national regulations influence the safety objectives and mitigation measures that need to be in place for the LIFE project. Finally, in the sixth and outermost layer, the ‘regional and global systems’ include the elements that would influence EES systems' design and safety standards.

3.2.3 Discretization of system elements

The identified systems found at all levels of the LIFE integration hierarchy are further discretized into individual elements, of which 48 were defined. This is shown in Table 15 to enable the relationship between each element to be examined for possible safety hazards that could arise due to their interactions. Earlier, it was stated that the scope of the thesis would be on the safety aspects of EESS, namely the hydrogen system, the lithium-ion and vanadium redox flow batteries. These are in effect items Ele 1.3 and Ele 1.5.

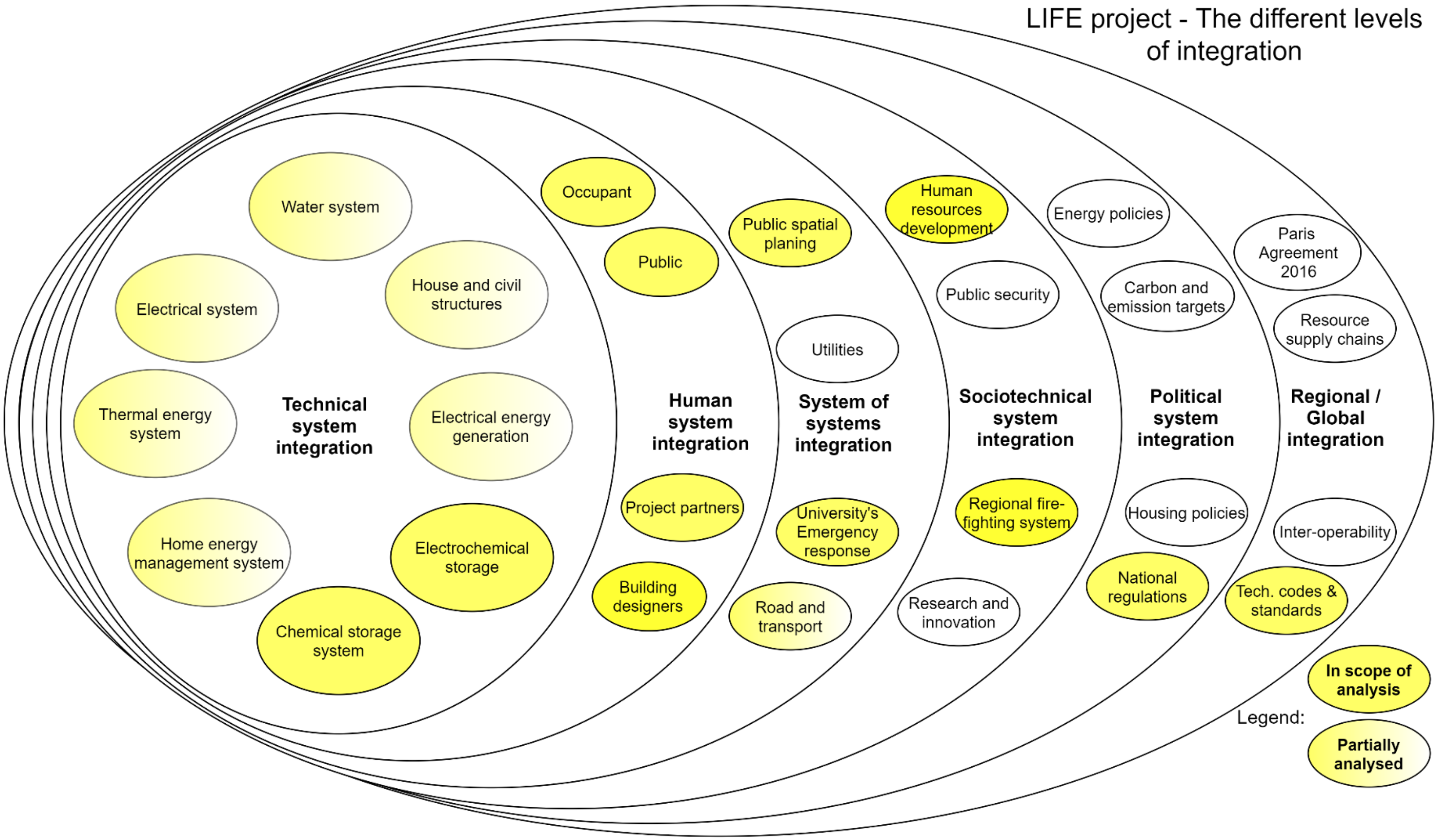


Figure 15 The different levels of integration of the LIFE project systems. The shaded circles represent the boundaries of this thesis study. A fully-shaded circle indicates that the system is within the scope of the safety hazard analysis that was performed; a partially-shaded circle denote that only limited attention was given within the analysis, and an unshaded circle indicates a complete exclusion from the analysis.

Table 15 Elements in the LIFE system

#	Element ID	Element function	#	Element ID	Element function
1	Hum 1	House occupant	25	Wat 5	Use treated water
2	Hum 2	Homeowner	26	Wat 6	Treat used water
3	Hum 3	Members of public	27	Wat 7	Use re-treated water
4	Hum 4	Project Partner / Supplier	28	Wat 8	Sewage discharge
5	Hum 5	Housebuilder	29	SoS 1	Spatial planning
6	Hum 6	Home designer	30	SoS 2	Electricity supply grid
7	Env 1	Weather elements	31	SoS 3	Water supply grid
8	Env 2	Ambient temperatures	32	SoS 4	Sewage grid
9	Ele 1.1	Import electricity	33	SoS 5	University of Twente's fire-fighting response system
10	Ele 1.2	Generate electricity	34	SoS 6	Road and transport system
11	Ele 1.3	The electrochemical energy storage system	35	ST 1	Regional fire-fighting system
12	Ele 1.4	Consume electricity	36	ST 2	Public security
13	Ele 1.5	The chemical energy storage system	37	ST 3	Human resources development
14	Ele 1.6	Home power distribution system	38	ST 4	Research and innovation
15	Ele 1.7	Home Energy Management System	39	P 1	Carbon and emission targets
16	Hea 1	Collect heat	40	P 2	Housing policies
17	Hea 2	Store heat	41	P 3	Energy policies
18	Hea 3	Increase heat	42	P 4	Building insurance policies
19	Hea 4	Consume heat	43	P 5	Financing systems
20	Hea 5	Recover heat	44	P6	National regulations
21	Wat 1	Import grid water	45	RG 1	Technical codes and standards
22	Wat 2	Collect rainwater	46	RG 2	Paris Climate Agreement 2016
23	Wat 3	Filter and store rainwater	47	RG 3	Resource supply chains
24	Wat 4	Treat rainwater	48	RG 4	Inter-operability

Legend for Element ID prefixes:

Prefix	Element groups	Prefix	Element groups
Hum	Humans	SoS	System of systems
Ele	Electrical systems	ST	Socio-technical systems
Env	Environmental factors	P	Political system
Hea	Heat systems	RG	Regional / Global systems
Wat	Water systems		

3.3 Safety objectives

Ideally, the safety objectives should reflect the University of Twente's policy around risk criteria and appetite and should be agreed upon by the LIFE project management at the project's onset. Since an explicit safety objective for the LIFE project does not yet exist, this thesis offers a possible proposal explained in this section.

The likelihood of fatality occurring due to an unsafe event was used as a basis for setting the safety criteria. Likely, such events would also simultaneously cause asset/financial, environmental and reputational impact on the organisation, but the overriding concern should be to prevent the loss of human lives.

The applicable regulations, codes and standards (RCS), reviewed in Section 2.2, provided some guidelines on possible acceptance criteria. The Dutch BEVI regulations stipulate that for the individual risk, the maximum cumulative probability of a death of an unprotected individual occurring as a direct result of incidences involving dangerous substances shall be 1×10^{-6} per year. For societal risk, ideally, an acceptable FN curve should be adopted by the LIFE project. In the absence of that, the thesis assumes that the acceptable societal risk taken for the LIFE project should at least meet to the Dutch society's threshold of risk acceptability. The acceptable region is the shaded area shown in the FN curve shown in Figure 8, page 20. The chosen acceptability criteria for the occurrence of a single fatality for the individual and society is quantitatively presented in Table 16, which conforms to the Dutch's BEVI requirements.

Table 16 The chosen acceptability risk criteria

	Acceptability value (y^{-1})
Individual	Less than 1×10^{-6}
Society	Less than 1×10^{-3}

The criteria mentioned above is now extended to qualitative terms.

It was explained in Section 2.1.3 that the Fine & Kinney method (Table 7, page 16) used by the University of Twente to assess workplace safety hazards has close similarities with the MIL-STD-882E standard risk matrix (Table 4, page 14). Both methods have their advantages and drawbacks. For instance, the F&N method does not mention asset-losses in its calculation, making safety its primary focus. The method also contains the Exposure parameter, which could reduce the levels of assessed risk. One possible interpretation that MIL-STD-882E risk matrix takes a more conservative risk criterion and assumes a constant exposure to the safety hazard.

Eventually, the thesis chose to adopt the risk matrix from the MIL-STD-882E standard when conducting the risk assessments for reasons motivated below:

- the risk matrix in MIL-STD-882E provides a more explicit definition of probability levels

- in addition to the safety consequences, the risk matrix from MIL-STD-882E can also evaluate environmental and asset damages, making it more flexible to use
- it is easier to communicate risk levels visually, having only three dimensions instead of four.
- The lack of Exposure parameter simplifies the risk assessment, whose objective is to provide a relative ranking of each hazard's risk levels. The Exposure parameter can be introduced later should the need arise to refine further the risks of specific hazards. In most of the analysed situations, the safety hazards during the 'use' phase would be a constant, since the exposure refers to the building inhabitants and members of the public around the LIFE labs.

The risk matrix shows five levels of risks: High/Red, Serious/Orange, Medium/Yellow, Low/Green and Eliminated/Blue, as shown in Figure 16. The risk level can be arrived at after selecting the appropriate probability levels in Table 4 and severity category from Table 5 from page 14.

Thus, the proposed safety acceptance criteria in qualitative terms are:

- The likelihood of a 'Catastrophic events', i.e. a fatality occurring, should be at most 'Improbable'. This implies a quantitative value of being lower than 10^{-6} per year. In the situation where no further risk-reduction measures could be undertaken without incurring a disproportionate cost under ALARP principles, then the probability of a 'Catastrophic event' occurring should be at most, 'Remote'. This implies a quantitative value should be less than 10^{-3} per year.
- The likelihood of a 'Critical event', i.e. the occurrence of a permanent partial disability, injury or occupational illness that results in hospitalisation of at least three personnel, should be at most 'Remote'. This implies a quantitative value of being lower than 10^{-3} per year. For ALARP situation, the probability of this happening should be at most, 'Occasional'. This implies that there is a likelihood of occurring sometime in the lifetime of the equipment, with a quantitative value of less than 10^{-2} per year.

As can be observed, the above requirements are consistent with the Dutch BEVI regulations for individual risks. The required actions for each risk level are further defined below and are graphically represented in Figure 16.

- High/red risk: unacceptable level of risk which needs to be reduced
- Serious/orange risk: tolerable if ALARP can be demonstrated. Otherwise, risk must be reduced further.
- Medium/yellow, Low/green, and Eliminated/blue risks: acceptable level of risk; no further mitigation is required

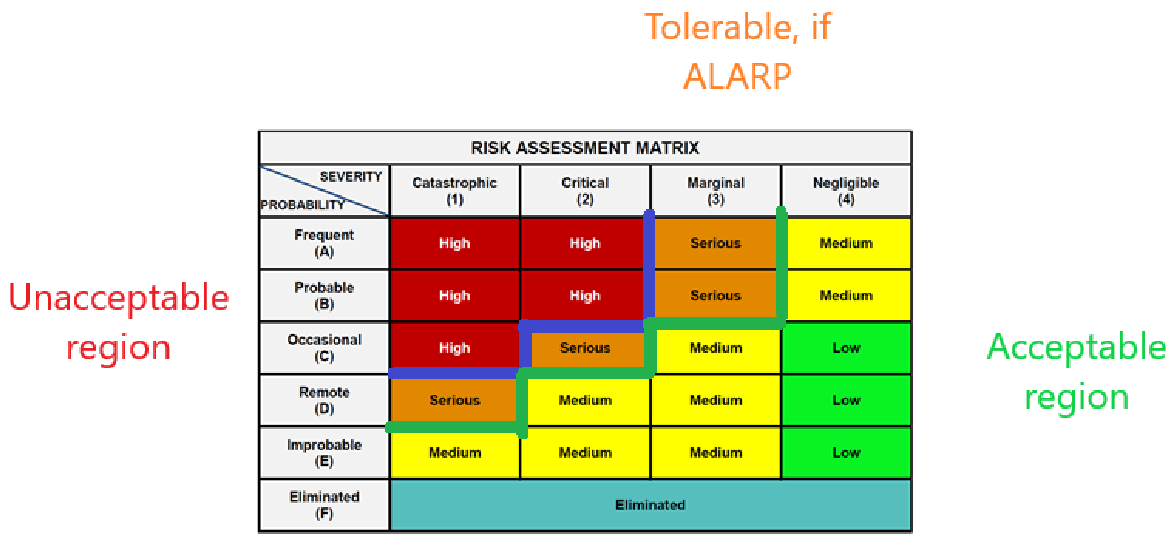


Figure 16 Mapping of safety criteria into targets on the risk assessment matrix

3.4 Identify hazards

In this section, the procedure used to conduct each technique and supporting tool is explained. The outcome in the application of these techniques is also presented.

A combination of safety hazard analysis techniques to identify and assess the hazards. Figure 17 shows the techniques and their order of application. Techniques labelled (i) to (iv) were conducted as part of the thesis efforts, while the LIFE project partners supplying the EESS has their analysis as part of their system-safety management plan. In the latter's case, any concerns that are of concern to the LIFE's system integrator were registered in the Hazard Register and Tracker.

The selection of the techniques was driven by the technique's different focus, the system hierarchy level that was analysed, and the phase of the asset's lifecycle at the time the thesis was written. Each hazard assessment technique was in effect a process by itself, requiring input data and producing an outcome.

Table 17 show the key characteristics of the selected techniques. It is seen that almost all the techniques used in the thesis are inductive types because these seek to understand all possible hazards (e.g. "what-if"). Bowtie and LOPA is the exception, being of the deductive type because it is applied to seek a more in-depth understanding of a hazard that has been identified.

3.4.1 Hazards Tracker register

All hazards identified during each analysis were transferred to the LIFE project's Hazards Tracking register for tracking, assigning the party responsible for implementing the mitigation measures, and monitoring the mitigation progress. The Tracker is a 'catch-all' repository which was continuously updated throughout the LIFE project progress. Hazards can be added anytime and regardless of the process or analysis techniques used.

Inevitably, subsequent hazard analysis techniques identified some hazards that had already been previously mentioned or added more details to the analysis. Sometimes, several entries were consolidated into a single entry if there was a benefit of reducing clutter and obtaining more clarity on describing a particular hazard. For this purpose, each hazard entry was tagged with the label 'Open' or 'Closed' status to indicate if the hazard requires continuous tracking. The 'Closed' status was assigned to hazards that have been identified from multiple techniques, or entries whose threats have been satisfactorily resolved and thus no longer require the LIFE project team's attention.

3.4.2 Preliminary Hazard List (PHL)

A brainstorming exercise was conducted, covering every system within the Technical System Integration circle (see Figure 15). Only hazards and the effects are stated at this juncture. The hazard causes were yet to be identified, and a corresponding risk score for each hazard is not yet determined to avoid being bogged down by analysis efforts. The analysis eventually yielded 109 entries, and these were transferred to the Hazards Tracker register. The full list is shown in Appendix 3. The technique can also be known as HAZID (hazards identification).

The identified hazards were then grouped into several main categories of hazards. The identification of safety-critical items (SCIs) was also initiated at this point. For each hazard category, systems or equipment that are essential in mitigating the hazard effects were identified. The SCIs referred to in the proposed system-safety approach follow the MIL-STD-882E standard definition and was explained in Section 2.1.5, page 17. In the context of this thesis, the terminology is independent of any legal purposes.

Table 18 shows the main categories of hazards and the identified SCIs serves to mitigate the safety hazards for the various systems in LIFE. For instance, all the hazards identified for the hydrogen system were grouped into four categories, and eight SCIs have been identified to mitigate the risk posed by these four categories of hazards.

All in, thirteen SCI categories were defined, from A1 until L as shown in Table 18. The list of hazard categories and SCIs was updated continuously throughout the entire safety analysis process as more hazards were identified.

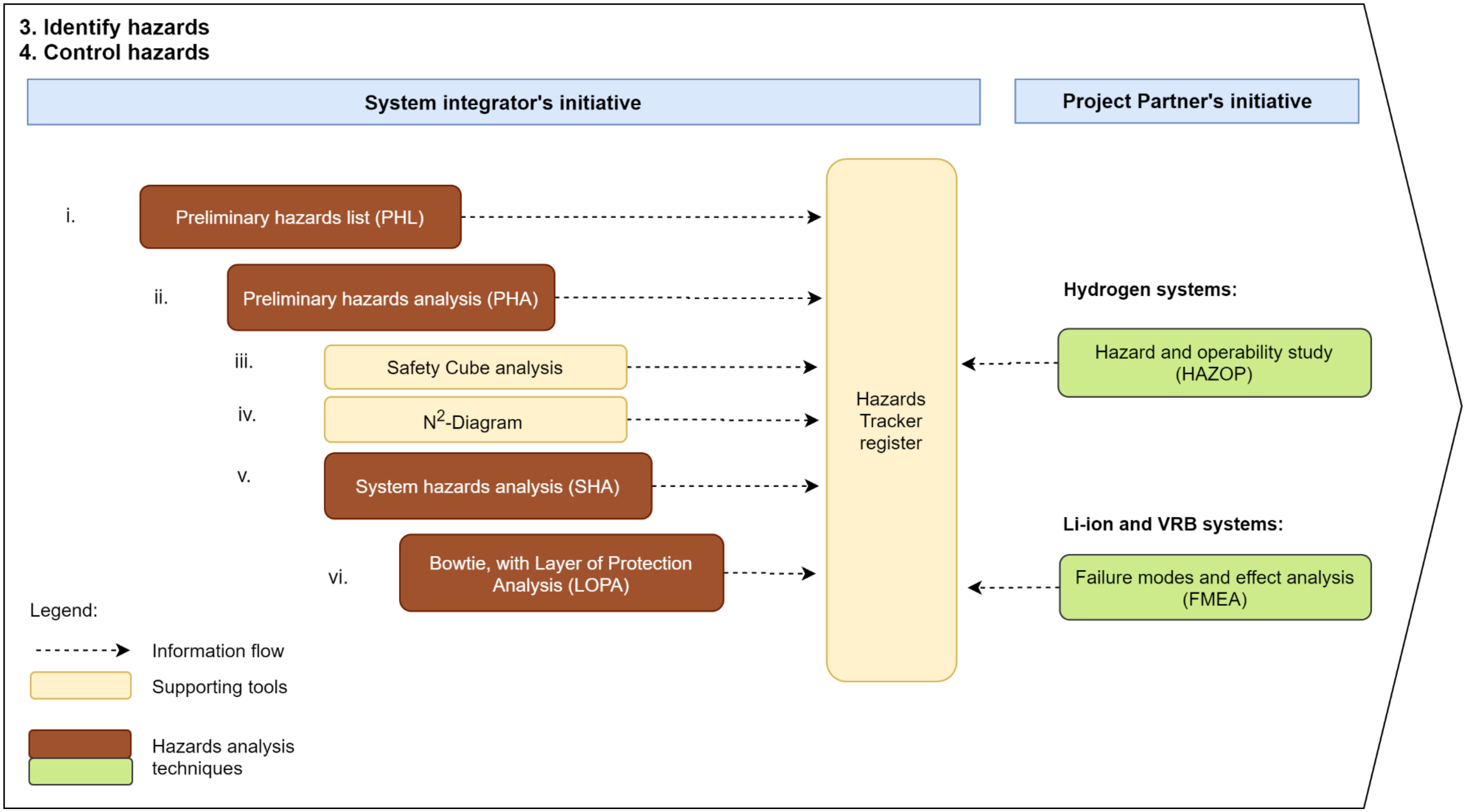


Figure 17 The safety assessment techniques used to identify and control safety hazards

Table 17 Characteristics of selected hazard assessment techniques

No.	Analysis Technique	Asset lifecycle application	Quantitative / Qualitative	Targetted hierarchy of analysis	Inductive / Deductive	Input	Output
i	Preliminary hazards list (PHL)	Conceptual design	Qualitative	Any system level	Inductive	• Indentured Equipment List • Functional Block Diagrammes • Conceptual system design specifications • Hazard checklists • System interfaces • Historical incidences	• List of hazards with very preliminary analysis • Categories of hazards • Identification of safety-critical items (SCIs)
ii	Preliminary hazards analysis (PHA)	Preliminary design	Qualitative	Any system level	Inductive	• Input similar to that used for PHL • Output from PHL	• Possible causes of hazards • Risk-scored hazards • Proposed mitigation measures • Updated list of categories of hazards and SCIs
iii	Safety Cube analysis	Conceptual and Preliminary design	Qualitative	Super-system	Inductive	• Indentured Equipment List • Functional Block Diagrammes • Conceptual system design	• General themes of interface-related hazards

No.	Analysis Technique	Asset lifecycle application	Quantitative / Qualitative	Targetted hierarchy of analysis	Inductive / Deductive	Input	Output
iv	N^2 diagram / DSM	Conceptual and Preliminary design	-	Any system level	Inductive	• Input similar to that used for Safety Cube analysis • Output to the Safety Cube analysis	• Interface-related hazards
v	System hazards analysis (SHA)	Detailed design	Qualitative	Super-system	Inductive	• Output from Safety Cube analysis • Output from N^2 diagram • Main categories of hazards, and list of Safety-Critical Items (SCIs)	• Identification of system-interface hazards • Risk-scored hazards • Hazard causes, effects and possible mitigations
vi	Bowtie with Layer of Protection Analysis (LOPA)	Preliminary and Detailed design	Qualitative and semi-quantitative	Super-system	Deductive	• High-severity hazards from SHA	• Mitigated risk scores • Safety barriers and mitigation measures
-	Hazard and Operability Analysis (HAZOP)	Detailed design	Qualitative	System	Inductive	• Detailed design and specifications • Learnings from past incidences	• Identification of system and sub-system hazards • Risk-scored hazards • Hazard causes, effects and corrective actions
-	Product Failure Mode and Effect Analysis (FMEA)	Detailed design	Quantitative	Any system level	Inductive	• Similar to that used in HAZOP • Past failure rates	• Failure modes, consequences and possible mitigation • Risk-scored hazards

3.4.3 Preliminary Hazard Analysis (PHA)

The Preliminary Hazard Analysis (PHA) technique is applied to analyse further the hazard listed from the previous step, in the Preliminary Hazard List (PHL). Each hazard was evaluated to include the possible causes, assign risk scores and make recommendations for addressing the threat. For reasons explained earlier, the PHA focused only on the EESS, namely the hydrogen, Li-ion battery, and VRB systems and for hazards deemed the responsibility of the LIFE project's system integrator.

The PHA yielded a total of 23 new hazards to be added to the Hazards Tracker register. These consisted of 7, 11 and 5 new entries for the hydrogen, Li-ion and VRB systems. Simultaneously, around 50 entries identified during the PHL had the status changed from 'open' to 'closed'. The 'closure' of the hazards at this juncture was done due to one of these reasons:

- The PHA entry provided a better and updated description of the hazard.
- The management of hazards was the core responsibility of the manufacturer, transporter and constructor. These relate to work-place safety and health-related issues during the factory fabrication of the equipment, the handling of hazardous materials during transportation and disposal.
- Upon further analysis, the hazard was not related to safety and health issues but related to adverse impacts on the environment, the product's lifespan, and the home occupant's comfort and comfort of living.

The PHA spreadsheet is shown in Appendix 4.

3.4.4 System Hazard Analysis (SHA)

The System Hazard Analysis (SHA) specifically identifies hazards caused by interfaces between the systems or other ecosystem elements. Causal factors are explored in greater detail. The SHA is especially useful when commercial-off-the-shelf (COTS) items are used, and the owner/user is not given much detailed design information. For specific concern, a separate analysis such as the Fault Tree Analysis can be used to explore the causal factors [23]

The SHA is conducted similarly to the Preliminary Hazard Analysis (PHA) but the focus is shifted to the interfaces and interactions between the EESS and the EESS with other systems. System hazards were identified using a three-step approach: firstly the Safety Cube, followed by the N^2 Diagram, and finally by utilising the Safety-Critical Items (SCIs) shown in Table 18.

In the Safety Cube, shown in Table 19, all possible themes interactions between the systems, the environment and humans were identified. The result is a 3-by-3 matrix showing the general themes.

Next, the N^2 Diagram, also known as a Design Structure Matrix (DSM), was used to identify the interactions' specific hazards. The N^2 Diagram is a tool to simplify the analysis of complex systems by focusing on the system's elements and how they relate to each other [157]. The 48 system elements, discretized in Table 15, were listed vertically in the first column and then repeated horizontally across the columns. The interaction between the elements is directional, meaning that a horizontal item 'sends a signal' to a vertical item, and not vice-versa. Furthermore, reflexive relations are not possible, meaning that an element cannot send a signal to itself.

The question was then asked, whether 'when the (horizontal row) element sends a signal to the (vertical column) element, was there a potential to give rise to a safety hazard'? When the answer was a 'yes', then a corresponding entry was created in the Hazards Tracker register. Hazards identified in this manner were indicated by the Hazards Tracker IDs on the N^2 Diagram, as shown in Appendix 5.

Finally, the list of Safety-Critical Items (SCIs) was expanded to identify interfaces and interactions further. The purpose of this was to analyse the causes that can result in the SCIs being made ineffective in providing safety functions. Only SCIs tagged to the EESS were used in the analysis, which yielded 22 new hazards entries.

A further six entries in the Tracker register were marked as 'closed' when the SHA offered a more comprehensive analysis compared to what was done during the compilation of the Preliminary Hazards List (PHL). The worksheets from the SHA exercise is shown in Appendix 6.

Table 18 Main hazard categories and the Safety-Critical Items (SCIs) for the LIFE technical systems

		Main LIFE systems							
#	**General category of safety hazards - during 'Use' life-cycle phase**	Hydrogen system	Li-ion battery system	Vanadium redox-flow battery system	PV electrical generation system	Water system	Thermal and heat pump system	Home energy management system	House and civil structures
1	Toxicity		C, D, F	C, D, F					
2	Flammability / Explosivity	A1, A2, B, C, D	C, D, F						B
3	Electrical injury	E	E	E	E	E	E	E	
4	Lithium battery thermal runaway		F, G						
5	Corrosivity	A1, A2		I					
6	Contact with hot substance						K		
7	Collapsing civil structure	A1, D, K			L				L
8	(Environment hazard): Pollution to soil, water and air		H	F, H					
9	(Health hazard): contamination of potable water and for washing					I			
10	(Health hazard): Environment: humidity and temperature								D
	Safety-critical item (SCI)								
A1	Electrolysis: Hydrogen production and storage	X							
A2	Electrolysis: Oxygen production and handling	X							
B	Fire detection and alarm	X	X	X					X
C	Gas detection and alarm	X	X	X					
D	Air ventilation	X	X	X					X
E	Electrical safety	X	X	X	X	X	X	X	
F	Battery siting / location		X	X					
G	Battery management system (BMS)		X and **	*					
H	Ambient temperature controls		**	*	*				
I	Liquid containment			X					
J	Water treatment and segregation					X			
K	Thermal insulation	X					X		
L	Civil structural integrity	X	X		X				X

* to preserve efficiency

** to preserve lifespan

Table 19 The Safety Cube for safety hazards from EESS in the LIFE project

to… / Effects from…	Human	System	Environment
Human	Effective and timely communication among or between building occupants, the public, building owners, maintenance staff, first responders when using novel technology.	- Consider hazards arising from intentional and unintentional usage. - Assign the appropriate level of reliability for human actions as safety barriers. - Maintenance and inspections of novel technology require a new set of skills or tools.	- Consider hazards arising from improper disposal of used equipment/materials during all phases of the lifecycle.
System	- Consider the scenarios where there is a need for operator intervention and the relative ease of making interventions - System-to-user interface confusing or inadequate.	System-to-system interactions have various possible outcomes. Explore further the interactions between elements in each integration hierarchy in the N^2 Diagram.	- Hazards of energy storage in residential and traffic zones - Unintentional discharge of hazardous materials during all phases of the lifecycle.
Environment	Possibility of humans responding to environmental changes (e.g. temperature, humidity, dampness, wind-speed, etc.) by changing equipment settings.	- Effects of environment changes (e.g. temperature, humidity, dampness, wind-speed, etc.) on equipment. - Lack of clarity of regulations on the system requirements.	None identified.

3.4.5 A summary of the identified hazards

Table 20 shows a snapshot of the Hazard Tracker register at the time the thesis was being drafted. The register contained 156 entries, out of which 44 remained unresolved (status 'open'). It can be seen that even in the initial stages, the focus has been on hazards related to EESS.

For the EES systems, all of the High/Red-risked hazards were attributed to the hydrogen system. For the Li-ion battery systems, the highest risk score Medium/orange risk. The VRB system had Medium/orange risks. Further details of these hazards will be provided in the section describing hazards control.

Table 20 Summary of the hazards tracker register – as of 1 October 2020

Assessed system	Initial risk score				
	High/red	Serious/ orange	Medium / yellow	Low/ green	Eliminated / blue
I. All hazards identified (156 entries)					
EES: Hydrogen	23	12	3	1	4
EES: Li-ion battery	-	46	7	2	2
EES: VRB	-	-	8	-	8
Electrical system	-	1	7	1	-
Home energy management system	-	-	1	1	-
House structure	-	1	3	4	-
Photovoltaic electricity generation	-	1	2	-	-
Thermal energy system	-	-	1	-	-
Water system	-	-	7	3	-
Overall / general	-	1	6	-	-
II. Hazards with 'open' status (44 entries)					
EES: Hydrogen	7	7	-	-	-
EES: Li-ion battery	-	11	3	-	-
EES: VRB	-	-	3	-	-
Electrical system	-	1		-	-
Home energy management system	-	-	1	-	-
House structure	-	-	1	-	-
Photovoltaic electricity generation	-	1	1	-	-
Thermal energy system	-	1	2	-	-
Water system	-	-	-	-	-
Overall / general	-	-	4	-	-

3.4.6 Analysis conducted by the EESS Project Partners

More in-depth safety hazard analyses are usually conducted during product developments' detailed-design lifecycle phase when the detailed engineering design data are available. The LIFE Partners for EESS conduct such analysis for their respective products. For instance, SuperB conducts a Failure Mode and Effect Analysis (FMEA) for their Li-ion battery system, whereas Hygear conducts the Hazard and

Operability Analysis (HAZOP) on their hydrogen systems. Accordingly, detailed-design safety hazard analysis was not performed as part of the thesis' scope. Instead, the outcome of the hazard analyses conducted thus far is discussed with the EES project partners to identify hazards that would require the project owner's attention.

3.5 Control hazards

After completing the System Hazard Analysis (SHA), hazards assessed as having 'catastrophic' consequences or unacceptable levels of risks were selected for further analysis and to control the risks essentially. This section describes how the Bowtie Analysis and Layer of Protection Analysis (LOPA) were applied to control some of the identified hazards, namely the ones with the highest risk.

The Bowtie Analysis and the Layer of Protection Analysis (LOPA) techniques are standalone techniques by themselves. Bowties are very useful for visualising and communicating the hazard being analysed, the possible hazard causes, consequences, and safety barriers. To create the Bowtie diagram, firstly the Top Event for a hazard was chosen for analysis, followed by identifying the causes and the consequences of the Top Event. Finally, the preventive and reactive mitigation barriers were identified, thus completing the most basic form of a Bowtie diagram. Preventive barriers are meant to break the chain of events to prevent a Top Event or a consequence from occurring. If the consequences are unavoidable, then the barriers serve to mitigate the outcome severity [40].

The LOPA is a simplified semi-quantitative hazard assessment technique, popularly used in process-safety assessments in the oil and gas industry. It is used to approximate the risk value for a single cause-and-consequence pair. The likelihood of a fatality occurring was used to represent the quantity of risk, which is handy because it is consistent with the language of the safety criteria described in Section 3.3.

A distinction was made between safeguards and independent protection layers.

- Safeguards: any device or system that interrupts the chain of events that lead to the consequences. However, the effectiveness of safeguards cannot be quantified.
- Independent Protection Layers (IPL): a safeguard that strictly fulfils three criteria: they must be effective in breaking the chain of events, be independent of other safeguards or causes, and must be auditable to assure its functionality. This concept is similar to the level of protection afforded by Safety Integrity Levels provided by instrumented protection functions, as defined in IEC 61508 [158].

All barriers are safeguards, but not all safeguards are IPLs. In the classic Bowtie method, there is the recognition that no single barrier is 100% effective at all times, thereby the recommendation to identify multiple barriers between the cause and consequence. This principle is akin to the Swiss-Cheese model [40]. In LOPA, each barrier is assigned a probability of failure on demand (PFD).

It is possible to combine the visual aspects of the Bowtie and the quantitative assessment aspects of the classic LOPA. This thesis adopted this approach, henceforth calling it the 'Bowtie-LOPA' method to differentiate it from the traditional standalone techniques.

To apply the LOPA on the Bowtie, data were obtained for the initiating event frequencies (IEF) for each possible hazard cause, and the probabilities of failure on demand (PFD) were assigned to each identified safety barrier. The IEF and PFD were sourced from industry suggested guidelines and equipment vendor's data. Some assumptions have been applied for situations where directly-obtainable data was unavailable. The IEF and PFD used in the analysis are tabled in Appendix 8.

The corresponding Bowtie diagram and LOPA calculations were generated using the BowtieXP software [40]. After the completion of the Bowtie-LOPA diagrams, the initial/unmitigated risk is first calculated, using the following steps:

A1. Obtain the Top Event frequency by a simple summation of all the IEF's from the causes. All the PFDs are ignored.

A2. Obtain the initial/unmitigated risk F_o, by multiplication of the Top Event frequency, the probability of human exposure P_H, and the probability of immediate fatality P_F.

The residual/mitigated risks were calculated using the following steps:

B1. Obtain the Top Event frequency. This time, the risk-reduction afforded by the safety barrier's PFD values are taken into account.

B2. The frequency of each consequence is calculated. As in step (B1), the risk-reduction of the safety barrier's PFD values are taken into account.

B3. The consequence with the highest frequency f_i^C is taken to represent the most likely outcome of the Top Event.

B4. The mitigated risk $f_{mit.}$ is obtained by multiplying f_i^C obtained in Step 3, with the probability of human exposure P_H, and the probability of immediate fatality P_F.

Both the mitigated risk and unmitigated risks are then evaluated against acceptability criteria. This thesis did not intend to dive into the mechanics of the LOPA calculations. This can be obtained at a more in-depth level in other literature, such as [159, 160]. Nonetheless, Appendix 8 contains a brief explanation of the main formulas used in this thesis to calculate the risk levels quantitatively.

Two versions of the Bowtie-LOPA were created for each Top Event to cater to the situation where the detailed design has not yet been finalised.

- Version 1 represents an 'idealised scenario' where it referenced almost all the possible barriers discussed in Section 2.3. Version 1 of the Bowties is highly idealised, and many applied barriers may be impractical or unjustified from a cost-benefit view. Nevertheless, Version 1 remains useful to evaluate if the aspired level of safety is overly conservative or otherwise. Such Bowties can help optimise resources in product development when used in the Conceptual design phase.

- Version 2 represents the 'LIFE as-built' system, where it incorporates only the system specifications, including the barriers stated in the conceptual design. Furthermore, the Bowtie is adjusted after obtaining input from the LIFE Partners.

3.5.1 Bowtie-LOPA analysis for hydrogen systems

The analysis performed up till the SHA on hazards related to the hydrogen system had so far yielded seven entries in the Hazards Tracker register with High/Red risk levels, and seven more with Serious/Orange risk levels. Table 21 shows an outline of these hazards, with further details shown in Appendix 7.

Table 21 Hazard Tracker ID and hazard descriptions that carry High/Red and Serious/Orange risk levels for the hydrogen system

Hazards with High/Red risk	**Hazards with Serious/Orange risk**
101 - Formation of a flammable gas mixture of hydrogen and oxygen 104 - Unintended release of hydrogen 128 - The high release rate of hydrogen into an indoor atmosphere 136 - Capacity or purpose of the area in the vicinity of hydrogen production and storage is changed (e.g. Addition of buildings/installations in the vicinity) 138 - Addition of hydrogen production and storage capacity 142 - Hydrogen gas ignite during maintenance or upkeep operations 149 - User misoperate, or unintentionally abuse the system during operation	102 - Formation of a flammable gas mixture of hydrogen and oxygen – within the electrolyser 105 - Presence of hydrogen in the atmosphere is undetected 106 - Hydrogen fire is undetected 107 - Hydrogen fire 137 - Storage/siting of flammable materials in the vicinity of hydrogen storage and production 146 - Pure oxygen 147 - High noise from the release of pressurised hydrogen from pressure-relief valve (PRV)

It can be seen that with the exception for the Hazard #146 – 'Pure oxygen' and #147 – 'High noise from PRV release', all the hazards displayed in Table 21 can be relatable to one another via one common safety scenario. Thus, it was decided to analyse these collectively using a single Bowtie diagram, with the Top Event 'unintended release of hydrogen from containment'.

Bowtie scenario

Hazard: Formation of a flammable gas mixture of hydrogen and oxygen indoors and outdoors
Top Event: Unintended indoor or outdoor release of hydrogen from containment.

The Bowtie diagram has six threats and ten consequences.

Note that there are significant differences in the hazards and mitigation between hydrogen systems placed indoors and outdoors. Since the hydrogen storage in the LIFE project would be placed outdoors, as per the conceptual design, it shall be seen that the likelihood for consequences (e.g. asphyxiation) would be correspondingly lower.

Threats / Causes:

1. Corrosion (Hydrogen embrittlement)
2. Leaking at joints
3. Outdoor storage tank rupture due to external impact
4. Outdoor storage tank rupture due to heat from external fires
5. Gas separation membrane failure within the electrolyser
6. Maintenance personnel mistake

Consequences:

1. The displacement of oxygen in an indoor environment, leading to a person's asphyxiation
2. The displacement of oxygen in an outdoor environment, leading to a person's asphyxiation
3. A delayed ignition for indoor systems
4. The immediate or spontaneous ignition/deflagration of mixture
5. Hydrogen mixture detonation, resulting in shock waves
6. Hydrogen flame propagation leading to an indoor secondary fire
7. Routing of indoor hydrogen to outdoors, leading to an outdoor secondary fire
8. Human exposure to the flame's high temperature/thermal radiation
9. Pressure-peaking phenomenon leading to the structural collapse of the enclosure
10. Ignition during maintenance (most likely consequence [81, 161])

A worked example of calculation of the initial risk and mitigated risk is shown, using Version 1 (i.e. 'idealised scenario') of the Bowtie-LOPA.

Initial risks

The scenario used is the loss of containment of hydrogen gas, leading to explosion and fire. The values used for the Initiating Event Frequencies (IEF) for each cause is shown in Table 22.

Using Equation (1) in Appendix 8, page 185, the initial risk of a single fatality is obtained. For the individual, two types of profile have been defined: the building resident and the maintenance personnel. The difference between the two lay in the exposure hours. The public refers to passersby or an adjacent neighbour who could be at home at all time.

Table 22 Adopted Initiating Event Frequencies (IEF) for identified causes/threats for Version 1 hydrogen system

No.	Cause	IEF (y^{-1})	Remarks / Source
1	Corrosion	1×10^{-4}	Pressure vessel residual failure, Table 5.1, CCPS LOPA (2001) [159]. Use conservative number, corresponding to the failure rate of small leaks (Purple Book, VROM 2005) [62]
2	Leaking at joints	1×10^{-3}	EU/Ineris/Air Liquide study (initiating event I8, from HP fittings, valves or piping connections)[162]
3	Storage tank rupture due to mechanical impact	1×10^{-2}	Third-party intervention, Table 5.1 [159]
4	Storage tank rupture due to external fire	1×10^{-2}	Large fire from aggregate causes, Table 5.1 [159]
5	Electrolyser membrane leak	1×10^{-5}	PFD data is unavailable. Worst case scenario for membrane leak, Table 5, Psara et al. [163] is 1×10^{-7}
6	Maintenance personnel mistake	1×10^{-3}	Lock-out-tag-out mistake Table 5.1 [159]

The assumptions used:

- **Human exposure**
    - of the building resident: The average Dutch household size was 2.2 in 2019 [164]. The assumption used was that three residents would be in the house 16 out of 24 hours per day, on average in a week. The higher number takes into account any visitors, and family members staying at home in the weekends.
    - of the maintenance personnel: Maintenance is done once a year, lasting a total of 24 hours (i.e. 8 hours x 3 days), as per discussion with HyGear.
    - of the public or adjacent neighbour: it was assumed that a single person is always exposed at any time of the day
- **The initiating event frequency (IEF)**: The cause with the most conservative of initiating event frequency (IEF) from the identified causes is used. From Table 22 these were Cause #3 and Cause #4 with the value 1×10^{-2}.
- **The probability of immediate fatality**: The value of '1' was used for hydrogen explosion and fire, based on the premise that it is almost impossible to avoid the direct impact of a hydrogen explosion or fire when it occurs in the immediate surrounding of the person (e.g. up to 5 meters).

The outcome is shown in Table 22. The acceptability criteria in quantitative terms were shown in Table 16, which had $1 \times 10^{-6}\ y^{-1}$ for the individual, and $1 \times 10^{-3}\ y^{-1}$ for society as maximum threshold values. The calculated likelihood value is rounded to the nearest non-zero decimal number, which is possible since LOPA uses an approximation of quantitative risk rather than precise values.

Table 23 Initial risk calculation for Version 1 of the hydrogen system

	Initiating Event Frequency (y^{-1}), *IEF*	**Human exposure** (y^{-1}), P_H	**Probability immediate fatality,** P_F	**Likelihood of fatality** (y^{-1}), $F_o = IEF \times P_H \times P_F$
Individual (resident)	1×10^{-2}	6.7×10^{-1}	1	7×10^{-3}
Individual (maintenance personnel)	1×10^{-2}	2.7×10^{-3}	1	3×10^{-5}
Societal (public)	1×10^{-2}	1	1	1×10^{-2}

It can be seen that the more conservative value for the Individual likelihood was for the Resident, and the value is used to represent the Individual risk. In any case, the Individuals and the Society's initial risks were shown to be unacceptable (i.e. failed to meet the acceptance criteria).

Risk mitigation

The identified preventive and mitigative Independent Protection Layers (IPLs) were then assigned a probability of failure on demand (PFD) values. These are shown in from Table 40 to Table 42, starting on page 191.

Mitigated risk

Using Equation (2) in Appendix 8, page 185, the **top event frequencies due** to a particular initiating event, f_i^T, is calculated after taking into account the IEF of all the potential initiating event/causes, and the PFD of all the potential IPLs or safety barriers. The illustration of how f_i^T is obtained for Cause #6 – 'maintenance personnel mistake' - can be seen in the Bowtie in Figure 19, and the calculation is shown below. Two IPLs, each with the assigned value of 0.1, have been put in place meaning that each reduces the likelihood of the Top Event from occurring by a factor of 10. Figure 30 f_i^T is similarly calculated for all the causes and is shown in Table 24.

$$\begin{aligned} f_6^T &= IEF_6 \times PFD_{6-1} \times PFD_{6-2} \\ &= (1 \times 10^{-3}) \times (0.1) \times (0.1) \\ &= 1 \times 10^{-5} \end{aligned}$$

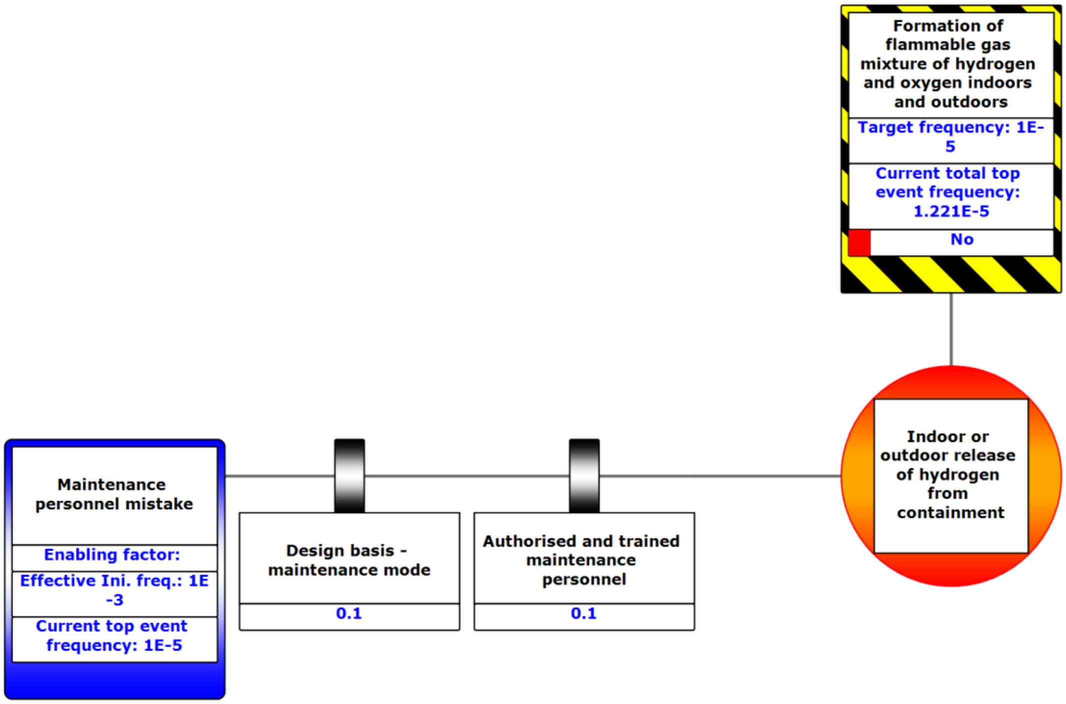


Figure 18 Bowtie diagram: Cause-branch for 'Maintenance personnel mistake'

Next, by using Equation (3) from Appendix 8, page 185, the **frequency of the top event for the aggregated initiating events**, f^T, is obtained by a simple summation of f_i^T of all causes, rounded up to the most significant decimal value. The value f^T is seen at the bottom-most row of Table 24.

Table 24 Top Event Frequencies for all causes after applying preventive mitigation for Version 1

Initiating Event, i	**Description**	**Top event frequencies, f_i^T (y^{-1})**
1	Corrosion (Hydrogen embrittlement)	1×10^{-6}
2	Leaking at joints	1×10^{-7}
3	Outdoor storage tank rupture due to external impact	1×10^{-6}
4	Outdoor storage tank rupture due to heat from external fires	1×10^{-8}
5	Gas separation membrane failure within the electrolyser	1×10^{-7}
6	Maintenance personnel mistake	1×10^{-5}
Frequency of the top event for aggregated initiating events, f^T		1×10^{-5}

Using Equation (4) from Appendix 8, page 185, **the frequency of consequence**, f_i^C, was calculated for each consequence. The illustration of how f_i^C is obtained for Consequence #10 – 'Ignition during maintenance' can be seen in the Bowtie shown in Figure 19.

As it turns out, there was only one Independent Protection Layer (IPL) which is the use of personal protective equipment (PPE); while all the other barriers were considered safeguards. Arguably, the use of PPE can also be highly dependent on human behaviours for compliance. Nevertheless, HyGear noted that their maintenance personnel are issued with standard PPE for their duties, and it is expected that the PPE is used whenever carrying out maintenance work, thus a justifying risk-reduction credit.

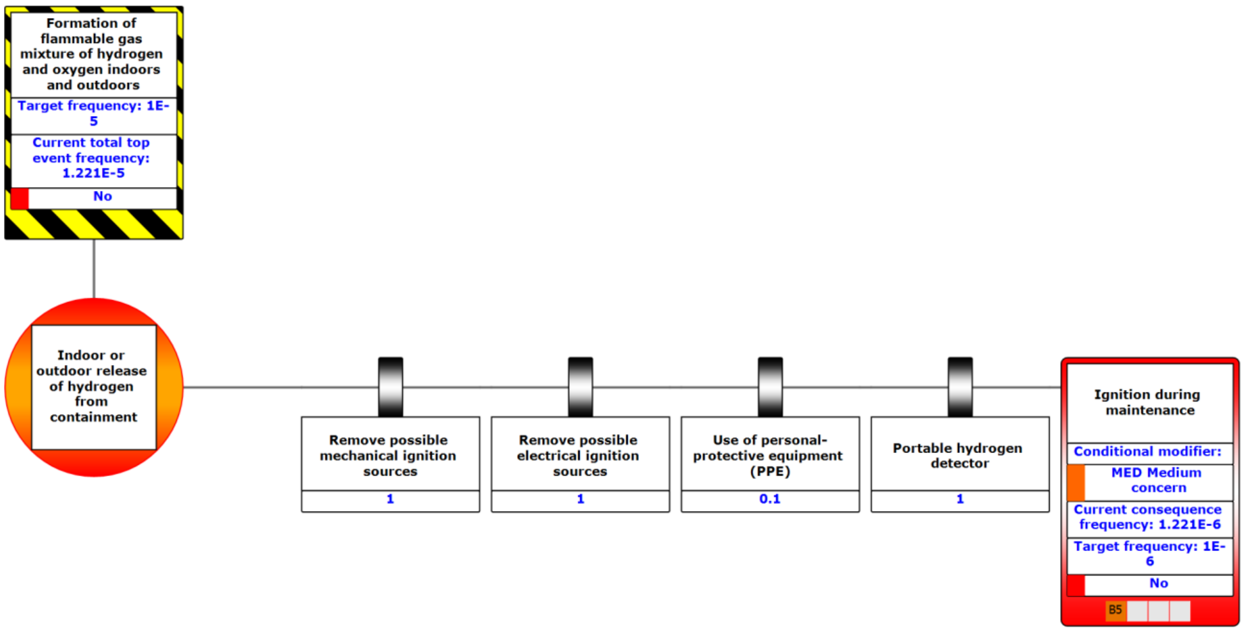


Figure 19 Bowtie diagram: Consequence-branch for 'Ignition during maintenance.'

The frequency of Consequence #10,

$$\begin{aligned} f_{10}^{C} &= f^{T} \times PFD_{10-1} \times PFD_{10-2} \times PFD_{10-3} \times PFD_{10-4} \\ &= (1 \times 10^{-5}) \times 1 \times 1 \times 0.1 \times 1 \\ &= 1 \times 10^{-6} \end{aligned}$$

The f_i^C for all the consequences are shown in Table 25. The consequence with the highest likelihood value is Consequence #10 – 'Ignition during maintenance', which outweighs the likelihood of the other consequences by order of magnitudes. Comparatively, the consequence with the most severe outcome for hydrogen systems, mentioned in [161], is Consequence #5 –' Hydrogen mixture detonation, resulting in shock waves' – has a likelihood of one million times smaller. Therefore, to gauge the likelihood of a fatality occuring, the frequency of consequence for Consequence #10 was used to calculate the mitigated risk for the hazard.

The Bowtie diagram for Version 1 of the analysis is shown from Figure 20 through Figure 22, complete with all the adopted Initiating Event Frequencies (IEFs) and Probability of Failure on Demand (PFD) of the barriers. The complete diagram could not be displayed to fit within an A4-sized page and displayed in two segments.

Table 25 Version 1 Hydrogen system Bowtie: Mitigated frequency of all consequences

Consequence	**Description**	**frequency of consequence** (y^{-1}), f_i^C
1	Indoor oxygen displacement leading to asphyxiation	1×10^{-8}
2	Outdoor oxygen displacement leading to asphyxiation	1×10^{-9}
3	Indoor systems: delayed ignition	1×10^{-9}
4	Immediate / spontaneous ignition (deflagration) of mixture	1×10^{-7}
5	Detonation resulting in shock waves	1×10^{-12}
6	Indoor flame propagation, leading to secondary fire	1×10^{-7}
7	Routing of indoor hydrogen to outdoors, leading to an outdoor secondary fire	1×10^{-9}
8	Human exposure to high flame temperature / thermal radiation	1×10^{-10}
9	Pressure-peaking phenomenon leading to the structural collapse of the enclosure	1×10^{-8}
10	Ignition during maintenance	1×10^{-6}

Using Equation (5) from Appendix 8, page 185, the mitigated frequency, $f_{mit.}$, is calculated. The probability of human exposure and the probability of fatality, P_H and P_F respectively, is similar to that used in the calculation for the initial risk. The unmitigated and mitigated risks for the individual and society is shown in Table 26.

The steps A1-A2 and B1-B4, described in page 79, was repeated for the Version 2 (i.e. 'LIFE as-built' design) of the Bowtie. The details of the risk calculation would not be repeated here but can be read in Appendix 8, from page 197 onwards.

The Bowtie diagram for Version 2 was a variation of Version 1 with the following changes made:

- Removed causes that have a very low likelihood of occurring:
  - Cause #4: Storage tank rupture due to heat from external fire; because HyGear's proposed tank designs are made of carbon steel which has higher tolerability to external fire compared to composite materials
- Removed barriers which would have a low likelihood of existing
  - In-line shut-off valves; because HyGear's design typically does not incorporate these
  - Use of fire-resistant materials on adjacent equipment; because the hydrogen storage area for the LIFE project is conceptually co-located with the High-Pressure Lab's existing gas storage area. As yet, there is no plan to make modifications to improve the fire-resistance of adjacent equipment.
  - Design considerations for electrolyser; because HyGear plans to source the electrolyser from a 3rd-party supplier and thus would not have the responsibility of its detailed design.

The initial and mitigated risks values for Versions 1 and 2 are summarised in Table 26. It was shown that the initial risks for individuals and society (public) were calculated to be unacceptable, corresponding with the outcome from the qualitative risk assessments**.** Furthermore, the acceptability margins were almost negligible for the mitigated Individual risks for both Version 1 and Version 2, i.e. borderline 'yes' and 'no', respectively. It was concluded that ALARP has to be demonstrated for the corresponding hazard, that would have led to Consequence #10 – 'Ignition during maintenance.'

For Societal risk, the mitigated risks for Versions 1 and 2 were successfully reduced to an acceptable level with a comfortable margin, by almost a factor of 1000 times smaller than the threshold value.

Table 26 Values of the initial/unmitigated risks, and the mitigated risks for Version 1 and 2 of the hydrogen Bowtie scenarios

	Acceptability value (y^{-1})	**Calculated value** (y^{-1})	**Acceptable risk?**
Individual risk			
Initial/unmitigated	Less than 1×10^{-6}	7×10^{-3}	No
Mitigated – Version 1		8×10^{-7}	Borderline Yes
Mitigated – Version 2		2×10^{-6}	Borderline No
Societal risk			
Initial/unmitigated	Less than 1×10^{-3}	1×10^{-2}	No
Mitigated - Version 1		1×10^{-6}	Yes
Mitigated - Version 2		3×10^{-6}	Yes

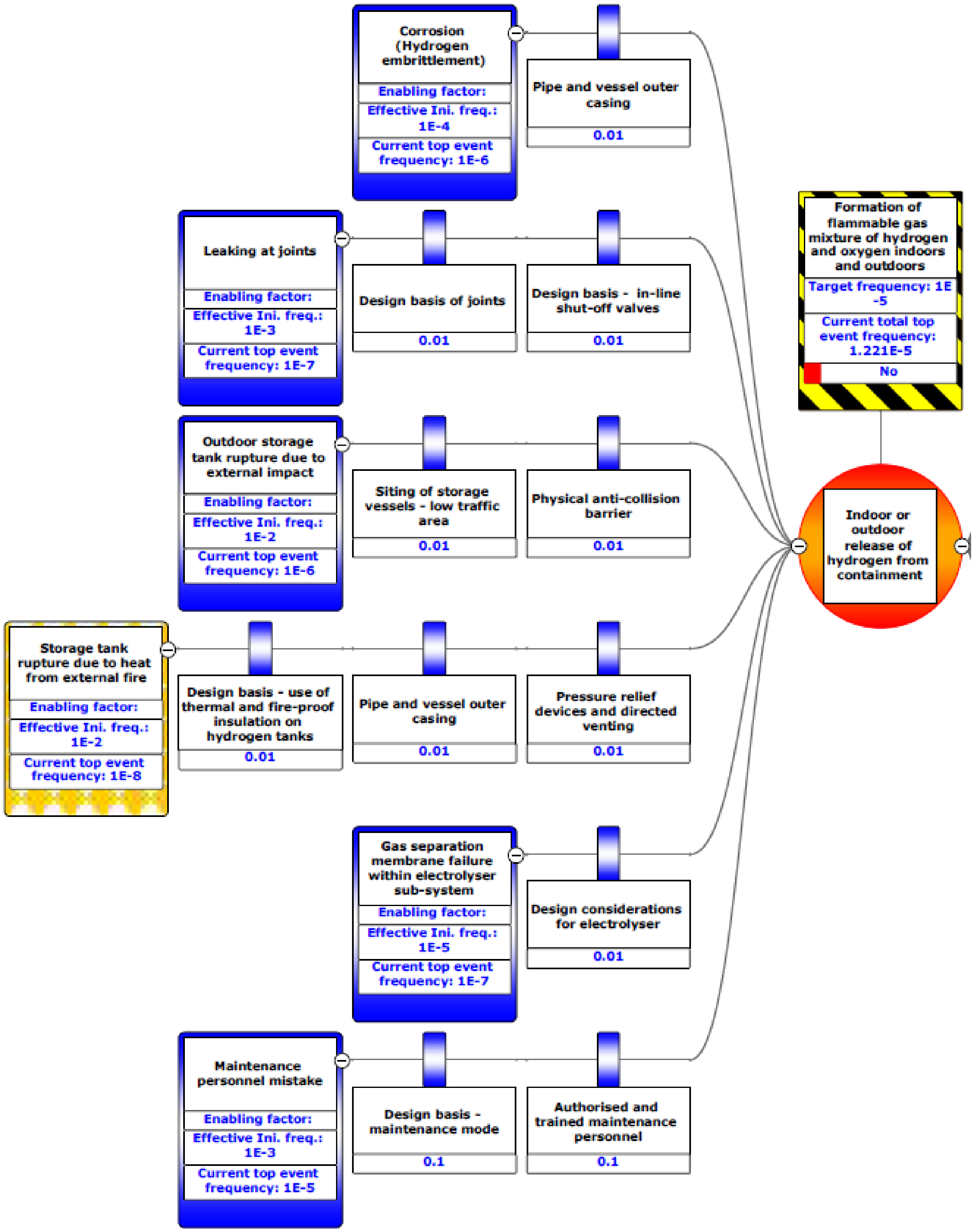


Figure 20 Version 1 analysis – the left-hand side of Bowtie (causes) for the top hazard of indoor/outdoor release of hydrogen from containment

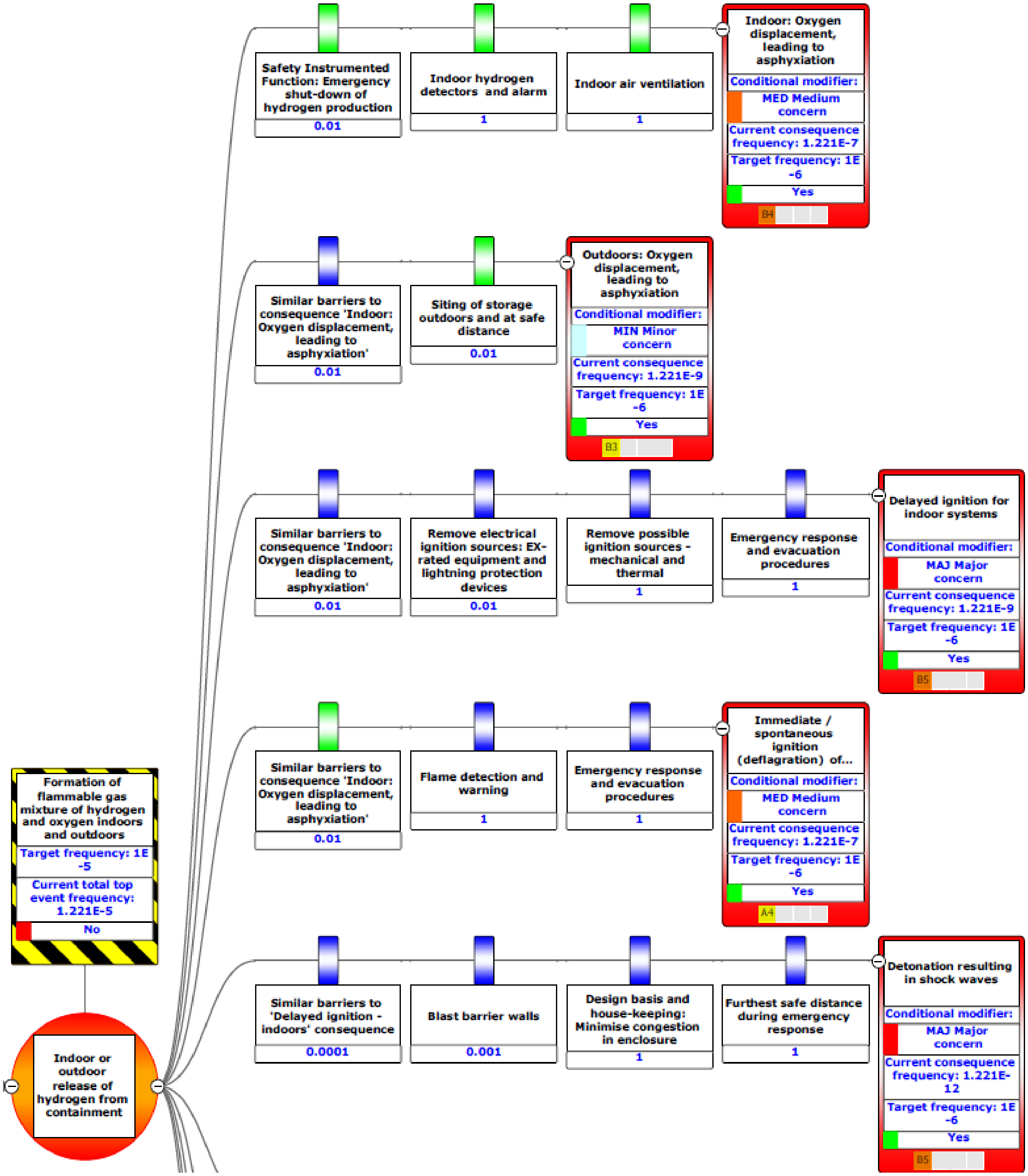


Figure 21 Version 1 analysis – the right-hand side (consequences) of Bowtie for indoor/outdoor release of hydrogen from containment (continued in Figure 22)..

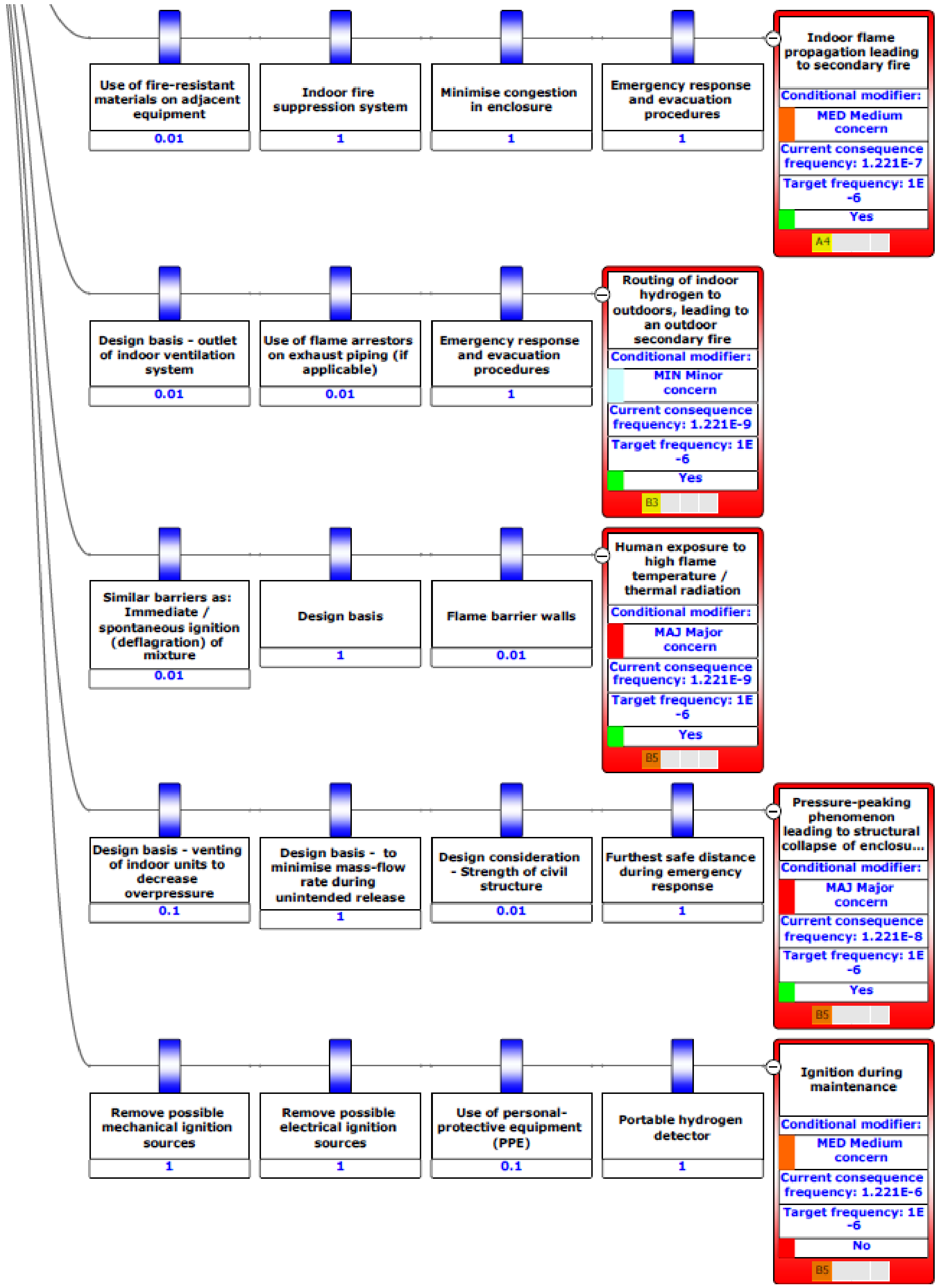


Figure 22 (continued from Figure 21) Version 2 of analysis – the right-hand side (consequences) of Bowtie for indoor/outdoor release of hydrogen from containment.

3.5.2 Bowtie-LOPA analysis for the Li-ion battery system

For the Li-ion battery system, analysis thus far identified no hazards with High/Red risk and twenty-one hazards with Serious/Orange risk levels. As shown in Table 27, fifteen of these hazards were highly related to the thermal runaway phenomenon. It was thus decided to use a single Bowtie diagram to analyse these fourteen hazards. The other six hazards that have low relation with thermal runaway phenomenon were analysed individually without using Bowties.

Table 27 Hazard Tracker ID and hazard descriptions that carry Serious/Orange risk levels for Li-ion battery system

Highly related to the thermal runaway phenomenon:
45 - Super-system: Battery-management system interface cables inadvertently is disconnected
47 - Super-system: during transportation, connectors become loose
65 - System: Storage in a fully discharged state (< 2V/cell)
66 - System: ultra-fast charging is used
68 - Use of second-life batteries
108 - Cascading thermal runaway
110 - Release of toxic gas, such as HCl, HF, CO, HCN, and potential SO_2 and H_2S
111 - Onset of overheating
112 - Heat accumulation and flammable gas release
113 - Combustion and explosion
114 - Thermal abuse
115 - Mechanical abuse
116 - Electrical abuse
117 - Poor cell electrochemical design
118 - Internal cell faults due to manufacturing defects
Low relation to the thermal runaway phenomenon:
43 - Super-system: adjacent systems emit vibrations, causing connectors to loosen
44 - Super-system: Battery disposed of not using proper channels
109 - Electrical injury
119 - Leakage of electrolyte
126 - Flooding
148 - Weight of battery and structural integrity of battery house

Bowtie scenario

Hazard: Chemical reactions within the electrolyte of general-type lithium-ion battery
Top Event: Onset of Lithium-battery cell thermal runaway

The Bowtie diagram has eight threat branches and three consequence branches.

Threats/Causes:

1. The battery exposed to external fire
2. The battery ambient temperature is higher than 70 degrees C (low likelihood).

3. The battery subjected to piercing, impact, crushing or vibration and then put into operation, i.e. charged and discharged
4. The battery is overcharging, i.e. the charging current or voltage exceeds that of the cell's rating
5. The battery is over-discharged.
6. External short-circuiting during transportation (not a likely cause during the use-phase in the LIFE project)
7. External short-circuiting due to a lightning strike (low likelihood)
8. Internal cell defects from the manufacturing processes

Consequences:

1. Combustion of adjacent battery cells and equipment
2. Toxic fume emission and personnel injury
3. Toxic water/chemical hazard following fire-extinguishment actions

Similar to the hydrogen Bowtie, both Versions 1 and 2 of the Bowtie diagrams were created. The changes made for Version 2 are as follow:

- Enhanced the Probability of Failure on Demand (PFD) of a barrier:
  - Cell design considerations; because a lithium iron phosphate type is used, thus enhancing the cell's thermal stability. The PFD is decreased by a factor of 10.
- Removed causes that have a very low likelihood of occurring:
  - Battery ambient temperature > 70^{o}C; because the ambient temperature has a more considerable impact on the battery longevity, rather than on the safety. Furthermore, it is highly unlikely that the ambient temperature can go above 70^{o}C, based on historical data and future projections where the average winter and summer is predicted to be warmer by only 2-3^{o}C in 2050 [165].
  - External short-circuiting conditions that lead to Li-ion battery thermal runaway only occur during transportation and battery storage.
- Removed barriers which would have a low likelihood of existing
  - The battery is placed in a water containment feature; because it is conceptually envisioned that such a facility is not required due to the low likelihood of a lithium iron phosphate battery fire occurring
  - Design considerations - Better heat insulation in between cells; because SuperB does not have the responsibility of the battery cell design, and thus is unable to assure that this feature exists.
  - There is no fire-suppression system installed, either as a preventive barrier (gas-flooding system to suppress electrical fires), or mitigative barrier (water-sprinkler system to suppress battery fires). This is on the basis that using CO gas monitor is used to detect both electrical fires and also the out-gassing battery phenomena.
- Remove a consequence which has a very low likelihood of occurring
  - Toxic water from fire-extinguishment; because the battery shed is not designed for on-site water submersion

The Bowtie diagram for Version 1 is shown in Figure 23 through Figure 25. The derivations of the unmitigated and mitigated risks are similar in steps used for the example used in previous section on the hydrogen system.

For brevity, only the main assumptions and outcomes for the analysis of the Li-ion Bowtie-LOPA are presented in the main section of the thesis. The full details of calculations are shown in Appendix 8, page 200 onwards. The initial and mitigated risks values are thus presented in Table 28.

Table 28 Values of the initial/unmitigated risks, and the mitigated risks for Version 1 and 2 of the Li-ion battery bowtie scenarios

	Acceptability value (y^{-1})	**Calculated value (y^{-1})**	**Acceptable risk?**
Individual risk			
Initial/unmitigated	Less than 1×10^{-6}	7×10^{-5}	No
Mitigated – Version 1		2×10^{-8}	Yes
Mitigated – Version 2		2×10^{-7}	Yes
Societal risk			
Initial/unmitigated	Less than 1×10^{-3}	1×10^{-4}	Yes
Mitigated - Version 1		3×10^{-8}	Yes
Mitigated - Version 2		3×10^{-7}	Yes

It was shown that the risk for the Individual was initially unacceptable, whereas the unmitigated risk for the Society was in the acceptable region. Following the application of relevant barriers, the mitigated risks in Versions 1 and 2, were reduced to within the acceptability range by quite a comfortable margin, by at least a factor of 0.1 lower than the acceptable risk threshold. There was no need to demonstrate that the mitigated risks meet the ALARP principles.

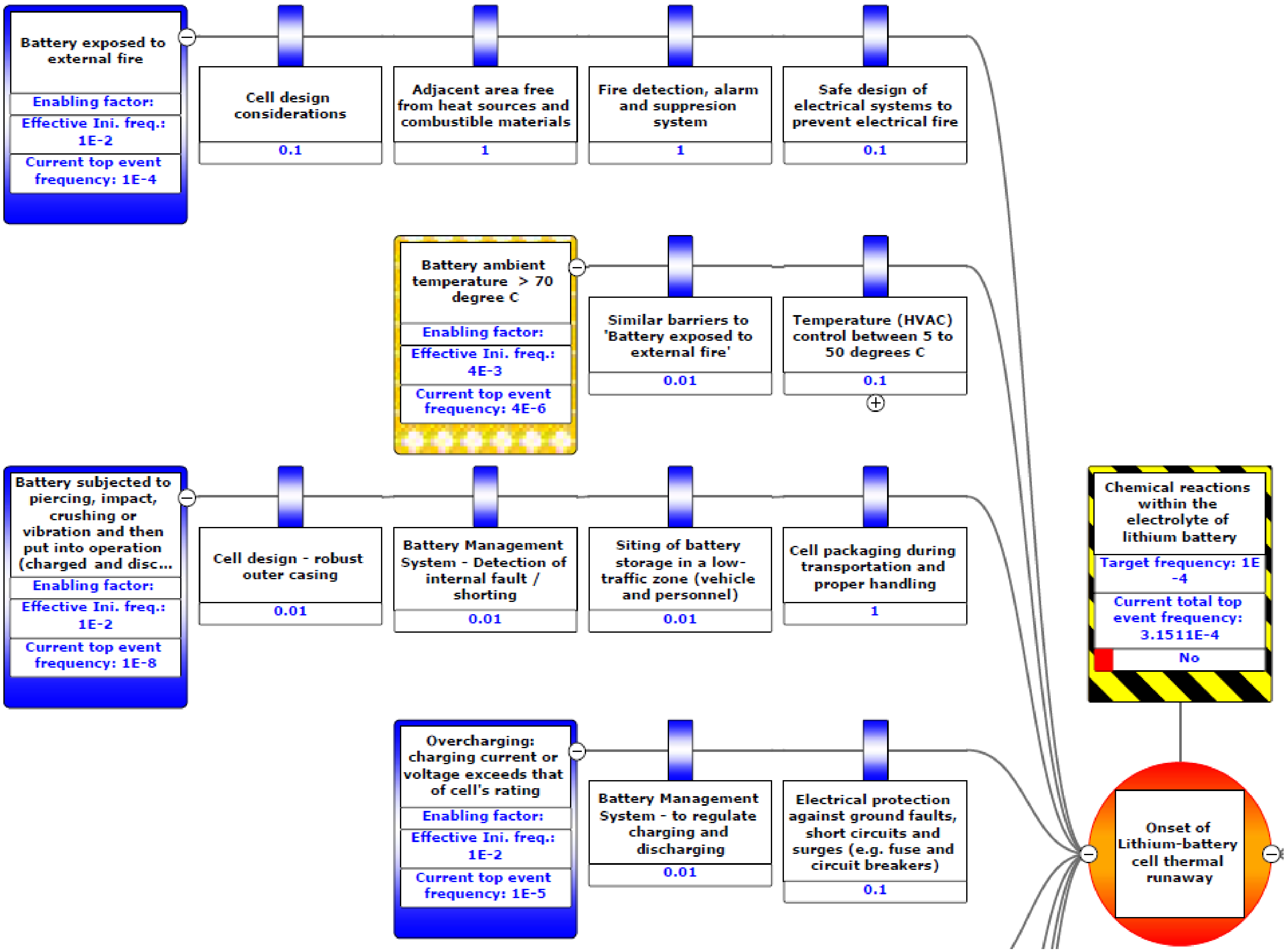


Figure 23 Version 1 analysis: Left-hand side of Bowtie (causes) for the Top Event 'onset of Lithium-battery cell thermal runaway.' (continued in Figure 24)

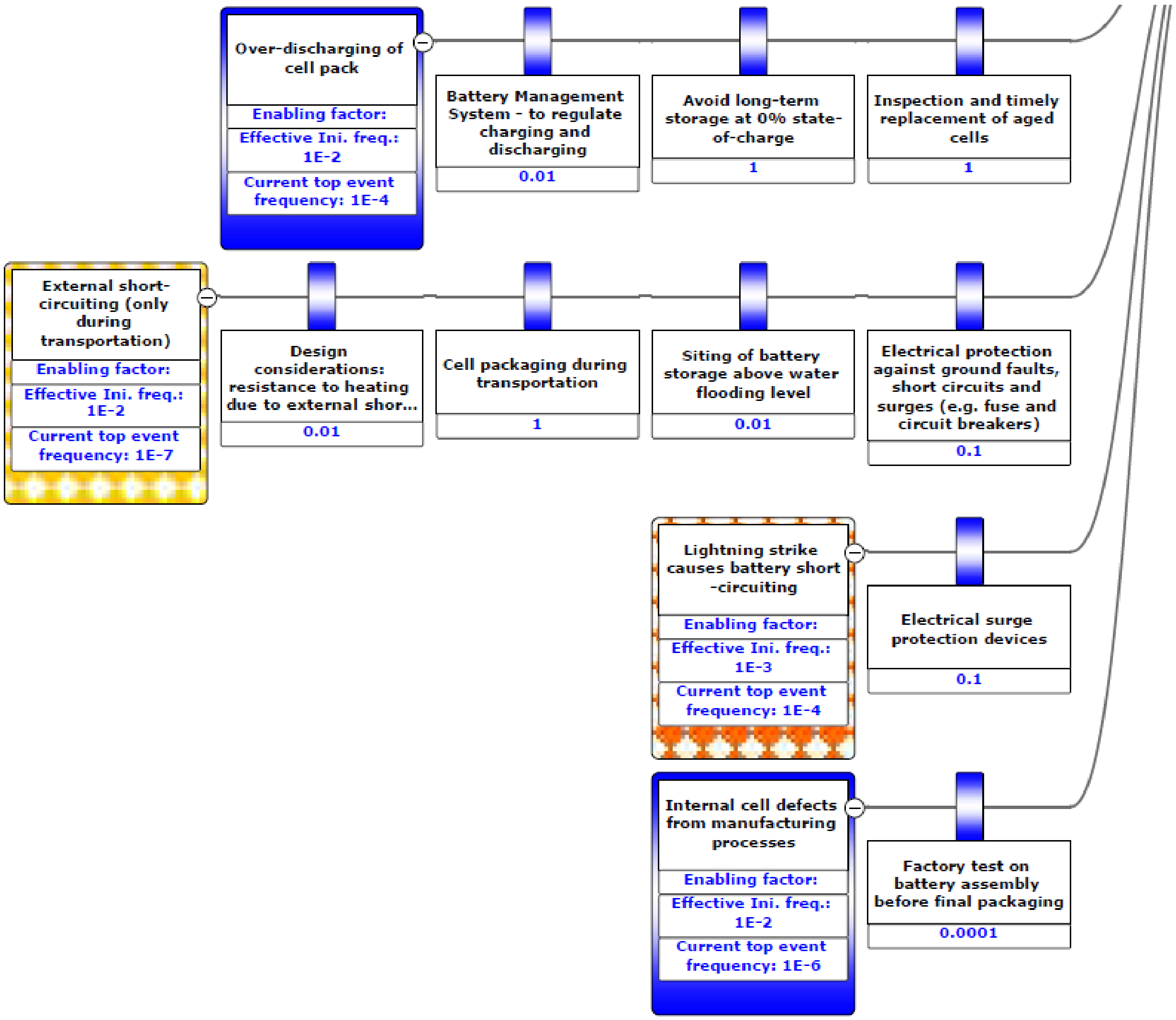


Figure 24 (continued from Figure 23) Left-hand side of Bowtie (causes) for the Top Event 'onset of Lithium-battery cell thermal runaway.'

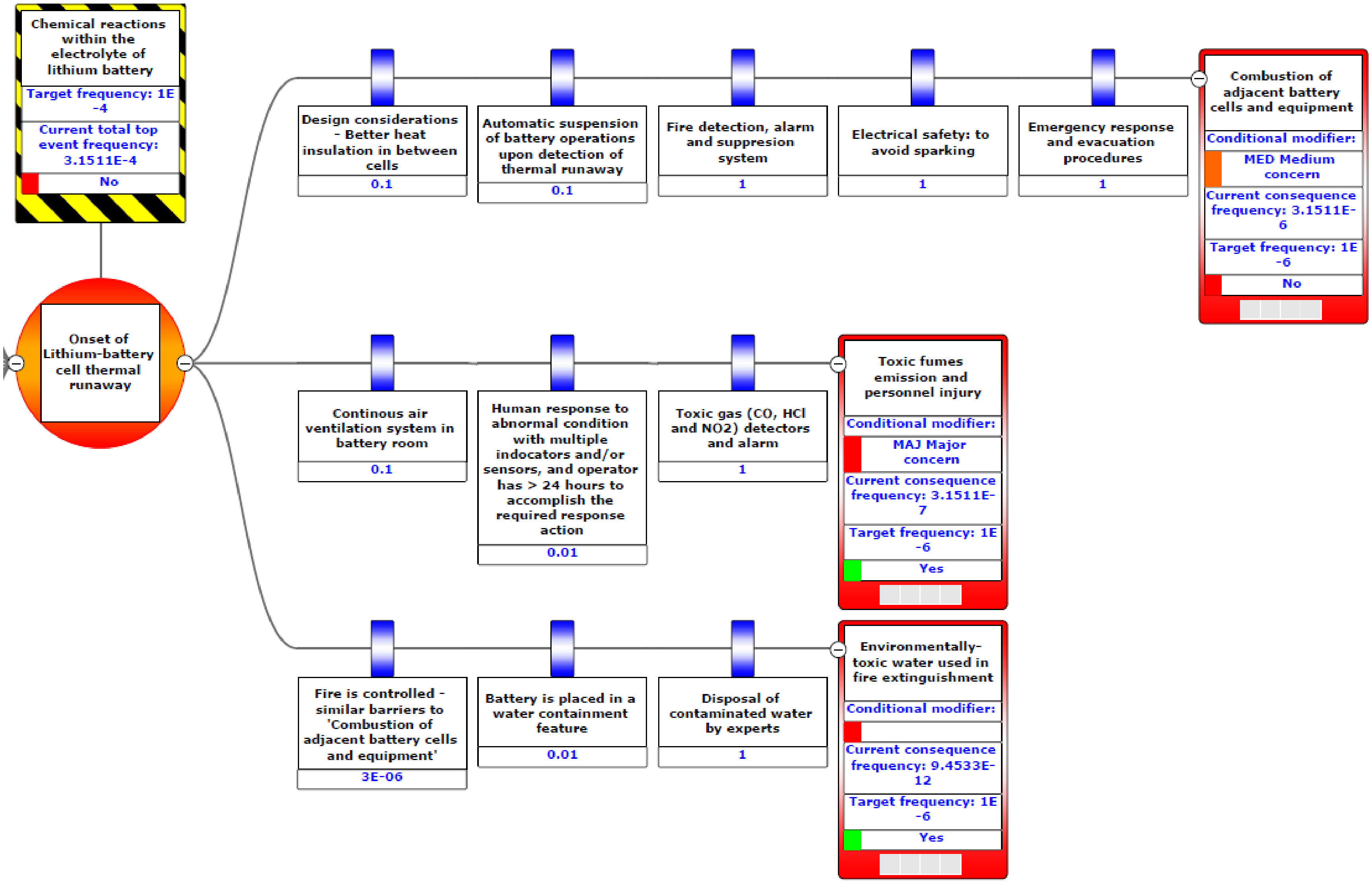


Figure 25 Version 1 analysis: Right-hand side of Bowtie (consequences) for the Top Event 'onset of Lithium-battery cell thermal runaway.'

Following the Version 2 of the Bowtie-LOPA analysis of the Li-ion system, nine of the Serious/Orange threats were found to have been mitigated, primarily due to design considerations already incorporated by SuperB in its Li-ion battery systems. These threats were marked as 'closed' in the Hazard Tracker ID, with the reason of closure indicated in Table 29.

Table 29 Hazards with 'closed' status following the Bowtie-LOPA analysis of Li-ion system

Hazard Tracker ID and description	Reason for closure
66 - System: ultra-fast charging is used	Less of a safety issue, and more of battery longevity issue
108 - Cascading thermal runaway	Adequate barriers are included in the system design. Furthermore, the probability is assumed 1 in 1 million cells. Phase 1 of LIFE project uses only 48 cells, and therefore the probability is considered 'remote'.
111 - Onset of overheating 112 - Heat accumulation and flammable gas release 113 - Combustion and explosion	Adequate barriers are included in the system design. Furthermore, the risk of flammable and toxic gas is still a hazard that requires mitigation.
115 - Mechanical abuse	Cell is encased by hard polymer casing. The risk of collision/impact hazard would be considered in the battery siting plan.
117 - Poor cell electrochemical design	Batteries used are of lithium-iron-phosphate type, which is less susceptible to thermal runaway
118 - Internal cell faults due to manufacturing defects	Adequate factory testing and quality assurance by SuperB ensures that manufacturing defects are minimised.
119 - Leakage of electrolyte	Cell case is made of leak-proof, hard non-corrosive polymer.
126 - Flooding	The location has not been flooded in the past ten years, even during heavy downpour in 2015

3.6 Demonstration of 'as low as reasonably practicable' (ALARP) risks

In the literature review section where the ALARP principle was introduced, it was also mentioned that the Dutch regulation on public safety (BEVI) has no provisions for ALARP. Nevertheless, a hypothetical example illustrates how hazards with residual risks that fell outside the acceptable range could be managed using ALARP principles. The following steps were used:

Step 1: Establish the ALARP-demonstration method. The decision-making criteria is established.

Step 2: Review the risk that needs ALARP demonstration and set a target

Step 3: Evaluate the available options to manage the risk

Step 4: Document the selected option and rationale.

In the Bowtie-LOPA analysis outcome for the hydrogen system shown in the previous section, it was concluded that ALARP needs to be demonstrated for the hazards that would lead to ‘ignition during maintenance’ consequences.

Step 1: Establish the ALARP-demonstration method

The means for accomplishing ALARP mentioned in [42] is adopted with some modification, shown in Table 30.

Table 30 Tools for accomplishing ALARP, adopted from [42].

<table>
<tr><th>Order of preference</th><th>Tools</th><th>Remarks</th></tr>
<tr><td>1</td><td>Use codes and standards</td><td>Use whenever possible. The solutions are based on established practices.</td></tr>
<tr><td>2</td><td>Use good practice and engineering judgement</td><td rowspan="2">Use when a deviation from codes and standards are required, and risk trade-off is possible.</td></tr>
<tr><td>3</td><td>Perform risk-assessment and a cost-benefit analysis</td></tr>
<tr><td>4</td><td>Use peer review and industry-wide comparisons</td><td>Use when the risk is not well-understood.
Disadvantages: challenging to get full data. The effectiveness of solutions also has a fair amount of uncertainty.</td></tr>
<tr><td>5</td><td>Consult stakeholders for views and solutions</td><td>Least ideal, and only use when considerable complexity is involved.
Disadvantages: Stakeholders may hold strong views. The effectiveness of solutions may contain a very high degree of uncertainty.</td></tr>
</table>

Next, a decision-making tool would be required. The concept of Implied Cost of Averting a Fatality (ICAF), described in Section 2.1.8 can be used. A hypothetical guide is proposed, shown in Table 31. Instead of taking an absolute value, a criterion that uses the percentage of the total EESS system development cost be used the basis for decision-making is proposed. It is worth emphasizing that the proposed guide is created purely to illustrate how ALARP principles might be applied and is not based on any official risk-acceptance policy of the LIFE project. The ICAF should be aligned to the risk-management policy and threshold values used by the University of Twente

Table 31 A proposed decision-making tool based on Implied Cost of Averting a Fatality, based on [42].

ICAF (€ / fatality avoidance)	Guidance
< 5% of cost	Always implement unless the risks are negligible
Between 20% to 40% of cost	Consider implementing, if the risk levels are high or if there are other benefits
> 40% of cost	Cost is grossly disproportionate

Step 2: Review the risk that needs ALARP demonstration and set a target

An example is made of Hazard #142 – 'hydrogen gas igniting during maintenance or upkeep operations'. The most likely cause of the consequence is 'maintenance personnel mistake' since the scenario can only occur during maintenance work. The Bowtie-LOPA scenario is shown again in Figure 26 for a closer inspection. The mitigated frequency for this consequence was calculated to be $1 \times 10^{-6}\ y^{-1}$.

To achieve a more comfortable margin, it was decided that as a target, the risk should be further reduced by a factor of 10, meaning that the mitigated/residual risk ought to be 1×10^{-7} or smaller.

Step 3: Review available options

Using the ALARP-demonstration tools shown in Table 30, it was decided to apply the top two tools in the order of preference, namely by reviewing the safety barriers and comparing them with codes, standards, good practice and engineering judgement.

Option 1: Review good practices in behavioural barriers

Guidelines such as [104, 109, 116] contain good practices related to the safety of hydrogen use and the maintenance of hydrogen systems. According to CCPS's LOPA guidelines [159], human actions are considered a relatively weak protection layer. The Probability of Failure on Demand (PFD) of 1×10^{-1} up to $1 \times 10^{-2}\ y^{-1}$ is allowed, if there are well-established management practices, procedures and training for the human.

In the Bowtie diagram, the PFD of $1 \times 10^{-1}\ y^{-1}$ has already been assigned to the maintenance personnel's collective behavioural barriers at the reactive side of the Bowtie. The three mitigative/reactive behavioural barriers are highly dependent on the diligence of the maintenance personnel. E.g. the act of removing any mechanical or electrical ignition sources during maintenance work. Thus it was decided that it would not be possible to assign an additional PFD credit.

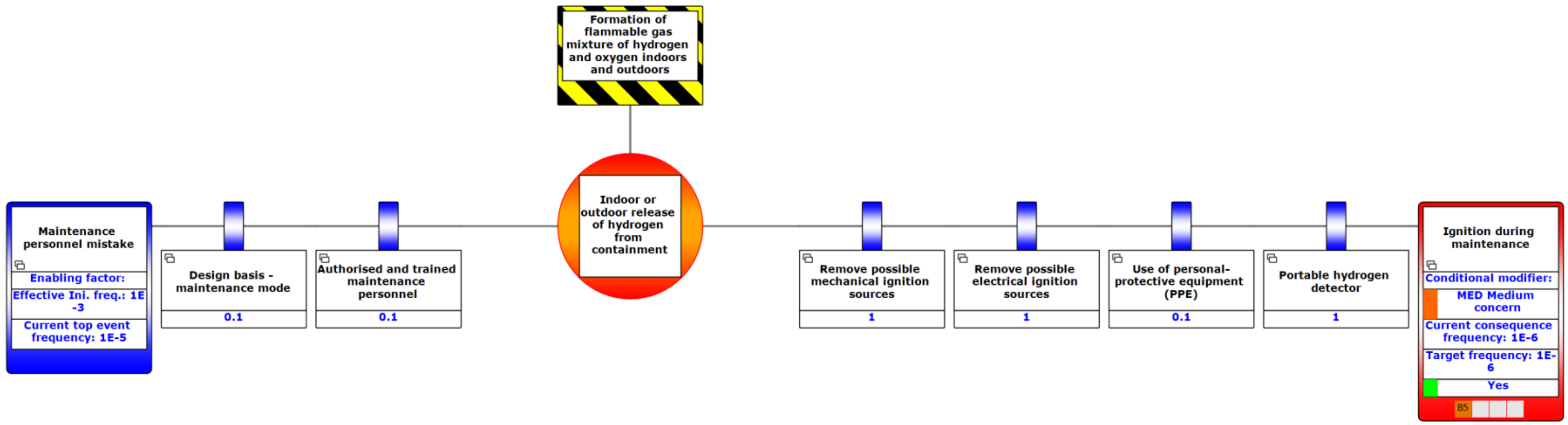
Option 2: Review the effectiveness of socio-technical barriers.

Two socio-technical barriers were put in place on the left-hand/preventive side of the Bowtie.

The first barrier is the practice allowing only personnel that have been authorised and have undergone specific training to perform maintenance activities on the hydrogen system. The policy implies that a structured training, certification and re-validation programme in place. At most, a PFD of $1 \times 10^{-1}\ y^{-1}$ is allowed according to [166] and this is currently assigned in the Bowtie.

The second barrier is 'design-basis: maintenance mode'. In the CCPS LOPA handbook, the guideline for PFD range for "inherently safe design" can be from 1×10^{-1} up to $1 \times 10^{-6}\ y^{-1}$. Inherently safer design features allow the scenario to be eliminated, for example, if a toxic or flammable material can be removed from the process [159, 160]. The currently assigned PFD of $1 \times 10^{-1}\ y^{-1}$ was made on the basis of conservatism. It is thus worth exploring if a more effective PFD can be used.

Figure 26 Bowtie-LOPA scenario for ALARP example



Hazard: Formation of a flammable gas mixture of hydrogen and oxygen indoors and outdoors	**Threat**: Maintenance personnel mistake, with Initiating Event Frequency (IEF) of $1 \times 10^{-3}\ y^{-1}$.
Top Event: Indoor or outdoor release of hydrogen from containment	**Consequence**: Ignition of the flammable mixture, leading to personnel death or injury

Mitigation / Layers of protection:

Barrier	Barrier side	Barrier type	PFD (y^{-1})
Design basis: maintenance mode for equipment	Proactive	Socio-technical	1×10^{-1}
Authorised and trained maintenance personnel	Proactive	Socio-technical	1×10^{-1}
Remove possible mechanical ignition sources	Reactive	Behavioural	1
Remove possible electrical ignition sources	Reactive	Behavioural	1
Use of personal protective equipment (PPE) in conjunction with a portable hydrogen detector	Reactive	Behavioural	1×10^{-1}
Portable hydrogen detector	Reactive	Behavioural	1
TOTAL RISK REDUCTION OF ALL BARRIERS			$\mathbf{1 \times 10^{-3}}$

Residual/Mitigated risk:

Consequence frequency $= IEF \times Total\ PFD = 10^{-3} \times 10^{-3} = 10^{-6}$

HyGear explained that before maintenance activities are performed on its current hydrogen systems, the system is purged with nitrogen until it is hydrogen-free. The result of this is that the flammable material, hydrogen gas, has been removed from the process. Thus the threat/scenario can be eliminated, going by LOPA guidelines. The PFD for the 'design-basis: maintenance mode' barrier, can then be given an additional credit to reduce risk, thereby decreasing it to 10 or 100 times y^{-1}. The provisos for this are:

1. The execution of 'maintenance mode' should not be complicated and easily understood by the operator/maintenance personnel.
2. The written procedure for executing the 'maintenance mode' should undergo an Operating and Support Hazard Analysis (O&SHA). Every task in the procedure is analysed for hazards, which could arise from personnel errors and create hazards to the equipment or the personnel.
3. These guidelines should be used when designing 'maintenance mode'.
    a. Doc 23.07/18 Safety training leaflet for hydrogen, by EIGA [116].
    b. Appendix A: Inherently Safer Technology Checklist from CCPS' book on 'Inherently Safer Chemical Process: A Life-Cycle Approach [167].
4. The hazard status is kept in 'open' status and should be reviewed after the final design for the 'maintenance mode' has been completed. The system used in the LIFE project would be a new design which has not yet been finalised. At the current phase of the LIFE project lifecycle (i.e. conceptual design phase), it is premature to assume that a similar nitrogen-purge feature can be easily implemented or easily performed.

Step 4: Document the selected options

The two options discussed in Step 3 utilised the top three in the order of preference of tools, sufficient to demonstrate ALARP without the need to use more complex tools. If Option 2 were implemented, it would be possible to reduce the mitigated frequency of the LOPA scenario to a value of $1 \times 10^{-7}\ y^{-1}$ or even smaller, thus placing the residual risk comfortably within the acceptable region.

The Implied Cost of Averting a Fatality (ICAF) decision-making tool was not used in the previous example. However, if the suggested options had utilised an engineering design change, then the ICAF needs to be calculated.

3.7 Emergency response and procedures

Emergency response forms part of hazards control. Because it requires human intervention, under LOPA guidelines, it is considered a safeguard rather than an independent protection layer (IPL). At an incident scene, critical information knowledge is beneficial to emergency response planning and execution. The Twente Region Fire Brigade explained that the on-scene first-responders usually have many priorities to attend to during an unsafe event. Following some discussions with the Fire Brigade staff members and the literature review on EES system safety, a 'top five' list of concerns is proposed to help first responders during safety incidences at the LIFE facilities. These concerns, shown in Table 36, are based on the premises of:

- The main scenario is a fire caused by or is affecting the hydrogen, Li-ion or VRB systems.
- As indicated in Version 2 of the Bowties, the minimum number of safety barriers has been included in the integrated EES design.
- The existence of necessary infrastructure supporting fire-fighting efforts, such as access for first-responders and their vehicles, and reachable water-hydrant or water sources (e.g. a pond).
- The Fire Brigade is equipped with the knowledge, techniques, tools and the PPE to deal with hydrogen and battery hazards Emergency response in general

Table 32 Top five concerns for first responders

#	Concern	Rationale
1	How do we know if there are EES systems – i.e. hydrogen or batteries – installed indoors or outside the residential buildings?	By making the first responders aware of such hazards, the first responders can quickly respond by applying the most appropriate measures. The Dutch fire brigade are continuously trained and updated in the knowledge of managing a range of hazardous materials, including hydrogen and Li-ion batteries [168]
2	Who can we contact to learn more about the installed EESS' specifications?	The first responders need to know the type of EESS, the installation layout and the installed safety barriers, which allows for the most appropriate responses to be applied.
3	How do we know if hydrogen is leaking indoors, or has ignited?	This is of paramount importance for indoor-systems, as the hazard is not visible from outside the building structure. Establishing the situation will enable the first-responders to take necessary precautions (e.g. use a breathing apparatus, or maintain a safe distance away from the hydrogen leak).
4	What is the safe distance for the installed hydrogen system?	Establish and maintain the hazard distance, defined as the "distance from the source of hazard to a determined physical effect value (normally, thermal or pressure) that may lead to a harm condition (ranging from 'no harm' to 'max harm') to people, equipment or environment [104].
5	How do we know if there are toxic gasses (HCl, CO and HF) in the battery room?	The presence indicates that the Li-ion batteries are still 'out-gassing'. If the ambient temperature in the battery room is also rising (although it would be challenging to ascertain this), it would indicate that the battery fire has not yet peaked. Subsequently, the battery should be cooled by water spray [130]. The VRB electrolyte is not flammable, but similar toxic gasses are produced if the electrolyte is heated [130].

3.8 Making the argument of a safe system

Finally, the Global Structuring Notation (GSN) was used to conceptually argue that the EES system is safe for use in the LIFE project. A predominantly textual argument can impede communication due to poor writing structure and frequent cross-references [169]. GSN is a graphical means to make safety arguments and offers an alternative to the textual argument. The use of symbols and diagrams allow for the presentation to be made more clearly. The readers can also use it and decide for themselves if an argumentation is complete or otherwise. The GSN uses several symbols and notation to show the relationship between individual elements in the safety arguments, with Figure 27 showing the main ones.

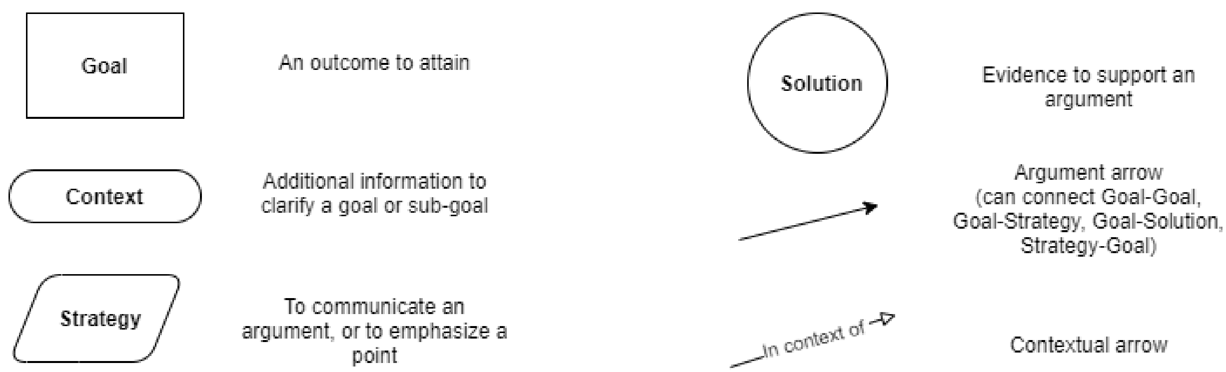


Figure 27 Main symbols used in GSN

Referring to Figure 28, the GSN is meant to be read as 'A is true' because B and C are also true'. An argument is only complete if valid evidence or solutions are supporting it. Because this is an argumentation, it is not an absolute fact that 'A is true'.

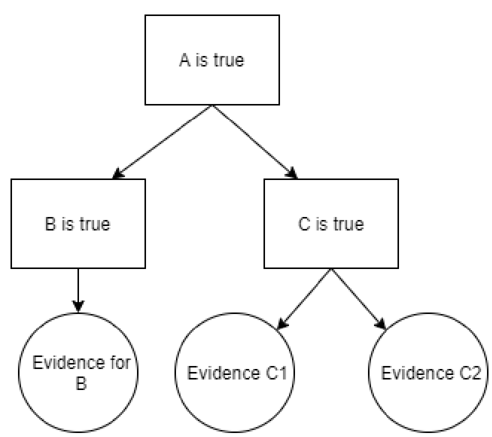


Figure 28 An example of a GSN diagram

Figure 29 shows the GSN for the EESS in the LIFE project and is supplemented by information found in:

- Table 33 relates the GSN's Solution with the hazard mitigations specified in the LIFE project's conceptual design. It can be seen that not all the mitigations listed in Table 34 were applied in the LIFE project.
- Table 34 is a compilation of hazard mitigations that have been discussed in Section 2.3 until Section 2.5.

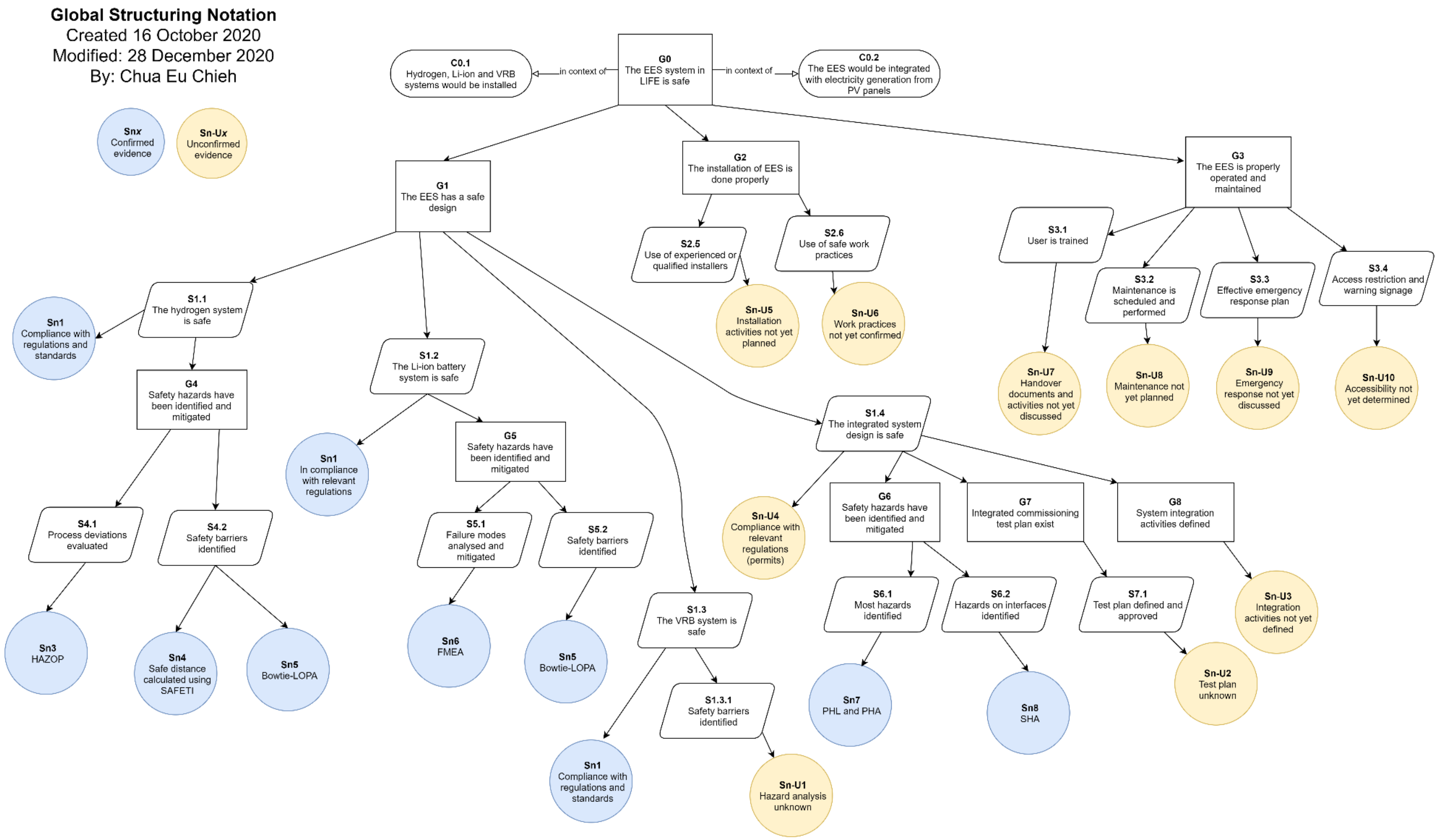


Figure 29 The Global Structuring Notation for LIFE's electrical energy storage systems. Table 33 provides a link between the solution (Sn#) with the specific mitigation detailed in this thesis. A solution with unconfirmed evidence is given the number (U#)

Table 33 Relation between GSN's Solution description with applied Mitigation

Sn #	Solution description	Hazard mitigation reference in the thesis
Hydrogen system design		
1	In compliance with relevant regulations and standards	Obtained certificate of conformity (CE) Refer to HF-1, 2, 4, 5, 6, 7, 8 and HT-1, 5 in Table 34.
3	Conducted HAZOP	HyGear's existing product development process
4	Calculated safe distance using SAFETI tool	Tebodin-Bilfinger's report
5	Conducted Bowtie-LOPA	See Appendix 8, page 187
Li-ion battery system design		
1	In compliance with relevant regulations and standards	Obtained certificate of conformity (CE)
5	Conducted Bowtie-LOPA	See Appendix 8, page 200
6	Conducted FMEA	SuperB's existing product development process
VRB system design		
1	In compliance with relevant regulations and standards	Obtained certificate of conformity (CE) Refer to VF-1 and VT-1,2
U1	Applied hazard analysis type is still unknown	Hazard type is yet unknown
Integrated system		
7	Conducted Preliminary hazards list and analysis (PHL and PHA)	See Appendix 3 and Appendix 4
8	Conducted System hazards analysis (SHA)	See Appendix 5.
U2	Integrated commissioning test plan defined and approved	Commissioning test plan not yet defined
U3	System integration activities defined	Integration activities not yet defined
U4	In compliance with relevant regulations	Permit obtained from the municipality
Installation and commissioning		
U5	Use of experienced or qualified installers	Installation activities not yet planned
U6	Use of safe work practices	Refer to Section 2.2.4, OSH regulations
Use and maintain		
U7	User is trained	Handover documents and activities not yet discussed
U8	Maintenance is scheduled and performed	Maintenance activities not yet discussed. Refer to HO-4,5; LO-5 and VO-2,4
U9	Effective emergency response plan	Emergency response not yet discussed. Refer to HO-1, LO-1,4 and VO-1. See Section 3.7.
U10	Authorised access and warning signage	Access and signage not yet discussed. Refer to HO-2,3; LO-2,3 and VO-3

Table 34 Compilation of mitigation types to support the GSN argument

Mitigation type	**Hydrogen systems**		**Li-ion battery systems**		**VRB systems**	
Functional	HF-1	Applicable regulations and standards	LF-1	Applicable regulations and standards	VF-1	Applicable regulations and standards
	HF-2	Joint integrity design	LF-2	Li-ion cell QA and QC		
	HF-3	Fire-resistance rating	LF-3	Battery room ventilation		
	HF-4	Proper construction materials and fabrication procedures	LF-4	Fire detection and suppression system		
	HF-5	Pressure relief devices	LF-5	Toxic and flammable gas detection		
	HF-6	Reliable electrolyser membrane	LF-6	Fire-rating of battery room		
	HF-7	Equipment for hazardous area classes	LF-7	Battery room ambient temperature controls		
	HF-8	Calculation of hazard distance	LF-8	Equipment for hazardous area classes		
Technical	HT-1	Equipment sitting outdoors	LT-1	Good Li-ion cell design	VT-1	Corrosion-resistant materials
	HT-2	Leak detection system	LT-2	BMS	VT-2	Leak detection and containment
	HT-3	Flame detectors	LT-3	Robust packaging		
	HT-4	Gas odourant				
	HT-5	Blast walls				
	HT-6	Guard rails				
Operational	HO-1	Emergency response plan	LO-1	Emergency response plan	VO-1	Emergency response plan
	HO-2	Restricted zones	LO-2	Authorised access	VO-2	Proper PPE
	HO-3	Warning signs	LO-3	Warning signs	VO-3	Warning signs
	HO-4	Perform preventive maintenance	LO-4	Post-fire recovery plan	VO-4	Perform preventive maintenance
	HO-5	Safe maintenance procedures (including PPE)	LO-5	Perform preventive maintenance		

The GSN clearly shows some safety goals lack demonstratable evidence (circle in beige), making the safety argument incomplete. Specifically, the following key findings were:

- There was insufficient information to confirm the type of hazard analysis techniques performed for the VRB system. However, because the Volterion VRB system is already marketed in Europe, it can be assumed that the 'CE mark' certification is available, implying that the product conforms to relevant regulations and standards.
- Safety for the integrated system has not yet been assured. The individual EESS would eventually be integrated with the PV electricity generation, the home energy management system and possibly the grid electricity supply. More hazards analysis might be required to understand risks arising from such integration. Furthermore, an integrated test plan for the entire LIFE project's commissioning has not yet been produced.
- Safety during construction and installation, operations and maintenance have not yet been assured.

The missing evidence for the installation, commissioning, use-and-maintain phases can be explained by the LIFE project's progress, which time where the details for these aspects is yet to be discussed. Nonetheless, these are essential safety aspects, and the thesis would make recommendations in the concluding chapter.

4 Discussion

In this section, the proposed approach and the outcome are evaluated.

4.1 Coverage of analysis

Almost half of the Hazards Tracker register's hazards were related to the 'Use' phase. A further 10% is related to 'Storage', arguably a subset of the 'Use' phase. Around 35% is applicable in all lifecycle phase of the EES while only 5% is related to the 'Design' or 'Dispose' phases. This could suggest an over-focus on the 'Use' phase while neglecting the other phases. However, concerns identified for the 'Use' phase should be translated into design considerations. Since the LIFE project is still at the Conceptual Design lifecycle phase, there is still design flexibility with an as-yet low committed cost.

The hazard analysis focus on EES systems, rather than all the system installed in the LIFE project, was a deliberate choice. These other systems - such as the electricity generation from PV panels, the building's civil structure, the water and heating systems - are not devoid of safety hazards. However, the familiarity of stakeholders in the housing sector with these hazards should mean that the risks have been mitigated reasonably well through standards, best practices and adherence to the relevant regulations.

When the proposed system safety approach was applied, the detailed design at the system-integration level was not yet finalised. As a result, many assumptions in the analysis need to be verified when further detailed-design data is available. The verification and the acceptance of the risk, which are Steps 5 and 6, would need to be formally conducted in the proposed system-safety approach. The Bowties, particularly the identified barriers, would need to be verified again after the design has been finalised.

4.2 The use and choice of the risk assessment matrix (RAM)

The choice of using the RAM from the MIL-STD-882E was explained in Section 3.3. The downsides of this choice are apparent. Firstly, references are made to asset damages, implying a value to human life. The latter makes it incompatible with some organization's and country's safety policy and culture. Secondly, the lack of 'Exposure' parameter does not allow for a lower risk category, whenever applicable. The RAM is also meant for use in the aerospace and military industry, making it challenging to expect broader adoption of it within the building or electrical energy storage sectors. The question then arises about what could be the most appropriate method for risk-scoring.

The response to that might be that no perfect solution exists. The ideal risk assessment method for projects would combine the needs of traditional sectors, such as the building industry, with emerging technology such as EESS might require a new tailor-made risk-assessment method. Yet, creating such a RAM would require considerable research efforts and also the consensus of the many stakeholders representing the technology type (e.g. hydrogen and batteries), system types (e.g. electrical systems and civil structures), and interested parties (e.g. the University management, EES provider, municipality and the homeowners).

The considerable challenges in developing an ideal RAM might be why [25] mentioned that a risk-based approach would remain an aspiration in assessing fire safety risks in buildings. Thus, the residential building sector's current practice relies much on prescriptive requirements, e.g. in the International Fire Code, the Dutch's Building Decree (*Bouwbesluit)*.

Thus, no matter which RAM or assessment method is adopted, a consistent scoring approach would enable identifying the most severe until the almost-negligible risks, a core purpose of a system-safety approach.

4.3 Choice of hazard assessment types

The six hazard assessment techniques applied in the approach, shown in Table 17, were Conceptual-design, Preliminary-design, and System-design assessment types. The techniques used by the Partners, namely the Failure Mode and Effect Analysis and HAZOP are Detailed-design type.

Missing from the proposed approach are three other hazard assessment types: the Operations-design, the Health design and the Requirements design types, leading to the possibility of some hazards not identified. [23] had recommended applying all seven hazard assessment types in a system safety analysis. This approach could, however, result in unnecessary efforts and complexity when used in the LIFE project. The question arises on what the right balance should be between analysis completeness and simplicity without over-analysis.

A possible response to that question is that since the EES systems used in the LIFE project are commercial-off-the-shelf (COTS) items, it can be expected that the respective LIFE Partners would have already conducted these assessments types during the detail design process. Supporting this argument is that operational procedures and manuals are available for the user, implying that Operations-design assessments have been performed. The 'CE' mark certification would also suggest that Human-health hazards present during the system production, use, maintenance and disposal have been identified and mitigated via proper engineering. Similarly, it is expected that the Requirements-type assessment, primarily to provide the traceability of safety requirements and assist in the closure of hazards, is part of the respective EES manufacturers' product design process.

Thus, it would be more beneficial to have a system integrator to collaborate closely with the EESS Partners to identify and manage all possible hazards without replicating the three remainder assessment types.

4.4 Rigour of the System-design analysis type

It had been mentioned that the System hazard analysis (SHA) and the Bowtie-LOPA were the two techniques used which fall under the category of the System-design analysis type. There are acknowledged limitations to the way the techniques were applied. For instance, Ericson recommends that the System hazards analysis (SHA) be applied during and after the detailed design to resolve subsystem interface problems [23]. The SHA should also investigate compliance with specified safety design criteria; possible independent, dependent and simultaneous hazardous events; and the common cause failures for the Safety Critical Functions (SCF).

Firstly, a detailed analysis of the Common-cause failures (CCFs) is missing from the current analysis. CCFs are significant and are also mentioned in ISO 12100 and IEC 61508. ISO 12100 defines CCFs as 'the failures of different items, resulting from a single event, where these failures are not consequences of each other [170]'. Ericson writes that this type of event exists in systems that rely on redundancy or uses identical components or software in multiple subsystems. For example, electrical power is a CCF source if multiple safety systems – such as the air ventilation system and gas detection systems - rely on the same power source. Another possible CCF source is the instantaneous ignition of hydrogen that can damage the emergency shutdown function and the hydrogen detection system simultaneously, severely undermining the effectiveness of the identified barriers. The CCFs should be investigated during the system integration's detailed design

4.5 Bowtie and LOPA analysis

4.5.1 Coverage of Bowties

A single Bowtie diagram was created to address one top event from the hydrogen and Li-ion battery systems. The Top Events were selected because these were the highest severity risk for each system. If time and resources permitting it would be beneficial to create Bowties for the remaining 'high/red' or 'serious/orange' hazards. Namely, these are for the hazards of pure oxygen in the hydrogen system, electricity-related hazards, and misuse or vandalism of the EES.

The Bowties could become a more effective safety management tool if they had included the barrier-preservation activities during the use-and-maintain phase and explicitly assigned the responsibility to carry out those activities [40]. These activities include maintenance, inspection and verification activities.

4.5.2 Uncertainties for the Initiating Event Frequencies (IEF) and the Probability of Failure on Demand (PFD) values

The majority of the IEF and PFD values were sourced from the Center for Chemical Process Safety (CCPS) LOPA handbooks [159, 160, 171]. As the institution's name suggests, the values are specifically meant the chemical process industry. It was reasoned that these values could be applied to analyse the EES systems because some components are common across the different sectors. For example, automatic gas fire-suppression systems and pressure relief valves are commonly used. Other barriers are conceptually simple enough that their designs are not expected to vary from one industry to another, for example, a physical anti-collision barrier and the siting of a hazardous facility or equipment.

An exact equivalent for the EES cannot be found in the CCPS LOPA handbooks for some cases. For example, it was assumed that the use of Lithium Iron Phosphate type battery could be credited with a risk-reduction of 100 times as per 'inherent safe design' criteria stated in the CCPS LOPA handbook. Another example is the IEF for the Li-ion battery overcharge or over-discharge causes, where no direct equivalent can be found in the CCPS LOPA handbook. IEF and PFD data was also picked from DNV-GL's study on Li-ion battery risk analysis [172]. However, these values could be considered less authoritative and need further verification, giving further analysis uncertainty.

To factor in the uncertainties of the selected IEF and PFD values, a more conservative number was chosen when a range of values is suggested. For instance, the CCPS LOPA (2001) handbook published the IEF for lightning strikes to be from 10^{-3} to 10^{-4}. The higher value was picked for the Bowtie-LOPA.

For an organisation implementing LOPA, using a specific value for the IEF and PFD is a management decision [159]. Further research efforts might be required to obtain more accurate data, perhaps data tailored explicitly for the use of EES systems in residential buildings. In the absence of such directly-obtainable data from existing literature, IEF values could be derived via Fault-Tree Analysis and using reliability information from equipment and component manufacturers. Similarly, the PFD of a system could be derived from reliability modelling. These activities are resource-intensive and thus was not performed in this thesis.

4.6 Hierarchy of precedence and the quantitative risk-reduction

The hierarchy of precedence was elaborated in Section 2.1.3. Table 35 shows its application in the context of LIFE's EESS systems with some examples of the identified safety barriers. Unsurprisingly, the risk-reduction capability by the different safety barriers used in LOPA is consistent with the principle in the hierarchy of precedence mentioned by Bahr, ISO Guidance Note 51 and MIL-STD-882E. For instance, the elimination of hazards and engineering design alteration receives a better (lower) probability-of-failure-on-demand (PFD) value than warning devices or procedural measures. Note that the PFD afforded by engineering design and safety devices is similar that afforded by Safety Instrumented Protection (SIL) levels 1 in IEC 61508-Part 1.

Table 35 Hierarchy of risk-reduction precedence

Order	Mitigation method	Description	Examples used in LIFE' EESS	Assigned PFD
1	Hazard elimination	Remove hazard through design or material alternatives	• Use of carbon steel tanks instead of composite tanks to store hydrogen • Cell design considerations – e.g.the use of lithium iron phosphate type instead of lithium cobalt oxide	- 0.1 or 0.01
2	Design alteration	Make design changes to reduce the severity of the mishap, or to reduce the probability of mishap occurring	• Storage of hazardous substance outdoors instead of indoors, to reduce the probability of indoor asphyxiation happening; Siting of equipment avoiding high-traffic zones • Use a robust cell casing material and design	0.01 0.01
3	Incorporate safety engineering features or devices	Introduces devices that reduce the severity of the mishap, or to reduce the probability of mishap occurring	• Installation of anti-collision barriers around storage tanks; Installation of adequate air ventilation system for indoor systems; Pressure relief devices on tanks • Use of a Battery Management System to monitor some battery parameters and provide some control to the charge and discharge process	0.01 0.01
4	Provide warning device	Alert personnel to the presence of a hazardous condition	• The installation of gas detectors and alarms – without connection to any automatic	1
5	Incorporate signage, procedures, training and personnel protective equipment.	Prepares personnel to manage the hazard. The sole use of this isolation method should be avoided.	• Emergency response and evacuation procedures • Inspection and replacement of aged battery cells	1

4.7 Standardised implementation of barriers

The suitability and safety requirements for installing EES systems in residential buildings need to be assessed on an individual project basis. While it is possible to generalise the hazards originating from hydrogen, Li-ion battery, and VRB systems, other factors influence such EES installations' system safety analysis. Some example of these factors are:

- the residential building type: For example, is the building type an apartment, a row-house, or a detached house which in turn determines the population density and the availability of space to place the EES equipment.
- If the building is an existing structure or new construction: The former is more limited in space flexibility, and may require extensive modifications to achieve the level of needed safety, for instance in the air ventilation and the safe distance requirements. The latter has more flexibility in designing customised solutions for the EES installations.
- EES type: The LIFE project has an on-site hydrogen production and storage facility, while there are possibilities that hydrogen is piped to a building, or delivered by trucks. There are also many variants of the Li-ion battery and VRB technology. For each option, different safety barriers might be required.

Because there is a range of options available to a building owner in setting up EESS, a guide might help the quick assessment of safety and suitability for installing an EES in a home. A simple 'yes/no' checklist can prompt the building owner (or builder) to agree with the EESS supplier on the required safety features and facility preparation responsibility. An abbreviated example of such a guideline for a Li-ion battery installation is shown in Table 36 with the complete checklist shown in Appendix 10.

A similar approach could be used for hydrogen systems.

Table 36 Excerpt of the proposed safety checklist

<table>
<tr><td colspan="7">Categories of concerns:</td></tr>
<tr><td colspan="7">➢ GENERAL CERTIFICATION</td></tr>
<tr><td colspan="7">➢ BATTERY SITING/LOCATION</td></tr>
<tr><td colspan="7">➢ SAFETY SYSTEMS FOR BATTERY ROOM / WORKSPACE</td></tr>
<tr><td colspan="7">➢ BATTERY ROOM ACCESS DURING USE</td></tr>
<tr><td colspan="7">➢ EMERGENCY RESPONSE DURING USE</td></tr>
<tr><td colspan="7">➢ INSTALLATION, USE, MAINTENANCE AND DECOMMISSIONING ACTIVITIES</td></tr>
<tr><td colspan="7">➢ BATTERY MANAGEMENT SYSTEM FEATURES</td></tr>
<tr><td rowspan="2">No.</td><td rowspan="2">Safety barrier categories</td><td colspan="2">Applicability to installed system</td><td colspan="2">Responsibility</td><td rowspan="2">Remarks / Notes</td></tr>
<tr><td>No</td><td>Yes</td><td>EESS Supplier</td><td>Homeowner / builder</td></tr>
<tr><td colspan="7">Example checklist:</td></tr>
<tr><td>#</td><td>CE label for the complete battery installation, including external protection circuits, charge controllers, etc.</td><td>☐</td><td>☒</td><td>☐</td><td>☒</td><td></td></tr>
<tr><td>#</td><td>Flood risk</td><td>☒</td><td>☐</td><td>☐</td><td>☒</td><td></td></tr>
<tr><td>#</td><td>Air ventilation system</td><td>☐</td><td>☒</td><td>☒</td><td>☒</td><td></td></tr>
<tr><td>#</td><td>Implementation of maintenance and inspection</td><td>☐</td><td>☒</td><td>☒</td><td>☒</td><td>Joint responsibility.</td></tr>
</table>

5 Conclusion and recommendations

This thesis set out to analyse the safety hazards of the EES systems that will be installed in the LIFE project at the University of Twente. The four research questions are restated below:

1. What could be the LIFE project's possible safety goals according to applicable regulations, codes, and standards (RCS)?
2. What approach could be used to identify all the hazards in an integrated EES system such as in LIFE?
3. How to demonstrate that the residual/mitigated risk is acceptable?
4. What are the top five concerns to be heeded by the fire brigade personnel when responding to safety incidences related to batteries and hydrogen system used in the LIFE project?

Based on the conducted literature review and the discussions with various LIFE EESS project Partners, the following conclusions were made:

In addressing the first question, the thesis affirmed the safety concerns around EES in residential buildings. EESS use is a nascent but fast-growing market. Installed capacity has increased rapidly in the last ten years, driven by the need to diversify away from fossil fuel-based energy sources. As such, the industry stakeholders in many countries are currently working on amending or updating the relevant regulations and standards to support and encourage the safe and faster adoption of EES technology.

The safety goals for EESS installation in residential buildings should be consistent with what is acceptable within the existing Dutch regulations. Currently, regulations related to EES technology in residential buildings in the Netherlands are either too strict in the case of hydrogen technology – or not restrictive enough in the case of battery installations.

For the hydrogen system, the classification of hydrogen as a hazardous product and hydrogen production as an industrial process under the relevant regulations had resulted in the need for rigorous hazard analysis and strict environmental and permitting requirements. A formal quantitative risk assessment (QRA) was requested by the municipality of Enschede, even though the quantity of hydrogen stored in the LIFE project does not exceed the lower-tier requirement in Part 2, Annex 1 of the SEVESO III directive, currently set at 5000 kg. The QRA has the benefit of ensuring that the hydrogen system conforms to society's expectation of safety, but the downside is a more protracted and expensive permitting process.

For the battery systems, the Enschede municipality regulations currently do not prescribe specific homeowners' requirements to install Li-ion battery or VRB systems. The Dutch Building Decree (*Bouwbesluit*) also does not mention particular provisions related to the use of hydrogen, Li-ion battery or VRB systems. This situation brings safety risks if unsafe systems are installed. The publication of new standards and guidelines for home batteries (*buurtbatterijen*) in the coming years should mitigate this concern.

In addressing the second question, the thesis had proposed a system-safety management approach for EES systems that are intended to be installed in residential homes. The analysis reaffirmed the most-severe risks for the respective EES systems, which are mentioned in various literature. In particular, hydrogen systems brings the risk of fire and explosions; Li-ion battery systems also carry the risk of fire; for VRB systems is the risk of contact with corrosive electrolyte.

The primary safety barriers, termed as 'Safety-critical items' (SCIs) were identified during the analysis. As noted by Hyresponse' hydrogen safety educational materials for first responders [84, 85, 88, 91, 104, 106, 112, 161, 173], the SCIs for hydrogen systems for the LIFE project are: the integrity of the pressurised hydrogen-containing equipment, the determination of the safe/hazard distance, the placement of hydrogen equipment outdoors, the proper design of air ventilation system for indoor equipment, and precautions during maintenance and operations. For the Li-ion battery system, research by DNV-GL [130, 131, 172] and the fire-safety agencies [66, 129, 174] it is the prevention of thermal-runaway phenomenon through the proper cell design and production, the use of an external electrical protection system, and the adequate air ventilation in the battery room to prevent an explosive environment from forming. The exact requirements would depend, naturally, on the installed battery capacity. For the VRB system, it is the ability to contain the corrosive electrolyte safely [147]. A common safeguard applicable across all three EES types is establishing operational, maintenance and emergency response procedures.

The exact specifications for the SCIs – i.e. for the ventilation system, the safe/hazards distance, the placement of gas detectors – needs to be worked and calculated using the relevant engineering tools. The LIFE Project Partners should be able to provide guidance and recommendations. When the SCIs were applied in the Bowtie and LOPA, the mitigated risk for hydrogen and Li-ion battery systems were approximated to be almost similar to the yearly odds of dying from sunstroke and lightning strikes in the United States, respectively shown in Figure 9. These messaging could perhaps be used in allying fears of the public towards adopting EES technology.

In addressing the third question, the thesis provided a hypothetical example of how risk could be quantitatively estimated, and ALARP levels achieved for EESS in residential buildings. The ALARP concept is used in many countries and international standards such as IEC 61508, but not used in the Netherlands because threshold values for risk-acceptability exist under Dutch regulations. Furthermore, a challenge in applying ALARP lies in assigning a 'disproportionate' value of averting a fatality. A conclusion would be to avoid using ALARP principles altogether when evaluating the EESS risks, and instead, aim to reduce the residual likelihood of fatality within acceptable levels.

In addressing the fourth question, the thesis made recommendations following a few knowledge sharing sessions with the Twente Fire Brigade. The fire brigade members are well aware of hazards from hydrogen and Li-ion batteries and have guidelines on dealing with safety incidences involving such technology. A 'top-five' list of concerns is meant to guide the LIFE project team to create a safer design.

The question arises of just how practical the proposed system-safety approach would be in an actual residential building construction project. While the system-safety steps are straight-forward, the analysis efforts can be considerable if started with a blank page. However, it is expected that many of the EES systems would be in the form or commercial-off-the-shelf (COTS) items where the manufacturer would vouch for the safety of their respective systems. In this situation, the homeowners or building construction companies would be responsible for the safe integration of the purchased EES system with perhaps other renewable energy generators.

Thus as a final conclusion point, the thesis suggests that the management of EES safety hazards in residential buildings can be made easier for implementation by codifying many safety requirements into prescriptive regulations and standards. To achieve this, all the relevant stakeholders, such as the EES manufacturers, installers, building construction companies, municipal, homeowners, fire brigade, might be required to clarify and agree on

- a streamlined and consistent permitting process
- the applicable regulations and standards
- an explicit mentioning of the necessary fire-safety engineering calculations, where applicable
- the mandatory and optional safety barriers
- the assignment of responsibilities for installation, operation and maintenance of the EES systems.
- a more prescriptive requirement for electrical safety
- the criteria for system tests during installation
- the mandatory and recommended documentation required for handover from the EES manufacturers to the homeowners.

This proposal is consistent with Hagen and Witlok's view[25] (described in Section 2.2, page 23) on the 75/25 split between managing fire-safety risk using rules, codes, and standards the application of fire-safety engineering on the high-risk cases.

5.1 Recommendations for the LIFE Project

Building on the outcome of the system-safety approach that has been applied, the author makes the following recommendations for the LIFE project.

1. **Track to closure all the hazard with 'Open' status:**
   - In the Hazard Tracker Register, forty-four entries require resolution. These need to be tracked as the project progresses.
   - Re-assess the Bowtie-LOPA after the integrated design has been completed. The mitigated risks could be different from the initial analysis as design changes occur.
   - Safety hazards, in all probability, would appear during the design integration. The analysis of such hazards has not yet been done, as shown in the GSN (Section 3.8). Failure Mode and Effect Analysis (FMEA) technique could be used for such an analysis.
   - Safety hazards during the construction, commissioning, use, maintain, and disposal phases have been mentioned in this thesis, but the mitigation efforts need to be further developed.

2. **Appoint the role of a LIFE system integrator**
    - The EESS project partners are responsible for delivering a safe product, but the ultimate responsibility for safety lies with the University of Twente. It was clear from the GSN (Section 3.8) that numerous safety issues could arise from integrating EESS with other LIFE systems. The role of the system integrator is to ensure that these interface concerns are managed well.

3. **Consider incorporating the recommendations from the first-responder guidelines.** These are:
    - Install and make visible the appropriate signage, where the EES systems are located. The signage should explicitly show the EES type and the hazards that are present. Some examples of the signage are shown in Appendix 11.
    - Technical documentation on the EESS should be easily accessible for first responders. The University of Twente's labs has a safety-information sheet placed outside the lab, which contains relevant information on the hazardous activities and substances found in the lab, and the details of a contact person in the case of an emergency [175]. A similar form can be used for the LIFE facilities.
    - Ensure that the guidelines are consistent with the University of Twente's existing safety management and emergency response procedures. Where applicable, the drafted guidelines should be incorporated into the University's emergency response procedures.
    - A hydrogen gas detection and warning system should be installed for hydrogen-related equipment placed indoors. A similar toxic gas (HCl, CO and HF) detection and warning system should be installed for the battery room. Ideally, there should be a way to indicate to first-responders outside the building if hydrogen or toxic gases are present indoors. This could be implemented, for instance, by installing a warning light, or a differentiated siren, or indicating on an external user panel (if such a system exists).
    - During an emergency scenario, the hydrogen system's hazard distance should be ascertained and stated on the aforementioned safety-information notice. As stated by [104], this can be determined by physical or numerical modelling, or by regulation. Monograms developed by some researchers, such as shown in Appendix 13, could also be used. The scenarios that need to be considered are for unignited gas release, ignited gas release (micro-flame, jet fire or a fireball), and detonation.

4. **Conduct a mock exercise for an emergency response involving the EES systems after completing the LIFE construction.** The mock exercise assesses the safeguards' effectiveness and adequacy in the LIFE project and identifies further areas for improvement. These include, but not limited to the first-responder guidelines, fire-fighting infrastructure and emergency response and evacuation preparedness and procedures.

List of references

[1] Schmid Group. "VRBF Operating Principle." https://schmid-group.com/en/business-units/energy-systems/vrfb-technology/vrfb-operating-principle/ (accessed August, 2020).

[2] Office of Energy Efficiency & Renewable Energy. "Hydrogen and Fuel Cell Technologies Office." US Department of Energy. https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office (accessed 23 November, 2019).

[3] Statistics Netherlands (CBS). "Share of renewable energy up to 7.4 percent." https://www.cbs.nl/en-gb/news/2019/22/share-of-renewable-energy-up-to-7-4-percent (accessed 28 November, 2019).

[4] Statistics Netherlands (CBS). "More wind and solar electricity." https://www.cbs.nl/en-gb/news/2018/09/more-wind-and-solar-electricity (accessed.

[5] M. Londo, R. Matton, O. Usmani, M. van Klaveren, C. Tigchelaar, and S. Brunsting, "Alternatives for current net metering policy for solar PV in the Netherlands: A comparison of impacts on business case and purchasing behaviour of private homeowners, and on governmental cost," *Renewable Energy,* vol. 147, no. 2020, pp. 903 - 915, 2019.

[6] E. Bellini, "Netherlands to replace net metering with new scheme for residential, commercial PV," ed: pv magazine, 2018.

[7] R. A. Huggins, *Energy storage: fundamentals, materials and applications*. Springer, 2016.

[8] M. Aneke and M. Wang, "Energy storage technologies and real life applications–A state of the art review," *Applied Energy,* vol. 179, pp. 350-377, 2016.

[9] A. Delsaux, K. Emmett, M. van Leeuwen, C. Korinthios, D. Assimakis, and A. Belisaire, "Regulatory progress for energy storage in Europe," March 2019. [Online]. Available: https://www.nortonrosefulbright.com/en/knowledge/publications/8b5285f4/regulatory-progress-for-energy-storage-in-europe#section6

[10] C. V. Burg, M. McDonagh, and J. Shepherd. (2019, August) Are lithium batteries on safe foundations? *BestMag Batteries & Energy Storage Technology*. 14-15, 39-54, 57-59.

[11] Bureau for Analysis of Industrial Risks and Pollutions (BARPI), "Accidents involving hydrogen," in "ARIA : Feedback on technological accidents," 2009. [Online]. Available: https://www.aria.developpement-durable.gouv.fr/synthese/analyses-and-feedback/accidentology-involving-hydrogen/?lang=en

[12] Organisation for Economic Co-operation and Development (OECD) and J. R. Shelton, *The OECD report on regulatory reform*. Paris: OECD, 1998.

[13] European Commission. "Electricity market design." https://ec.europa.eu/energy/topics/markets-and-consumers/market-legislation/electricity-market-design_en (accessed July, 2020).

[14] W. D. Eggers, M. Turley, and P. Kishnani, "The future of regulation - Principles for regulating emerging technologies," in "Deloitte Centre for Government Insights," Deloitte, 2018. [Online]. Available: https://www2.deloitte.com/us/en/insights/industry/public-sector/future-of-regulation/regulating-emerging-technology.html

[15] N. Gupta, A. R. H. Fischer, and L. J. Frewer, "Socio-psychological determinants of public acceptance of technologies: A review," *Public Understanding of Science,* vol. 21, no. 7, pp. 782-795, 2012, doi: 10.1177/0963662510392485.

[16] N. J. Bahr, *System SafetyEngineering and RiskAssessment - A Practical Approach*, Second ed. CRC Press, 2015, p. 436.

[17] *NEN-EN-ISO 9000 Quality management systems – Fundamentals and vocabulary*, International Organization for Standardization (ISO), 2015.

[18] B. S. Blanchard and W. J. Fabrycky, *Systems engineering and analysis*, 5 ed. Pearson, 2014.

[19] Cambridge Online Dictionary. "Meaning of 'safety' in English." https://dictionary.cambridge.org/dictionary/english/safety (accessed 9 April, 2020).
[20] T. Aven, "What is safety science?," *Safety Science,* vol. 67, pp. 15-20, 2014, doi: 10.1016/j.ssci.2013.07.026.
[21] *Guide 51 Safety aspects — Guidelines for their inclusion in standards*, International Organization for Standardization (ISO), 2014.
[22] *NEN-ISO 31000 Risk management - Guidelines*, International Organization for Standardization (ISO), 2018.
[23] C. A. Ericson, *Hazard Analysis Techniques for System Safety*. Fredericksburg, VA: John Wiley & Sons, 2005, p. 495.
[24] *MIL-STD-882E System Safety*, United States Department of Defense, 2012.
[25] R. Hagen and L. Witloks, *Basis for Fire Safety - Substantiating fire protection in buildings*. Instituut Fysieke Veiligheid (IFV), 2018.
[26] W. M. K. Trochim, "Deduction & Induction," *vol. 2020*, *Research Methods Knowledge Base*, D. Cirillo, Ed., Sydney, Australia: Conjoint.ly. [Online]. Available: https://conjointly.com/kb/deduction-and-induction/#:~:text=In%20logic%2C%20we%20often%20refer,general%20to%20the%20more%20specific.&text=Inductive%20reasoning%20works%20the%20other,to%20broader%20generalizations%20and%20theories.
[27] C. Peace, "The risk matrix: uncertain results?," *Policy and Practice in Health and Safety,* vol. 15, no. 2, pp. 131-144, 2017/07/03 2017, doi: 10.1080/14773996.2017.1348571.
[28] M. Oturakci, C. Dağsuyu, and A. Kokangul, "A New Approach to Fine Kinney Method and an Implementation Study," *Alphanumeric Journal,* vol. 3, no. 2, 9/2015 2015, doi: 10.17093/aj.2015.3.2.5000139953.
[29] Euronorm BV. "Fine & Kinney method." https://www.euronorm.net/content/ce-marking/category/risk-analysis/fine-and-kinney-method.php (accessed December, 2020).
[30] *NPR-ISO Guide 73 Risk management — Vocabulary*, International Organization for Standardization (ISO), 2009.
[31] R. Bell, "Safety critical systems - A brief history of the development of guidelines and standards," Engineering Safety Consultants, 2017. [Online]. Available: http://esc.uk.net/resources/safety-critical-systems-a-brief-history-of-the-development-of-guidelines-and-standards/
[32] International Electrotechnical Commission (IEC). *Functional_safety brochure IEC 61508*. (2015). [Online]. Available: https://www.iec.ch/functionalsafety/explained/
[33] M. Rajabalinejad, L. van Dongen, and M. Ramtahalsing, "Systems integration theory and fundamentals," *Safety and Reliability,* vol. 39, no. 1, pp. 83-113, 2020, doi: 10.1080/09617353.2020.1712918.
[34] B. Ale, "Tolerable or Acceptable: A Comparison of Risk Regulation in the United Kingdom and in the Netherlands," (in eng), *Risk Analysis,* vol. 25, no. 2, p. 231, 2005.
[35] SKYbrary, "Acceptable Level of Safety," EUROCONTROL, Ed. [Online]. Available: https://www.skybrary.aero/index.php/Acceptable_Level_of_Safety#:~:text=The%20term%20%22acceptable%20risk%22%20describes,that%20the%20event%20might%20bring
[36] L. Gooijer, N. Cornil, and C. L. Lenoble, "An international comparison of four quantitative risk assessment approaches - Benchmark study based on a fictitious LPG plant," National Institute of Public Health and the Environment (RIVM), 620552001/2011, 2011. [Online]. Available: https://www.rivm.nl/bibliotheek/rapporten/620552001.pdf
[37] J. J. Bommer, H. Crowley, and R. Pinho, "A risk-mitigation approach to the management of induced seismicity," *Journal of Seismology,* vol. 19, no. 2, pp. 623-646, 2015.
[38] J. L. Saw *et al.*, "Societal risk: initial briefing to societal risk technical advisory group," 2009.

[39] SKYbrary. "Risk Assessment." https://www.skybrary.aero/index.php/Risk_Assessment# (accessed 5 July, 2020).
[40] CGE Risk Management Solutions B.V. (2015). BowtieXP Methodology Manual.
[41] Research Safety Management Solutions Group, *Injury facts*. National Safety Council, (in English), 2017.
[42] Risktec Solutions Ltd., "Risk-based Decision Making and ALARP," *Risktec Essentials*, vol. 3. [Online]. Available: https://www.risktec.tuv.com/
[43] J. Inge, "The safety case, its development and use in the United Kingdom," in *Equipment Safety Assurance Symposium 2007*, 2007. [Online]. Available: http://safety.inge.org.uk/20071115-Inge2007a_The_Safety_Case-U.pdf. [Online]. Available: http://safety.inge.org.uk/20071115-Inge2007a_The_Safety_Case-U.pdf
[44] N. G. Leveson, "The use of safety cases in certification and regulation," Massachusetts Institute of Technology, ESD-WP-2011-13, 2011. [Online]. Available: https://dspace.mit.edu/handle/1721.1/102833
[45] European Commission. "CE marking." European Commission. https://ec.europa.eu/growth/single-market/ce-marking_en (accessed November, 2019).
[46] J. B. Saffers and V. V. Molkov, "Hydrogen safety engineering framework and elementary design safety tools," *International Journal of Hydrogen Energy,* vol. 39, no. 11, pp. 6268-6285, 2014, doi: 10.1016/j.ijhydene.2013.06.060.
[47] Communication department of the European Commission. "Regulations, Directives and other acts." https://europa.eu/european-union/law/legal-acts_en (accessed November, 2019).
[48] National Fire Protection Association (NFPA). "Reporter's Guide: About codes and standards." https://www.nfpa.org/News-and-Research/Publications-and-media/Press-Room/Reporters-Guide-to-Fire-and-NFPA/About-codes-and-standards (accessed November, 2019).
[49] European Committee for Standardization (CEN). "European Standards." https://www.cen.eu/work/products/ENs/Pages/default.aspx (accessed November, 2019).
[50] CEN/CENELEC. "What is a European Standard (EN)?" https://www.cencenelec.eu/standards/DefEN/Pages/default.aspx (accessed November, 2019).
[51] *NPR-CEN-ISO/TR 22100-1 Safety of machinery - Relationship with ISO 12100 - Part 1: How ISO 12100 relates to type-B and type-C standards*, International Organization for Standardization (ISO), 2015.
[52] F. Laumann, F. Verbecke, A. Duclos, A. Zanoto, and L. Zhiyong, "Description of selected FCH systems and infrastructure, relevant safety features and concepts," HyResponse, 2015. [Online]. Available: http://www.hyresponse.eu/public_deliverables/D2.1%20Description%20of%20selected%20FCH%20systems%20and%20infrastructure%20relevant%20safety%20features%20and%20concepts.pdf
[53] Hydrogen Europe. HyLAW Online Database [Online] Available: https://www.hylaw.eu/about-hylaw
[54] J. P. van der Meer, R. Perotti, and F. de Jong, "National Policy Paper - Netherlands," in "HyLAW," Hydrogen Europe, 2018. [Online]. Available: https://www.hylaw.eu/sites/default/files/2019-03/HyLAW_National%20Policy%20Paper_Netherlands.pdf
[55] W. e. S. Ministerie van Volksgezondheid. "Rijksinstituut voor Volksgezondheid en Milieu." https://www.rivm.nl/en (accessed.
[56] Rijkswaterstaat. "Kenniscentrum InfoMil." Ministerie van Infrastructuur en Waterstaat. https://www.infomil.nl/ (accessed November, 2019).
[57] BRZO.nu. "Wat is een BRZO bedrijf?" https://brzo.nu/wat-is-een-brzo-bedrijf/ (accessed November, 2019).

[58] Fuel Cell & Hydrogen Energy Association (FCHEA). "Codes & Standards." http://www.fchea.org/rcs3 (accessed August, 2020).
[59] S. Nilsen *et al.*, "Determination of hazardous zones for a generic hydrogen station–a case study," in *2nd International Conference on Hydrogen Safety, San Sebastian, Spain*, 2007, pp. 11-13.
[60] Eaton Crouse-Hinds. *Principles of Ex-Protection*. (2017). [Online]. Available: https://www.crouse-hinds.de/en/principles-of-explosion-protection/
[61] Publicatiereeks Gevaarlijke Stoffen (PGS), *PGS 3 Guidelines for quantitative risk assessment (Purple Book)*. VROM, 2005.
[62] (2005). *PGS 3-Guidelines for quantitative risk assessment (Purple Book)*.
[63] PGS, "PGS 15 Opslag van verpakte gevaarlijke stoffen," in "Publicatiereeks Gevaarlijke Stoffen," 2016.
[64] S. Ugarte *et al.*, "Energy storage: which market designs and regulatory incentives are needed," in "European Parliament Committee on Industry, Research and Energy: Brussels, Belgium," 2015. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/STUD/2015/563469/IPOL_STU(2015)563469_EN.pdf
[65] European Association for the Coordination of Consumers Representation in Standardisation (ANEC). "Domestic Appliances." https://anec.eu/priorities/domestic-appliances (accessed May, 2020).
[66] R. Verboom, J. Middelkoop, H. Spobeck, P. Aantjes, and J. Middelkoop. IFV, VRH, VRR, and LIOGS. (2019). Handreiking Elektriciteit Opslag Systemen (EOS > 25 kWh Li-ION).
[67] *2018 International Fire Code (IFC)*, International Code Council, 2017.
[68] A. Price, Ed. *Battery storage guidance note 1: Battery storage planning*. London: Energy Institute, 2019. [Online]. Available: https://publishing.energyinst.org/topics/power-generation/battery-storage/battery-storage-guidance-note-1-battery-storage-planning.
[69] European Commission, "Evaluation of the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC," 9 April 2019 2019. [Online]. Available: https://ec.europa.eu/environment/waste/batteries/evaluation.htm
[70] G. Desmet, P. Vermeyen, and R. Belmans, "Overview of regulations for electrical safety in European residential buildings," in *Proceedings of the 3rd in Electrical Power Engineering IEEE Benelux Young Researchers Symposium*, 2006.
[71] *Bouwbesluit*, 2012.
[72] Rijksoverheid. "Bouwbesluit 2012." (https://www.rijksoverheid.nl/onderwerpen/bouwregelgeving/bouwbesluit-2012 (accessed October, 2020).
[73] Netherlands Focal Point (NL-FOP) for EU-OSHA. "Dutch Working Conditions Legislation." European Agency for Safety and Health at Work (EU-OSHA). https://www.arboineuropa.nl/en/legislation/wetgeving-in-het-engels/ (accessed August, 2020).
[74] University of Twente. "Protocols and Guidelines." https://www.utwente.nl/en/intranet/crisis/protocols-and-guidelines/ (accessed 2020).
[75] B. Kolodziejczyk and W.-L. Ong, "Hydrogen power is safe and here to stay," *World Economic Forum Agenda*. [Online]. Available: https://www.weforum.org/agenda/2019/04/why-don-t-the-public-see-hydrogen-as-a-safe-energy-source/#:~:text=One%20major%20reason%20is%20the%20public%20perception%20of%20hydrogen%20safety.&text=Among%20those%20who%20believed%20hydrogen,thought%20it%20was%20very%20dangerous.

[76] K. Itaoka, A. Saito, and K. Sasaki, "Public perception on hydrogen infrastructure in Japan: influence of rollout of commercial fuel cell vehicles," *International Journal of Hydrogen Energy,* vol. 42, no. 11, pp. 7290-7296, 2017.
[77] P. Ruiz, C. Jiménez, M. Llorca, and L. F. Vega, *Hydrogen: applications and safety considerations* (H2 TRUST project). Barcelona, Spain: MATGAS 2000 AIE, 2015, p. 200.
[78] The Editors of Encyclopaedia Britannica, "Hindenburg," ed: Encyclopædia Britannica, 2019.
[79] International Association for Hydrogen Safety. HySafe incident sharing [Online] Available: https://hysafe.info/category/accident/
[80] European Commission. Hydrogen Incident and Accident Database 2.0 (HIAD) [Online] Available: https://odin.jrc.ec.europa.eu/giada/Main.jsp
[81] Y. Suwa, H. Miyahara, K. Kubo, K. Yonezawa, Y. Ono, and K. Mikoda, "Design of safe hydrogen refueling stations against gas-leakage, explosion and accidental automobile collision," in *Proceedings of the 16th World Hydrogen Energy Conference*, 2006, vol. 139: Citeseer.
[82] B. Decourt, B. Lajoie, R. Debarre, and O. Soupa, "The hydrogen-based energy conversion FactBook," *The SBC Energy Institute,* 2014.
[83] J. Hord, "Is hydrogen a safe fuel?," *International journal of hydrogen energy,* vol. 3, no. 2, pp. 157-176, 1978.
[84] S. Tretsiakova-McNally and D. Makarov. HyResponse. (2016). Lecture – Hydrogen properties relevant to safety. Available: http://www.hyresponse.eu/training-mat-1.php
[85] S. Tretsiakova-McNally and D. Makarov. HyResponse. (2016). Lecture – Hazards of hydrogen use indoors. Available: http://www.hyresponse.eu/training-mat-1.php
[86] L. C. Cadwallader and H. Zhao, "Personnel safety with pressurized gas systems," *Process Safety Progress,* vol. 35, no. 4, pp. 330-336, 2016.
[87] UK Health and Safety Executive. *Take care with oxygen*. (2008). UK Health and Safety Executive. [Online]. Available: https://www.esfrs.org/EasySiteWeb/GatewayLink.aspx?alId=789#:~:text=The%20dangers%20are%20fire%20and,such%20as%20oil%20and%20grease).
[88] S. Tretsiakova-McNally and D. Makarov. HyResponse. (2016). Lecture - Harm criteria for people and environment, damage criteria for structures and equipment. Available: http://www.hyresponse.eu/training-mat-1.php
[89] NACE International. "Hydrogen Embrittlement." National Association of Corrosion Engineers. https://www.nace.org/resources/general-resources/corrosion-basics/group-3/hydrogen-embrittlement (accessed November, 2019).
[90] The Welding Institute (TWI). "What is high temperature hydrogen attack (HTHA)/hot hydrogen attack?" The Welding Institute (TWI). ttps://www.twi-global.com/technical-knowledge/faqs/what-is-high-temperature-hydrogen-attack-htha-hot-hydrogen-attack (accessed November, 2019).
[91] S. Tretsiakova-McNally and D. Makarov. HyResponse. (2016). Lecture – Safety of hydrogen storage. Available: http://www.hyresponse.eu/training-mat-1.php
[92] UK Health and Safety Executive (HSE). "Electrical standards and approved codes of practice." https://www.hse.gov.uk/electricity/standards.htm (accessed August, 2020).
[93] M. Cotterell *et al.*, *Code of practice for electrical energy storage systems* (IET Standards). The Institution of Engineering and Technology (IET), 2017.
[94] HyResponse. "European hydrogen emergency response training program for first responders." HyResponse. http://www.hyresponse.eu/about-hyresponse.php?LMCL=mzAz0p (accessed 2020).
[95] Hydrogen Tools (H2 Tools). "Best practices." Pacific Northwest National Laboratory. https://h2tools.org/bestpractices/best-practices-overview (accessed 2019).

[96] J. d. Bruin *et al.*, "Impact of Sustainable Gases on Joints used in Gas Distribution Networks – Literature Review," Kiwa N.V., 2012.
[97] V. A. Kunte and S. Pareek, "Safety in design during piping engineering," *Hydrocarbon Processing*, February 2018. [Online]. Available: https://www.hydrocarbonprocessing.com/magazine/2018/february-2018/environment-and-safety/safety-in-design-during-piping-engineering
[98] *ISO 19880 - Gaseous hydrogen — Fuelling stations — Part 1: General requirements*, International organization for Standardization (ISO), 2020.
[99] *API Recommended Practice 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry*, American Petroleum Institute, Washington, 2011.
[100] *API 510 Pressure Vessel Inspection Code: In-service Inspection, Rating, Repair, and Alteration*, American Petroleum Institute, 2014.
[101] N. C. Menon, A. M. Kruizenga, K. J. Alvine, C. San Marchi, A. Nissen, and K. Brooks, "Behaviour of polymers in high pressure environments as applicable to the hydrogen infrastructure," in *Pressure Vessels and Piping Conference*, 2016, vol. 50435: American Society of Mechanical Engineers, p. V06BT06A037.
[102] J. Hodges, W. Geary, S. Graham, P. Hooker, and R. Goff, "Injecting hydrogen into the gas network–a literature search," Health and Safety Laboratory, Buxton, 2015.
[103] P. Millet, A. Ranjbari, F. De Guglielmo, S. Grigoriev, and F. Auprêtre, "Cell failure mechanisms in PEM water electrolyzers," *international journal of hydrogen energy,* vol. 37, no. 22, pp. 17478-17487, 2012.
[104] S. Tretsiakova-McNally and D. Makarov. HyResponse. (2016). Lecture – Introduction to FCH applications and hydrogen safety. Available: http://www.hyresponse.eu/files/Lectures/Introduction_to_FCH_applications_and_hydrogen_safety_notes.pdf
[105] H.-J. Linström and J. Buhn. *Basic concepts for explosion protection*. (2018). Bartec.
[106] S. Tretsiakova-McNally and D. Makarov. HyResponse. (2016). Lecture - Hydrogen fires. Available: http://www.hyresponse.eu/training-mat-1.php
[107] J. LaChance, W. Houf, B. Middleton, and L. Fluer, "Analyses to support development of risk-informed separation distances for hydrogen codes and standards," in "Sandia Report SAND2009-0874," 2009.
[108] D. P. DK and W. Rattigan, "Hazards of liquid hydrogen," in "UK Health and Safety Laboratory," 2010.
[109] D. K. Pritchard, M. Royle, and D. Willoughby, "RR 715 Installation permitting guidance for hydrogen and fuel cell stationary applications: UK version," Health and Safety Executive (HSE), 2009.
[110] S. Tretsiakova-McNally and D. Makarov. HyResponse. (2016). Lecture - Unignited hydrogen releases, their prevention and mitigation. Available: http://www.hyresponse.eu/training-mat-1.php
[111] I. Azkarate *et al.*, "Research Priority Workshop on Hydrogen Safety," Joint Research Centre, Petten, NL, 2018. [Online]. Available: https://hysafe.info/wp-content/uploads/2018/05/2016_JRC111028_report_rpw_2016_2018-03-20_final.pdf
[112] S. Tretsiakova-McNally and D. Makarov. HyResponse. (2016). Lecture - Sources of hydrogen ignition and prevention measures. Available: http://www.hyresponse.eu/training-mat-1.php
[113] Y. S. Najjar and S. Mashareh, "Hydrogen leakage sensing and control," *Biomedical Journal of Scientific & Technical Research,* vol. 21, no. 5, pp. 16228-16240, 2019.

[114] Occupational Safety and Health Administration (OSHA). "Hydrogen: Fire and Explosion." United States Department of Labor. https://www.osha.gov/dep/greenjobs/hydrogen_fire.html (accessed 2020).
[115] T. Nozu, R. Tanaka, T. Ogawa, K. Hibi, and Y. Sakai, "Numerical simulation of hydrogen explosion tests with a barrier wall for blast mitigation," in *Proceedings of the 1st International Conference on Hydrogen Safety, September*, 2005, pp. 8-10.
[116] Safety Advisory Group. *Safety Training Leaflet 07 Hydrogen*. (2018). Brussels. [Online]. Available: https://www.eiga.eu/nc/publications/eiga-documents/doc-230718-hydrogen/?sword_list%5B%5D=hydrogen
[117] Air Liquide. *Safety Data Sheet for Compressed Hydrogen Gas*, 2020. [Online]. Available: http://alsafetydatasheets.com/download/se/Hydrogen_compressed-SE_ENG.pdf.
[118] V. Molkov, *Fundamentals of Hydrogen Safety Engineering (Part 1)* (free download e-book). www.bookboon.com, 2015, p. 216.
[119] FAA Office of Security and Hazardous Materials Safety, "Events with Smoke, Fire, Extreme Heat, Or Explosion Involving Lithium Batteries," 2 August 2020. [Online]. Available: https://www.faa.gov/hazmat/resources/lithium_batteries/media/Battery_incident_chart.pdf
[120] G. Hare, "Lithium Batteries - What's the problem?," Fire and Emergency New Zealand, Wellington, NZ, 2019.
[121] J. Deign. (2017, 18 December 2017) Engie Investigates Source of Belgian Battery Blaze. *Energy Storage*. Available: https://www.greentechmedia.com/articles/read/engie-investigates-source-of-belgian-battery-blaze#gs.4ff3n1
[122] Arizona Public Service Electric (aps). "McMicken investigation." https://www.aps.com/en/About/Our-Company/Newsroom/Articles/Equipment-failure-at-McMicken-Battery-Facility (accessed 2020).
[123] G. Hering. (2019, 14 June 2019) As fire investigation concludes, South Korea battery makers eye market relaunch. *Energy*. Available: https://www.spglobal.com/marketintelligence/en/news-insights/trending/bVy2KGU3Opsle5Vv8QG0-Q2
[124] Tesla. "Tesla Vehicle Safety Report." (accessed 2020).
[125] J. Roman. (2020) Beyond EVs. *NFPA Journal*. Available: https://www.nfpa.org/News-and-Research/Publications-and-media/NFPA-Journal/2020/January-February-2020/Features/EV-Stranded-Energy/ESS
[126] Cadex. "Is Lithium-ion the Ideal Battery?" Battery University Group. https://batteryuniversity.com/learn/archive/is_lithium_ion_the_ideal_battery#:~:text=Because%20of%20the%20inherent%20instability,met%20when%20charging%20and%20discharging. (accessed 2020).
[127] J. Clark. "Reactions of the Group 1 Elements with oxygen and chlorine." https://www.chemguide.co.uk/inorganic/group1/reacto2.html#:~:text=Lithium%20burns%20with%20a%20strongly,would%20simply%20be%20more%20intense.&text=Lithium%20is%20the%20only%20element,a%20nitride%20in%20this%20way. (accessed 2020).
[128] K. Liu, Y. Liu, D. Lin, A. Pei, and Y. Cui, "Materials for lithium-ion battery safety," *Science advances,* vol. 4, no. 6, p. eaas9820, 2018.
[129] C. Mikolajczak, M. Kahn, K. White, and R. T. Long, *Lithium-ion batteries hazard and use assessment* (Fire Protection Research Foundation). Springer Science & Business Media, 2012.
[130] D. Hill, "Considerations for ESS Fire Safety," DNV GL, 2017. [Online]. Available: https://www.dnvgl.com/
[131] B. Gully, H. Helgesen, J. E. Skogtvedt, and D. Kostopoulus, "Technical Reference for Li-ion Battery Explosion Risk and Fire Suppression," in "Maritime Battery Safety Joint Development project," DNV GL, 2019. [Online]. Available: https://www.dnvgl.com/

[132] T. A. Hayes. *Improving Product Safety through Lithium-Ion Battery Manufacturer Audits* (2018). Thought Leadership. Exponent. [Online]. Available: https://www.exponent.com/~/media/knowledge/thought-leadership/2018/tl_pdf/tl_improving-product-safety-through-lithiumion-battery-manufacturer-audits.pdf
[133] C. Pitorac, "Li-ion Battery Testing from Manufacturing to Operation Process " *International Journal of Technical Research and Applications,* vol. 3, no. 4 (July-August 2015), Renewable Power Sources , Power Systems and Energy Conversion, pp. 58-61, 2015. [Online]. Available: https://www.ijtra.com/view/li-ion-battery-testing-from-manufacturing-to-operation-process.pdf.
[134] J. Schnell and G. Reinhart, "Quality Management for Battery Production: A Quality Gate Concept," *Procedia CIRP,* vol. 57, pp. 568-573, 2016, doi: 10.1016/j.procir.2016.11.098.
[135] D. D. Agwu, F. Opara, N. Chukwuchekwa, D. Dike, and L. Uzoechi, "Review Of Comparative Battery Energy Storage Systems (Bess) For Energy Storage Applications In Tropical Enviroments," 09/29 2018.
[136] Cadex. "BU-808: How to Prolong Lithium-based Batteries." Battery University Group. https://batteryuniversity.com/index.php/learn/article/how_to_prolong_lithium_based_batteries (accessed 2020).
[137] W.-Y. Chang, "The State of Charge Estimating Methods for Battery: A Review," *ISRN Applied Mathematics,* vol. 2013, pp. 1-7, 2013, doi: 10.1155/2013/953792.
[138] Cadex. "BU-901: Fundamentals in Battery Testing." https://batteryuniversity.com/learn/article/difficulties_with_testing_batteries (accessed 2020).
[139] S. K. Heiskanen, J. Kim, and B. L. Lucht, "Generation and Evolution of the Solid Electrolyte Interphase of Lithium-Ion Batteries," *Joule,* vol. 3, no. 10, pp. 2322-2333, 2019, doi: 10.1016/j.joule.2019.08.018.
[140] R. Bisschop, O. Willstrand, F. Amon, and M. Rosenggren, *Fire safety of lithium-ion batteries in road vehicles*. RISE - Research Institutes of Sweden, Safety and Transport, Safety, 2019.
[141] Q. Pan, R. Weyhe, A. Melber, I. Klavina, and B. Friedrich, "Investigation on packaging materials for safe transport of spent Li-ion batteries," *PACKAGING MATERIALS FOR LI-ION BATTERIES,* 2013.
[142] Sonnen. *Safety data sheet for Lithium Iron Phosphate Battery*, 2015. [Online]. Available: http://www.sonnensupportaustralia.com.au/uploads/2/9/8/5/29857561/sonnen_-_sonnen_lfp2_-_battery_sds.pdf.
[143] J. Van Ginkel and E. Hasselaar, "Indoor air quality influenced by ventilation system design," in *ENHR conference 2006: Housing in an expanding Europe. Theory, policy, implementation and participation, Ljubljana, July 2-5, 2006*, 2006: Urban Planning Institute of the Republic of Slovenia.
[144] L. Kong, C. Li, J. Jiang, and M. Pecht, "Li-Ion Battery Fire Hazards and Safety Strategies," *Energies,* vol. 11, no. 9, p. 2191, 2018, doi: 10.3390/en11092191.
[145] M. Ghiji *et al.*, "A Review of Lithium-Ion Battery Fire Suppression," *Energies,* vol. 13, no. 19, p. 5117, 2020, doi: 10.3390/en13195117.
[146] M. Dassisti *et al.*, "Vanadium: A Transition Metal for Sustainable Energy Storing in Redox Flow Batteries," in *Reference Module in Materials Science and Materials Engineering*, 2016.
[147] M. Paiss, "Energy Storage System Safety: Comparing Vanadium Redox Flow and Lithium-Ion Based Systems," 2017. [Online]. Available: http://energyresponsesolutions.com/
[148] A. H. Whitehead, T. J. Rabbow, M. Trampert, and P. Pokorny, "Critical safety features of the vanadium redox flow battery," *Journal of Power Sources,* vol. 351, pp. 1-7, 2017, doi: 10.1016/j.jpowsour.2017.03.075.

[149] N. Nhede. (2019, 8 August 2019) The vanadium redox flow battery – A game changer for energy storage safety. *Smart Energy International*. Available: https://www.smart-energy.com/industry-sectors/storage/the-vanadium-redox-flow-battery-a-game-changer-for-energy-storage-safety/
[150] W. Wang. *Vanadium Redox Flow Batteries - Improving the performance and reducing the cost of vanadium redox flow batteries for large-scale energy storage*. (2012). US Department of Energy. [Online]. Available: https://www.energy.gov/sites/prod/files/VRB.pdf
[151] S. Yin, L. Zhou, X. Du, and Y. Yang, "Influence of temperature on performance of all vanadium redox flow battery: analysis of ionic mass transfer," *Ionics,* vol. 25, no. 2, pp. 593-606, 2018, doi: 10.1007/s11581-018-2626-z.
[152] A. Trovò, "Battery management system for industrial-scale vanadium redox flow batteries: Features and operation," *Journal of Power Sources,* vol. 465, p. 228229, 07/01 2020, doi: 10.1016/j.jpowsour.2020.228229.
[153] R. Francis. (2009) The performance of stainless steels in concentrated sulphuric acid. *https://www.stainless-steel-world.net/*. 4. Available: https://www.rolledalloys.com/shared/library/technical-papers/corrosive/The-Performance-of-Stainless-Steels-in-Concentrated-Sulfuric-Acid.pdf
[154] D. Michaud. "Sulfuric Acid Resistant Alloys." https://www.911metallurgist.com/sulfuric-acid-resistant-alloys/ (accessed 2020).
[155] M. Rajabalinejad, *Safety by Design - Engineering Products and Systems*, 1 ed. Brave New Books, 2020, p. 175.
[156] Systems Engineering Body of Knowledge (SEBoK). "Sociotechnical System (glossary)." https://www.sebokwiki.org/wiki/Sociotechnical_System_(glossary) (accessed 2020).
[157] Laboratory for Product Development and Lightweight Design. "The Design Structure Matrix (DSM)." https://dsmweb.org/understand-dsm-2/ (accessed 2020).
[158] *IEC 61508 Functional safety of electrical/electronic/programmable electronic safety-related systems. Part 5: Examples of methods for the determination of safety integrity levels*, International Electrotechnical Commission (IEC), 2010.
[159] Center for Chemical Process Safety (CCPS), *Layer of protection analysis: simplified process risk assessment*. New York: Wiley, 2001, p. 292.
[160] Center for Chemical Process Safety (CCPS), *Guidelines for Initiating Events and Independent Protection Layers in Layer of Protection Analysis (LOPA)*: VitalSource Bookshelf, 2015. [Online]. Available: https://bookshelf.vitalsource.com/#/books/9781118948729/.
[161] S. Tretsiakova-McNally and D. Makarov. HyResponse. (2016). Lecture - Dealing with hydrogen explosions. Available: http://www.hyresponse.eu/training-mat-1.php
[162] J. L. Saw *et al.*, "The EU FireComp Project and risk assessment of hydrogen composite storage applications using bow-tie analysis," Proceedings of Hazards 26, 2016, vol. Symposium series, no. 161.
[163] N. Psara, M. van Sint Annaland, and F. Gallucci, "Hydrogen safety risk assessment methodology applied to a fluidized bed membrane reactor for autothermal reforming of natural gas," *International Journal of Hydrogen Energy,* vol. 40, no. 32, pp. 10090-10102, 2015.
[164] Statista. "Average household size in the Netherlands from 1950 to 2019, by number of residents." https://www.statista.com/statistics/521777/netherlands-average-household-size-by-number-of-residents/#:~:text=It%20shows%20that%20between%201950,1950%20to%202.15%20in%202019. (accessed.
[165] (2014). *KNMI 14: Klimaatscenario's voor Nederland*.
[166] W. Bridges, "LOPA and Human Reliability–Human Errors and Human IPLs," in *12th Process Plant Safety Symposium and 6th Global Congress on Process Safety, San Antonio, TX*, 2010.

[167] Center for Chemical Process Safety (CCPS), "Appendix A: Inherently Safer Technology Checklist," in *Inherently Safer Chemical Processes*: American Institute of Chemical Engineers, 2008, pp. 293-330.
[168] Nederlandse Vereniging voor Brandweerzorg en Rampenbestrijding (NVBR), *Operationele Handreiking Incidentbestrijding Gevaarlijke Stoffen (OH-IBGS)*. 2020.
[169] T. Kelly and R. Weaver, "The goal structuring notation–a safety argument notation," in *Proceedings of the dependable systems and networks 2004 workshop on assurance cases*, 2004: Citeseer, p. 6.
[170] *NEN-EN-ISO 12100 Safety of machinery - General principles for design - Risk assessment and risk reduction*, International Organization for Standardization (ISO), 2010.
[171] Center for Chemical Process Safety (CCPS), "Protection Layers," in *Guidelines for Safe and Reliable Instrumented Protective Systems*: American Institute of Chemical Engineers, 2007, pp. 267-299.
[172] M. Pierce, "Quantitative Risk Analysis for Battery Energy Storage Sites," DNV GL, 2019. [Online]. Available: https://www.dnvgl.com/
[173] Air Liquide, Ulster University, and Joint Research Centre, "D5.1 Pre-normative research on safe indoor use of fuel cells and hydrogen systems," 2012.
[174] R. Verboom *et al.* IFV, VRR, VRH, and LIOGS. (2019). Handreiking Opslag Li-ion energiedragers (accu's en batterijen).
[175] University of Twente. University of Twente. (2019). Veiligheidsinformatie Laboratorium-Experimenteerruimte / Laboratory-Experimental space safety information. Available: https://www.utwente.nl/.uc/f1e45a16f0102f0ea9b00a9acc2017506abe315290aa300/veiligheidsformulier-lab.pdf
[176] European Commission. "Machinery." https://ec.europa.eu/growth/sectors/mechanical-engineering/machinery_en (accessed August, 2020).
[177] European Commission. "The Low Voltage Directive (LVD)." https://ec.europa.eu/growth/sectors/electrical-engineering/lvd-directive_en (accessed August, 2020).
[178] European Commission. "General Product Safety Directive." https://ec.europa.eu/info/general-product-safety-directive_en#:~:text=EU%20rules%20on%20product%20safety,are%20sold%20on%20the%20market.&text=They%20also%20have%20to%20make,avoid%20any%20risks%20to%20consumers (accessed August, 2020).
[179] European Chemicals Agency (ECHA). "Understanding CLP." https://echa.europa.eu/regulations/clp/understanding-clp (accessed August, 2020).
[180] European Chemicals Agency (ECHA), *Guide on Safety data sheets and Exposure scenarios*, 2018. Accessed on: August 2020.
[181] IATA, "Transport of Lithium Metal and Lithium Ion Batteries," in "2019 Lithium Battery Guidance Document," 2018. [Online]. Available: https://tadiranbatteries.de/pdf/IATA_Lithium_Battery_Guidance_2019.pdf
[182] Koorsen Fire & Security. "The International Fire Code - History and Role in Fire Safety Today." https://blog.koorsen.com/the-international-fire-code-its-history-and-role-in-fire-safety-today (accessed September, 2020).
[183] P. Wiley. "Corrosion Resistance of Stainless Steel to Sulfuric Acid." Sciencing.com. https://sciencing.com/corrosion-stainless-steel-sulfuric-acid-8723157.html (accessed 2020).
[184] *Layer of Protection Analysis Simplified PRocess Risk Assessment*. New York: Center for Chemical Process Safety for American Institute of Chemical Engineers, 2001.

[185] M. A. Lundteigen and M. Rausand. N. U. o. S. a. T. Department of Mechanical and Industrial Engineering. Chapter 8 PFD formulas in IEC 61508. Available: https://www.ntnu.edu/ross/books/sis/slides
[186] M. Ruiter and J. Domrose, "Fatal residential fires in Europe: A preliminary assessment of risk profiles in nine European countries," Institute for Safety Fire Service Academy (IFV), Arnhem, NL, 2018. [Online]. Available: https://www.ifv.nl/kennisplein/Documents/20181120-BA-EFA-Fatal-residential-fires-in-Europe.pdf
[187] D. Hanea and B. Ale, "Risk of human fatality in building fires: A decision tool using Bayesian networks," *Fire Safety Journal,* vol. 44, no. 5, pp. 704-710, 2009, doi: 10.1016/j.firesaf.2009.01.006.
[188] H. Wessels, "Evaluation of a radio interferometry lightning positioning system. KNMI Scientific Rep," WR-98-04, 1998.
[189] ADR. ADR Book 2017 - Dangerous Goods by Road [Online] Available: https://adrbook.com/en/
[190] *NEN-EN-ISO 7010 Graphical symbols - Safety colours and safety signs - Registered safety signs*, International Organization for Standardization (ISO), 2020.
[191] S. Øvergaard, "Issue paper: Definition of primary and secondary energy," *Statistics Norway, Oslo,* 2008.
[192] B. Decourt and R. Debarre, "Electricity storage," *Leading the enrgy transition factbook. Schlumberger Business Consulting (SBC) Energy Institute, Gravenhage,* 2013.
[193] M. Van der Hoeven, "Technology roadmap: Energy storage," *International Energy Agency (IEA), Paris, France, Tech. Rep,* 2014.
[194] J. Fernando. "Death Valley Curve." https://www.investopedia.com/terms/d/death-valley-curve.asp (accessed 15 December, 2019).
[195] M. Rogner and N. Troja, "The world's water battery: Pumped hydropower storage and the clean energy transition," *The International Hydropower Association (IHA), Chancery House, St Nicholas Way, Sutton, London SM1 IJB, United Kingdom,* 2018.
[196] L. Munuera and C. Pavarini. "Energy Storage." EIA. https://www.iea.org/reports/energy-storage (accessed 3 July, 2020).
[197] O. Schmidt, A. Hawkes, A. Gambhir, and I. Staffell, "The future cost of electrical energy storage based on experience rates," *Nature Energy,* vol. 2, no. 8, pp. 1-8, 2017.
[198] C. J. Barnhart and S. M. Benson, "On the importance of reducing the energetic and material demands of electrical energy storage," *Energy & Environmental Science,* vol. 6, no. 4, pp. 1083-1092, 2013.
[199] Air Liquide. "Planet hydrogen." https://energies.airliquide.com/resources/planet-hydrogen-hydrogen (accessed 23 November, 2019).
[200] Fuel Cells Technology Office, "Hydrogen Storage." [Online]. Available: hydrogenandfuelcells.energy.gov
[201] M. Dresselhaus *et al.*, "Basic Research Needs for the Hydrogen Economy. Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use, May 13-15, 2003," DOESC (USDOE Office of Science (SC)); Argonne National Lab.(ANL), Argonne …, 2004.
[202] R. Heinberg and D. Fridley, *Our Renewable Future: Laying the Path for One Hundred PercClean Energy*. Island Press, 2016.
[203] F. Crotogino, "Larger scale hydrogen storage," in *Storing energy*: Elsevier, 2016, pp. 411-429.
[204] M. Lappalainen, "Techno-economic feasibility of hydrogen production via polymer membrane electrolyte electrolysis for future Power-to-X systems," Master thesis, Faculty of Natural Sciences, Tampere University, 2019.
[205] Hydrogen Europe. "Electrolysers." https://hydrogeneurope.eu/electrolysers (accessed 23 November, 2019).

[206] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few, "Future cost and performance of water electrolysis: An expert elicitation study," *International Journal of Hydrogen Energy,* vol. 42, no. 52, pp. 30470-30492, 2017.
[207] N. H. Behling, "Chapter 2 - Fuel Cells and the Challenges Ahead," in *Fuel Cells*, N. H. Behling Ed.: Elsevier, 2013, pp. 7-36.
[208] H. Barthélémy, "Hydrogen storage–Industrial prospectives," *International journal of hydrogen energy,* vol. 37, no. 22, pp. 17364-17372, 2012.
[209] M. Vetter and S. Lux, "Rechargeable Batteries with Special Reference to Lithium-Ion Batteries," in *Storing Energy*: Elsevier, 2016, pp. 205-225.
[210] Office of Energy Efficiency & Renewable Energy. "How Does a Lithium-ion Battery Work?" US Department of Energy. https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work (accessed July, 2020).
[211] M. Brain. "How Lithium-ion Batteries Work." How Stuff Works. https://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery.htm (accessed July, 2020).
[212] Cadex. "BU-205: Types of Lithium-ion." Battery University. https://batteryuniversity.com/learn/article/types_of_lithium_ion (accessed July, 2020).
[213] I. Belharouak, Y. K. Sun, W. Lu, and K. Amine, "On the Safety of the Li[sub 4]Ti[sub 5]O[sub 12]∕LiMn[sub 2]O[sub 4] Lithium-Ion Battery System," *Journal of The Electrochemical Society,* vol. 154, no. 12, 2007, doi: 10.1149/1.2783770.
[214] A. B. Gallo, J. R. Simões-Moreira, H. K. M. Costa, M. M. Santos, and E. Moutinho dos Santos, "Energy storage in the energy transition context: A technology review," *Renewable and Sustainable Energy Reviews,* vol. 65, pp. 800-822, 2016/11/01/ 2016, doi: https://doi.org/10.1016/j.rser.2016.07.028.

Appendix 1 Comparison between some commonly-used hazard assessment techniques

This summary of key characteristics of some commonly-applied safety hazard analysis techniques is based on the author's understanding of Ericson's textbook, Hazard Analysis Techniques for System Safety [23].

Legend for headers:

* I = inductive; D = deductive

** Qual. = qualitative; Quant. = quantitative

***Application efforts is an approximation, based on the aggregated factors of the required time, skill level to implement the technique, the level of depth of analysis, and the need for specialised tools and knowledge.

No.	Techniques	Typical industry use	Qual. / Quant.	I / D	Typical application…			Primary output	Advantages	Limitations
					in the lifecycle phase	at system hierarchy level	efforts			
1	Preliminary hazard list	Many industries	Qual.	I	Conceptual design	Any	Low	All known or suspected hazards	Inexpensive, does not require considerable expertise to apply and very quickly indicates where the major hazards will exist	Only identify hazards; does not investigate hazards
2	Preliminary hazard analysis	Many industries	Qual.	I / D	Preliminary design	Any	Low	Hazard causal factors, coonsequ3ences and relative risk. Safety-critical	Easy to perform, relatively inexpensive, and provides risk analysis of	Should not be the only hazard analysis technique applied

No.	Techniques	Typical industry use	Qual. / Quant.	I / D	Typical application… in the lifecycle phase	at system hierarchy level	efforts	Primary output	Advantages	Limitations
								functions (SCFs) and top-level mishaps (TLMs)	the majority of system hazards	
3	Subsystem hazard analysis	Many industries	Qual.	I / D	Detailed design	Sub-system and below	Medium	Verify sub-system or component compliance with safety requirements	Focuses on hazards and not just failure modes (such as in FMEA), and is cost-effective	Useful only if detailed design effort is involved, and less useful for commercial off-the-shelf systems.
4	System hazard analysis	Many industries	Qual.	I / D	Detailed design	Super-system	Medium	Hazards due to the interaction between interfaces, functional faults and interactions	Identifies hazards that are overlooked by other analyses.	Success is dependent on completion of other system analyses - i.e. PHA, SSHA, SRCA and O&SHA
5	Operating and support hazard analysis	Many industries	Qual.	I / D	Detailed design	Super-system	Medium	Hazards from operator tasks and activities, necessary warnings and precautions in operational procedures	Considers human system integration factors; cost-effective	May have some overlap with HHA
6	Health hazard assessment	Many industries	Qual.	I / D	Detailed design	System	Medium	Focus on human health issues - e.g. ergonomics, noise,	Easily performed, does not require considerable expertise to	May have some overlap with O&SHA

No.	Techniques	Typical industry use	Qual. / Quant.	I / D	Typical application…			Primary output	Advantages	Limitations
					in the lifecycle phase	at system hierarchy level	efforts			
								vibration, temperature, chemicals, etc.	apply, relatively inexpensive yet effective	
7	Safety requirements/ criteria analysis	Many industries; particularly useful in software development	Qual.	N/A	Detailed design	System	Medium	Traceability analysis to 1) ensure all hazards are linked to a safety requirement; 2) the requirements have been considered in design and test specifications	Easy to perform	Useful only if requirements engineering is applied
8	Fault tree analysis	Many industries, especially in military equipment, nuclear power plants.	Qual./ Quant.	D	Any, especially during detailed design	Any	High	Critical cut-sets of root causes, and the quantified probability of occurrence of a specified undesired event	A graphical and logical representation of faults. Effective results, even with only qualitative evaluation. Also useful in the evaluation of safety, reliability and performance aspects	Can be labour intensive. Difficult to capture temporal factors (changes and transitional states). Can become very complex and difficult to review

No.	Techniques	Typical industry use	Qual. / Quant.	I / D	Typical application… in the lifecycle phase	at system hierarchy level	efforts	Primary output	Advantages	Limitations
9	Event tree analysis	Nuclear power plants	Qual./ Quant.	D	Detailed design	System	High	Models accident scenarios and to evaluate the risk of various outcome scenarios resulting from an initiating event	Graphical representation of various outcomes due to a failure, error, fault or mishap	Can only have one initiating event. Multiple ETAs needed for evaluating multiple events. Partial success or failures not distinguishable. Possible to overlook system dependencies.
10	Failure mode and effects analysis	Many industries, especially in automotive. Popular for reliability evaluation, especially of mechanical systems	Qual./ Quant.	I	Detailed design	From component up to the system level	Medium	Evaluates failure modes, its effects, and quantification of risks.	Powerful as a reliability evaluation technique	Only considers single failure modes. RPN score not relevant for safety assessment. Does not identify non-failure mode hazards (e.g. timing errors, energy sources, etc.)
11	Barrier analysis	Used as a secondary tool complement primary analysis tool	Qual.	I	Detailed design	System	Low	Provides focus potentially hazardous energy sources	Simple and provides visual illustration energy flows to target	Does not include other sources, e.g. materials, human interfaces, system interfaces and environment.

No.	Techniques	Typical industry use	Qual. / Quant.	I / D	Typical application…			Primary output	Advantages	Limitations
					in the lifecycle phase	at system hierarchy level	efforts			
12	Hazard and Operability analysis	Chemical processing and oil & gas	Qual.	I	Detailed design	System	Medium -to-high	Hazards caused by deviation from design operational intent	Rigorous, well-established, and commercial software available.	More suited for continuous-flow processes. Requires significant effort (need multi-disciplinary team effort and experienced facilitator)
13	Bowtie diagramme	Started in oil and gas; expanding to other industries	Qual.	D	Preliminary ; Operate	Super-system	Medium	Scenarios of unsafe events related to a hazard. Causes, consequences, preventive and mitigative barriers.	Provide a visual means to communicate safety issues. Management activities can be linked to protection barriers.	Practicable to apply on selected scenarios
14	Layer of protection analysis	Started in chemical processing,	Semi-quant.	D	Any phase	Super-system	Medium -to-high	Identification of independent protective barriers; semi-quantitative calculation of residual risks	A simpler alternative to a full quantitative risk assessment; allows decision if risk acceptability; many industrial references and guidelines	Risk is not precise, just an approximation. Requires more effort than qualitative analysis methods. Results normally not directly comparable from

No.	Techniques	Typical industry use	Qual. / Quant.	I / D	Typical application…			Primary output	Advantages	Limitations
					in the lifecycle phase	at system hierarchy level	efforts			
										one organisation to another.

Appendix 2 Supplemental information of applicable regulations, codes and standards (RCS)

The list is not meant to be an exhaustive and comprehensive list, but only to supplement the information written in the thesis's main text.

EU Directives

- Machinery Directive 2006/42/EC: governs the harmonisation of essential health and safety requirements for machinery at the EU level. It combines mandatory health and safety requirements and voluntary harmonised standards, such as CEN, ISO, and IEC bodies. The directive only applies to products that are to be placed on the EU market for the first time [176].
- ATEX 'Workplace' Directive 99/92/EC (known as 'ATEX 137') concerning the minimum requirements for improving the health and safety protection of workers potentially at risk from explosive atmospheres.
- ATEX 'Equipment' Directive 2014/34/EU (known as 'ATEX 114') supersedes the previous Directive 94/9/EC (known as 'ATEX 95'), concerning the equipment and protective systems intended for use in potentially explosive atmospheres.
- Pressure Equipment Directive 2014/68/EU (recast from Directive 97/23/EC). Commonly known as 'PED', it applies to the design, manufacture and conformity assessment of stationary pressure equipment with a maximum allowable pressure higher than the 0.5 bar.
- *Warenwetbesluit drukapparatuur* 2016 (WBDA), literally translated as the 'Pressure Equipment (Commodities Act) Decree' is the Dutch regulation that in harmony with the EU's PED.
- Low Voltage Directive (2014/35/EU). Also known as the 'LVD', this Directive ensures that electrical equipment within certain voltage limits provides a high level of protection for European citizens. The LVD covers health and safety risks on electrical equipment operating with an input or output voltage of between 50 - 1000 VAC and 75 - 1500 VDC. It applies to a wide range of electrical equipment for both consumer and professional usage, such as household appliances, cables, power supply units, laser equipment, certain components. Any consumer goods with a voltage below 50 VAC or 75 VDC is covered by the General product safety directive (2001/95/EC) [177].
- 'Major Hazards' Directive 2012/18/EU, or SEVESO-III defines the control (prevention of major accidents and the limitation of their effects) of major-accident hazards involving dangerous substances. It lists the substances and the threshold quantity beyond which a substance is considered hazardous.
- Industrial Emissions Directive 2010/75/EU defines industrial emissions and the need for integrated pollution prevention and control. The directive aims to achieve a high level of protection of human health and the environment taken as a whole by reducing harmful industrial emissions across the EU, in particular through better application of Best Available Techniques (BAT) (standards). The IED is based on several pillars, in particular (1) an integrated approach, (2) use of best available techniques, (3) flexibility, (4) inspections and (5) public participation.

- Strategic Environmental Assessment (SEA) Directive 2001/42/EC defines the effects of specific plans and programmes on the environment. The directive specifies that a Strategic Environmental Assessment is mandatory if a public project or programme has significant environmental impact.
- Environmental Impact Assessment (EIA) Directive 2011/92/EU defines public and private projects where an EIA is mandatory. The procedure is quite similar to SEA, but with some differences.
- General Product Safety Directive 92/59/EEC is aimed at levelling the product safety regulations among EU member-states for a single European market. It complements sector-specific legislation such as specific rules for non-food products, such as toys, electrical and electronic goods, cosmetics, chemicals and other specific product groups. It does not cover pharmaceuticals, medical devices or food, which fall under separate legislation [178].
- Batteries Directive (2006/66/EC). This Directive is aimed at minimising the negative impact of batteries and accumulators and waste batteries and accumulators on the environment. It achieves this by, for example, prohibiting completely or partially the presence of hazardous components in batteries; and by establishing measures to ensure the proper management of waste batteries [69].

Transportation regulations

- Classification, Labelling and Packaging (CLP) Regulation 1272/2008 is a binding EU regulation that requires manufacturers, importers or downstream users of substances or mixtures to classify, label and package their hazardous chemicals appropriately before placing them on the market. Once a substance or mixture is classified, the identified hazards must be communicated to other stakeholders' supply chain, including consumers [179]. The use of Safety Data Sheets (SDS) is a means to provide the users of chemicals with the necessary information to help them protect human health and the environment [180].
- United Nations Recommendations on the Transport of Dangerous Goods - Manual of Test and Criteria. Subsection 38.3, commonly known as 'UN 38.3', addresses the procedures and tests for lithium metal and lithium-ion batteries.
- ADR - European Agreement concerning the International Carriage of Dangerous Goods by Road. It concerns the packaging and labelling of transported dangerous goods, and the construction, equipment and operation of the vehicle carrying the goods in question. Hydrogen, lithium-ion and vanadium pentoxide, used in sulphuric acid manufacturing, are designated as hazardous goods.
- IMDG - International Maritime Dangerous Goods (United Nations) is a standard guide to all aspects of handling dangerous goods and marine pollutants in sea transport, including packaging and labelling.
- Dangerous Goods Regulations (DGR), published by the International Air Transport Association (IATA). Besides, IATA also publishes the Lithium Battery Shipping Guidelines (LBSG), a manual for manufacturers, retailers, wholesalers, freight forwarders and others in the supply chain to ensure compliance when shipping lithium batteries [181].

Other useful guidelines used in the UK and US

Safety guidelines for hydrogen systems

- ANSI/AIAA G-095-2004. Guide to Safety of Hydrogen and Hydrogen Systems. Published by the American National Standards Institute (ANSI)/American Institute of Aeronautics and Astronautics (AIAA)

Pressurised vessels and piping

American Society for Mechanical Engineers (ASME) is a US-based organisation. Its standards are recognized worldwide.

- ASME Boiler and Pressure Vessel Code Section VIII - Rules for Construction of Pressure Vessels. This is the equivalent of NEN-EN 13445.
- ASME B31.3 – Process Piping.

Fire safety

Many states in the USA reference both the International Fire Code and NFPA standards in their regulations. These are not applicable in the Netherlands, but provides useful references for this research [182].

Appendix 3 Preliminary Hazards List (PHL)

The headers used in the PHL spreadsheet are explained below.

- ID: a running number to identify the analysis entry
- System: the equipment or installation found in the LIFE project
- Lifecycle: the phase in the equipment's life when the hazard is present
- Hazard: a description of the identified hazard
- Hazard effects: a description of the possible consequences of the hazard, if left unmitigated
- Comments: additional remarks to help the understanding, or explanation of the identified hazard

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -1	Home energy management system, HEMS	Use	To explore further effects of HEMS failing to operate, operating incorrectly, receiving or sending erroneous information.	To be determined	
PHL -2	Electrical system	Use	Constant switching on/off of high-power electricity consumers, such as pumps and electrolyser	Power spike or surges, potentially damaging electrical item.	
PHL -3	House structure	Construction, Use, Disposal	Functional: Electrical power supply disruption	Occupant faces hassle	Less effect on safety. More relevant as inefficiency aspect
PHL -4	House structure	Construction, Use, Disposal	Super-system: combustible and flammable material of construction	Fire and explosion risk	
PHL -5	House structure	Construction, Use Disposal	Super-system: High humidity	fungus growth	
PHL -6	House structure	Construction, Use Disposal	Super-system: High temperature	unbearable temperature for occupants; unsuitable operating range for equipment	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -7	House structure	Construction, Use, Disposal	Super-system: Low temperature	unbearable temperature for occupants; unsuitable operating range for equipment	
PHL -8	House structure	Construction, Usage, Disposal	Super-system: Strong winds	structure collapse	
PHL -9	House structure	Use	System: Electrical shock	Lowest severity scenario: uncomfortable feeling; Worst case scenario - death	
PHL -10	Hydrogen system	Storage, Use	Functional: Accumulation of hydrogen in an enclosure	LEL (low-level explosion) mixture is reached; can potentially ignite with the addition of energy sources	
PHL -11	Hydrogen system	Construction	Functional: Electrical shock from electrolyser or fuel cell	Injury to human operator and maintenance personnel	
PHL -12	Hydrogen system	Use	Functional: failure of electrolyser to shut-off during activation of safety devices	Continuous production of hydrogen and oxygen, a combustible condition	
PHL -13	Hydrogen system	Use	Functional: a malfunction in hydrogen/water separator, specifically on the water transfer line, or membrane perforation leading to the formation of H2-O2 ATEX	Formation of combustible mixture	To check during the detailed design phase of the hydrogen system, if such a separator design is used
PHL -14	Hydrogen system	Storage, Use	Functional: released hydrogen undetected	Accidental ignition of hydrogen mixture	
PHL -15	Hydrogen system	Storage, Use	Operational: Boiling Liquid Expanding Vapour Explosion (BLEVE)	Extensive damage to property and potential loss of human lives	Not applicable - only for storage of pressurised liquid
PHL -16	Hydrogen system	Storage, Use	Operational: Deflagration and detonation of the hydrogen	Damage to equipment, structure and potentially human injury or fatality	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -17	Hydrogen system	Storage	Operational: Filling orientation	Not applicable	How does this influence safety?
PHL -18	Hydrogen system	Use	Operational: Formation of a flammable mixture of hydrogen and oxygen - in electrolyser or fuel-cell	Combustion of the hydrogen-oxygen mixture within the electrolyser process piping	
PHL -19	Hydrogen system	Storage	Operational: Heating effects during refilling of hydrogen storage tanks	LEL (low-level explosion) mixture is reached; can potentially ignite with the addition of energy sources	
PHL -20	Hydrogen system	Use	Operational: High heat caused by a hydrogen fire	Damage to equipment, structure and potentially human injury or fatality; secondary fires	
PHL -21	Hydrogen system	Storage	Operational: High-pressure hydrogen jets	Injury to skin	
PHL -22	Hydrogen system	Storage	Operational: Ignition of hydrogen	Damage to equipment, structure and potentially human injury or fatality; secondary fires	
PHL -23	Hydrogen system	Storage	Operational: Invisible flame of burning pure hydrogen, in daylight	As above	
PHL -24	Hydrogen system	Storage	Operational: Pressure peaking phenomenon	As above	
PHL -25	Hydrogen system	All	Operational: Propagation of hydrogen flames	As above	
PHL -26	Hydrogen system	Storage	Operational: Rapid and smokeless hydrogen burning	As above	Similar to PHL-29, thus no need to repeat

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -27	Hydrogen system	Storage	Structural: Hydrogen embrittlement: loss of the material strength	Sudden loss of containment, potentially leading to massive damage of equipment, adjacent structure and fatality	
PHL -28	Hydrogen system	Storage	Structural: Interaction of hydrogen with materials used for liners (metals of plastic): may lead to permeation, embrittlement	Can be similar to effects stated in PHL-28, or if slow permeation of hydrogen, leading to the accumulation of hydrogen to form LEL mixture (if in enclosed space)	
PHL -29	Hydrogen system	Storage	Structural: Loss of containment causing micro leaks and micro leaks	Similar to PHL-31. Can also lead to localised flames	
PHL -30	Hydrogen system	Use	Structural: Overpressure of system	Worst-case scenario - rupture of the storage tank, Structural: fireball, blast waves and burning projectiles	
PHL -31	Hydrogen system	Storage	Super-system: External fire/heat or thermal radiation causes mechanical rupture of the storage tank	Similar to PHL-31	Depending on fire-resistance levels, e.g. 12 minutes
PHL -32	Hydrogen system	Storage	Thermal pressure relief device (TPRD) malfunction – fails to open.	Similar to PHL-31	
PHL -33	Hydrogen system	Design	The unfamiliarity of first-responders, or fire-brigade with the associated hazards and mitigation techniques against hydrogen or battery fires	Ineffective or inadequate emergency response; an escalation of fire	
PHL -34	Lithium-ion battery	Use	Function: Battery Management System malfunctions	Loss of control of safe charging	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -35	Lithium-ion battery	Use	Operational: Electric shock during operation, maintenance and emergency response	Injury to occupants or maintenance personnel	
PHL -36	Lithium-ion battery	Use	Operational: Incorrect fire-fighting techniques	Uncontrollable chemical reaction; the fire is not extinguished	Li-ion: ok to use water; Li metal: should not use water, but Class D fire-extinguisher
PHL -37	Lithium-ion battery	Use	Operational: Physical damage due to misuse/abuse (to define exactly misuse actions)	Internal short-circuiting, leading to overheating and fire	
PHL -38	Lithium-ion battery	Production, Transport, Use, Disposal	Operational: Stranded/residual energy during emergency response.	Arc flash, electric shock (if the system is > 100 V)	Not applicable for LIFE project, since the max voltage is 48 V
PHL -39	Lithium-ion battery	Production	Structural: metallic particles punctures separators cause thermal runaway	Shorting, and subsequent overheating, fire	
PHL -40	Lithium-ion battery	Use	Sub-system: during an emergency (i.e. fire), the *uitgangspuntendocument (UPD, or principle document)* is not available to first-responders	Ineffective or inadequate emergency response; the escalation of fire	
PHL -41	Lithium-ion battery	Use	Sub-system: Pressure build-up within casing/construction	More severe reaction than controlled-release design	
PHL -42	Lithium-ion battery	Transport	Supersystem: during transport, mishandling causes internal short-circuiting	Overheating and fire	
PHL -43	Lithium-ion battery	Use	Super-system: adjacent systems emit vibrations, causing connectors to loosen	Shorting, and fire	
PHL -44	Lithium-ion battery	Disposal	Super-system: Battery disposed of not using proper channels	Environmental pollution	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -45	Lithium-ion battery	Use	Super-system: Battery-management system interface cables inadvertently is disconnected	The removal of a protection layer to prevent over-charging and thermal runaway.	
PHL -46	Lithium-ion battery	Design	Super-system: During a burning scenario, the release of toxic (hydrogen fluoride, others?) gas	Severe toxicity threat and the results are crucial findings for risk assessment and management, especially for large Li-ion battery packs.	
PHL -47	Lithium-ion battery	Construction	Super-system: during transportation, connectors become loose	Shorting, and fire	
PHL -48	Lithium-ion battery	Design	Super-system: During venting reaction (i.e. no ignition), the release of flammable by-product gas	Fire and explosion risk	Does LFP produce hydrogen as a vent gas?
PHL -49	Lithium-ion battery	Use	Super-system: External fire causes the battery to have runaway-temperatures	Causes instability to battery internals, leading to overheating with cascading effect to adjacent batteries	
PHL -50	Lithium-ion battery	Use	Super-system: Flooding from a water-pipe burst, or adjacent equipment	Battery and auxiliary circuitry damage	
PHL -51	Lithium-ion battery	Use	Super-system: Humidity variation	Only a risk during the production of lithium cells as it affects the quality, performance, and shelf life of the batteries.	
PHL -52	Lithium-ion battery	Use	Super-system: Projectiles of construction materials caused by exploding battery	Injury and damage	
PHL -53	Lithium-ion battery	Disposal	Super-system: recycling is not optimal	Environmental pollution and health risk	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -54	Lithium-ion battery	Use	Super-system: Run-off/residue water used in fire-fighting/cooling efforts is contaminated with chemicals	Environmental pollution and health risk	
PHL -55	Lithium-ion battery	Use	Super-system: temperature too high or too low during charging and discharging	Stressed battery, leading to instability, excessive heating, and other anomalies	Operating range: 5-45 ^{o}C?
PHL -56	Lithium-ion battery	Use	System: aged battery / battery reaches end- of-life	Unstable charging/discharging, leading to thermal runaway	
PHL -57	Lithium-ion battery	Use	System: charging below freezing temperatures (0^{o}C)	None. Only leads to reduced battery life and also the onset of thermal runaway.	
PHL -58	Lithium-ion battery	Use	System: During parallel charging of batteries of varying ages or state of charge	Stressed battery, leading to instability, excessive heating, and other anomalies	
PHL -59	Lithium-ion battery	All	System: Electrolyte separator failure	Failure to prevent overheating; internal short-circuiting / self-discharge	
PHL -60	Lithium-ion battery	Use	System: Fault current	Overheating of equipment and conductors, excesses forces, and at times even serious arcs, blasts, and explosions.	
PHL -61	Lithium-ion battery	Use	System: Toxic gas released by venting (burning) Li-ion cells	Harm to personnel	
PHL -62	Lithium-ion battery	Use	System: gradual temperature increase	Stressed battery, leading to instability, excessive heating, and other anomalies	
PHL -63	Lithium-ion battery	Use	System: Inadequate natural cooling to stop temperature runaway of batteries	Fire and explosion risk	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -64	Lithium-ion battery	Use	System: overcharged batteries	Stressed battery, leading to instability, excessive heating, and other anomalies	
PHL -65	Lithium-ion battery	All	System: Storage of cells when they are in a fully discharged state (< 2V per cell)	Partial electrical short, leading to instability during recharge	
PHL -66	Lithium-ion battery	Usage	System: ultra-fast charging is used	Stressed battery, leading to instability, excessive heating, and other anomalies	
PHL -67	Lithium-ion battery	All	System: Weight of battery components causes a heavy load on workspace structure	Injury during lifting; inadequate strength of mounting components	LIFE: 18.5kg per pack x 48 packs per house = 888 kg?
PHL -68	Lithium-ion battery	Use	Use of second-life batteries	possible growth of internal cell dendrites resulting from the continued charge/ discharge cycles until the capacity has degraded to 80% of nominal, increasing the risk of internal short-circuiting and later a thermal runaway	Typically in automotive cars, where the cost of battery renewal can cost as much as one-third the car price
PHL -69	Redox-flow battery (Volterion)	Use	Cooling system failure	overheating of cells	
PHL -70	Redox-flow battery (Volterion)	Production, Use, Disposal	Corrosive electrolyte (sulphuric acid-based solution) leading to membrane failure	Internal short-circuiting of battery, leading to overheating of electrolyte	Content: VRB electrolyte is 15% vanadium, 25% sulphuric acid, 60% water (by volume) ?

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -71	Redox-flow battery (Volterion)	Production, Use, Disposal	Corrosive eletrolyte (pH < 1) leads to stainless steel corrosion	Loss of containment of electrolyte, leading to environmental pollution and possible harm to human health	[183]
PHL -72	Redox-flow battery (Volterion)	Use	Electrolyte temperature < 5*C leads to precipitation of V2+/V3+ in the negative electrode	Lower battery efficiency	
PHL -73	Redox-flow battery (Volterion)	Use	Electrolyte temperature > 40*C leads to precipitation of V5+ in the positive electrode	Lower battery efficiency	
PHL -74	Redox-flow battery (Volterion)	Transport, Use Disposal	Leakage of electrolyte	Damage to adjacent and ancillary equipment; health hazard to people	
PHL -75	Redox-flow battery (Volterion)	Use	Overcharging, leading to elevated electrolyte temperature and hydrogen production (?)	Can lead to a thermal runaway situation	
PHL -76	Redox-flow battery (Volterion)	Use	Pump running dry	Damage to pumps components; potential leakage upon re-starting	
PHL -77	Redox-flow battery (Volterion)	Disposal	Solid ion-exchange cell membranes can be highly acidic or alkaline	Corrosive; health hazard	
PHL -78	Redox-flow battery (Volterion)	Production	Toxicity of vanadium in power form (before being mixed into liquid form during operations)	Inhalation by human operators	In liquid form, vanadium is not toxic
PHL -79	Hydrogen system	Use	Functional: Forced-ventilation does not function	Similar to PHL-13	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -80	House structure	Use	Emergency response vehicles not able to be in proximity of houses due to narrow access blocked access or soft ground	Fire-fighting efforts adversely impacted	
PHL -81	Water system	Use	Contamination of blue/white water by grey and/or black water	Upon contact, there could be a health impact on humans and plants; pollution to the environment due to drainage water	
PHL -82	Water system	Use	Water pipe leakage	Damage to household equipment, or the building itself, depending on the severity of the leak. If the leak is from black or greywater, there might be an impact on human health.	
PHL -83	Water system	Use	Low or high water pressure	For low pressure, the impact is a hassle for the user due to insufficient water volume. For high pressure, it may lead to leakage at outlets or piping joints.	
PHL -84	Water system	Use	Growth of microorganism in pipes and storage	Health impact to humans, such as diarrhoea, vomiting, irritation to skin and eyes, respiratory problems (non-exhaustive list), depending on microorganism type.	
PHL -85	Water system	Use	Insufficient treatment of water by the Grey and Blue boxes	Upon contact via direct or indirect methods, there could be health impact to humans and plants; pollution to the environment due to drainage water.	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -86	Water system	Use	Contaminant in grey-water: chemicals such as boron and phosphorus	Upon contact via direct or indirect methods, there could be a health impact on humans and plants; pollution to the environment due to drainage water.	
PHL -87	Water system	Use	Contaminant in grey-water: detergents and cleaning products	As above	
PHL -88	Water system	Use	Contaminant in grey-water: bleach and disinfectants	As above	
PHL -89	Water system	Use	Contaminant in grey-water: faeces and vomit	As above	
PHL -90	Water system	Use	Level of acidity/alkaline is unsuitable for vegetation and soil organisms	Perishing and growth disruption of plants	
PHL -91	Electrical system	Use	Electrocution or fire hazard caused by improper or deteriorated installations (e.g. wiring), inadequate electrical protection, overload due to new device installations, inappropriate usage, or intentional abuse	Electrocution, or fire - leading to loss of lives and/or property and equipment damage. Depending on the magnitude of electrical current, effects range from mild discomfort to severe injuries such as burns, tissue damage, cardiac arrest, which can be fatal.	For risk related to household equipment - see LVD, Machinery Directive, or General Product Safety Directive
PHL -92	Electrical system	All	Thermal effects	Excessive generation of heat, bringing the risk of fire or damage to the electrical item.	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL -93	Electrical system	All	Overcurrent	The excessive current that can lead to effects similar to electrocution and damage to electrical equipment	
PHL -94	Electrical system	All	Fault current	Excessive current/amperes that lead to tripping of relays, damage to insulation and components. The latter may lead to fire and electrocution hazards	
PHL -95	Electrical system	All	Voltage disturbances and electromagnetic influences (EMI)	Degrades the performance of electrical circuits, leading to malfunctioning or loss of equipment's function.	
PHL -96	Electrical system	All	Power supply interruption	Electrical equipment is unable to function.	
PHL -97	All systems	Construction	All worksite safety hazards due to civil, earthwork and structure construction. See Table B.3 in ISO 12100.	Injury due to cuts, falling objects, tripping, falling from heights, crushing, physical over-burdened and activities done in confined spaces, lifting, grinding, welding and cutting activities.	
PHL -98	Thermal energy system	Usage	Hot surfaces of the heated medium	Scalding and burns	
PHL -99	PV electricity generation	All	Electrical hazards, such as electrocution	Personnel injury and potential building fire	
PHL - 100	PV electricity generation	Disposal	Material recycling and disposal	Health and safety impact on personnel handling materials during disposal and recycling process. There is also	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
				environment hazard if materials (such as lead, cadmium, silicon and other toxic chemicals) are not correctly handled and disposed	
PHL - 101	Hydrogen system	Use	High noise from the release of pressurised hydrogen	Up to 140 dB noise can be generated from a 200 bar release, causing permanent loss of hearing for personnel nearby (within 50 m)	
PHL - 102	Hydrogen	Use	Operation: User misoperate, or unintentially abuse the system	Equipment malfunction, leading to unsafe conditions	
PHL - 103	Overall system	Use	Operation: User misoperate, or unintentially abuse the system	Equipment malfunction, leading to unsafe conditions	
PHL - 104	Home energy managemen t system, HEMS	Use	Imbalance between supply and demand during autarkic mode	Frequent power outage, or inability to obtain power when required	
PHL - 105	Overall system	Use	House dweller unaware, or lack basic understanding on operation of EESS installed in the building	House occupant unable to provide a satisfactory response to abnormal conditions	

ID	System	Lifecycle	Hazard	Hazard Effects	Comments
PHL - 106	Overall system	Construction	Homeowner unaware, or lack basic understanding on operation of EESS installed in the building	Homeowner unable to provide a satisfactory response to abnormal conditions	
PHL - 107	Overall system	Design	Homeowner installs EESS without complying with spatial planning requirements	Places home and surrounding in potentially hazardous conditions	
PHL - 108	PV electricity generation	Use	Too much locally-generated electricity is fed back into the grid	Grid voltage disturbances and transformer tripping, leading to a localised power outage	
PHL - 109	Overall system	Design	Energy generation or storage systems does not match required usage	Equipment does not perform up to expectations; disruptions to the quality of living in the house	

Appendix 4 Preliminary Hazards Assessment (PHA)

The definition of the headers in the spreadsheet are as follow:

- System: identifies the system being analysed
- Analyst: the person responsible for the analysis
- Date: the analysis date
- ID: a running number to identify the analysis entry
- Sub-system: the components within the system
- Hazard: a description of the identified hazard
- Causes: the possible source or origin of the hazard
- Effects: the potential consequences of the hazard, when an unsafe event triggers it
- Lifecycle: the phase in the equipment's life when the hazard is present
- Initial risk score: the assessment of the unmitigated risk, using the risk assessment table found in Table 6, page 15.
- Recommended action for the system integrator: These are suggested risk-mitigation measures, which should be further explored during the detailed design phase.
- Final risk score: the assessment of the potentially mitigated risk, supposing that the mitigation measures are effectively implemented. The score is derived from the same risk assessment table used to score the initial risk. For some hazards, no final risk score is available as the details of the mitigation measures has not yet been confirmed to the Safety Analyst. For such cases, the score is marked as 'tbd' (to be determined).
- Comments: additional remarks to help the understanding, or explanation of the identified hazard

Hydrogen system

System: Hydrogen			Analyst: Chua Eu Chieh			Date: 12 March 2020		
ID	**Hazard**	**Causes**	**Effects**	**Lifecycle**	**Initial risk score**	**Recommended action for system integrator**	**Final risk score**	**Comments**
Sub-system: Hydrogen production								
PHA-1	Formation of a flammable gas mixture of hydrogen and oxygen	Unintended release of hydrogen, leading to the formation of hydrogen mixture falling within the lower explosion (LEL) and upper explosion limits (UEL) in the atmosphere	Ignition, deflagration or detonation of the mixture. High flame temperatures and pressure shock wave will lead to property damage, personnel injury and potential fatality	Use	1C	Conduct a more detailed analysis (e.g. HAZOP and Bowtie studies) to understand how the hazard can be prevented and mitigated. Use a Quantitative Risk Assessment (QRA) to determine the safe distance for the individual and the public.	2C	Re-evaluate risk after the design of the hydrogen system has been completed by HyGear
Sub-system: Electrolyser								

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
PHA-2	Formation of a flammable gas mixture of hydrogen and oxygen	Mixing of hydrogen and oxygen within the electrolyser sub-system	Ignition, deflagration or detonation. Property damage and potential fatality	Use	1D	Similar to PHA-1 recommendations. Ensure the design of electrolyser sub-systems prohibits the mixing of hydrogen and oxygen, particularly in the gas separator, and to minimize the accumulation of hydrogen and oxygen.	tbd	Re-evaluate risk after the design of the electrolyser system has been completed by HyGear
Sub-system: Electrical components								
PHA-3	Electrical injury	Improper electrical design, low manufacturing quality, and equipment damaged during installation and maintenance	Electrocution, fire hazard, damaged electrical equipment and personnel injury	Construct, Use	3D	Design and test equipment according to relevant standards, such as NEN 1010. Underlying severity is low since low-voltage systems are used, and the presumption that electrical equipment has undergone testing and complies with relevant standards	3E	
Sub-system: Storage tanks								

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
PHA-4	Unintended release of hydrogen	The integrity of hydrogen storage vessel or piping compromised, resulting in leaks	Unignited or ignited gas release. Unignited release displaces oxygen, leading to asphyxiation. If the release rate is sufficiently high, pressure peaking phenomena may occur, leading to collapse of the structure housing the hydrogen system. High-pressure hydrogen jets can cut bare skin. The ignited release is described in PHA-1.	Use	1C	Similar to PHA-1 recommendations. To consider mitigation for high-pressure storage design, fire-resistant rating for storage tanks, suitable construction materials for gaseous hydrogen, siting of storage outdoors, safe separation distance, and use of thermally activated pressure relief valves. Apply periodic inspection and maintenance of equipment.	1D	Re-evaluate risk after the design of hydrogen system has been completed by HyGear
Sub-system: Hydrogen detection equipment								

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
PHA-5	Presence of hydrogen in the atmosphere is undetected	The inability of odourants in providing early warnings due to buoyancy and diffusivity of hydrogen atoms. High hydrogen purity requirement in fuel-cell may also exclude the usage of odourants	Late detection of hydrogen leads of formation of the flammable mixture and/or personnel injury or fatality	Use	1D	Use proper construction materials for equipment. Ensure appropriate fitting of hydrogen system components. Apply a proper inspection and maintenance programme to preserve the integrity of fittings. Combine the usage of point detectors and ultrasonic gas leak detectors to detect leakage of hydrogen. Proper positioning of detectors and sensors.	1E	Re-evaluate risk after the design of hydrogen system has been completed by HyGear
PHA-6	Hydrogen fire is undetected	Hydrogen flame is nearly invisible in daylight	Personnel exposure will lead to severe injury or fatality	Use	1D	Use of flame detectors. Restrict access to the storage and production area.	1E	As above
PHA-7	Hydrogen fire	Ignition of hydrogen or hydrogen mixture	High temperatures, leading to personnel injury and/or causing secondary fires on adjacent equipment	Use	1D	Develop a fire-fighting strategy for first responders. Minimise pipe diameters so that flame length is minimised. Minimise hydrogen pressure and inventory in the system. Consider the usage of fire barrier walls. Ensure	1E	As above

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
						proper positioning of outlet for ventilation and from thermal pressure-release devices.		

Lithium-ion battery system

System: Lithium-Ion battery	**Analyst: Chua Eu Chieh**	**Date: 2 April 2020**

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
Sub-system: Cells								
PHA-8	Cascading thermal runaway	Chemical reactions within the lithium-ion cell, initiated from any of these five causes: thermal abuse, mechanical abuse,	Release of combustible and toxic gases, leading to possible fire	Use	2C	For commercial-off-the-shelf batteries, ensure that the batteries are compliant to the relevant standards. Ensure that the design, installation and usage of batteries address the five mentioned causes of thermal runaway. The battery supplier should have performed safety	2D	Probability is assumed 1 in 1E6 cells. Phase 1 of LIFE project uses only 48 cells, and therefore the probability is

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
		electrical abuse, poor cell electrochemical design, internal cell faults due to manufacturing defects;				assessments, such as FMEA or Bowtie, to identify possible causes and mitigation for thermal runaway.		considered 'remote'.
PHA-9	Electrical injury	Electrical charges stored within the batteries	Amperes used in LIFE Li-ion system can reach up to 300A.	Construct, Use, Dispose	1D	Ensure that only trained personnel can access and maintain batteries. Batteries should be de-energised before attempting any handling. Perform periodic maintenance on electrical safety devices	1E	0.01A and more can cause severe personnel injury; 0.1 - 0.2A can cause fatality.
PHA-10	Release of toxic gas, such as HCl, HF, CO, HCN, and potential SO2 and H2S	During the thermal runaway phenomenon, the high temperatures within the cells cause deterioration of electrolytes and melting of the plastic casing.	A range of adverse effect on personnel, such as irritation, blistering and inhalation-related injuries.	Use	2C	Design of the battery should prevent thermal runaway phenomenon. If the occurrence of thermal runaway is unavoidable, then recovery barriers, such as the installation of an adequate ventilation system at the battery storage location, should be implemented.	2D	

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
PHA-11	Onset of overheating	Growth of lithium dendrite in the electrolyte, electrolyte separator flaws, overcharging, external force/pressure	The onset of the thermal runaway phenomenon	Use	2C	Use batteries supplied by reputable manufacturers and have been certified and tested according to relevant standards. Design of the battery should prevent thermal runaway phenomenon.	2D	
PHA-12	Heat accumulation and flammable gas release	Decomposing separator, decomposing solid electrolyte layer interface, exposure of anode. Exothermic reactions happen in adiabatic conditions causes heat accumulation within cells.	Temperature increase and oxygen accumulation within the cell creates a combustible environment. The toxic gas release has harmful effects on personnel.	Use	2C	As above	2D	
PHA-13	Combustion and explosion	Presence of oxygen, heat (both as a by-product of	Damage to the battery, adjacent equipment and	Use	2C	As above	2D	

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
		reactions in stage 2) and fuel (from inorganic electrolytes)	potential harm to personnel					
PHA-14	Thermal abuse	Cell exposure to elevated temperature > 70 degrees Celcius, typically from external heat sources	Can trigger the onset of overheating	Use	2C	Avoid the storage of combustible products in the vicinity of battery rack, and also heat sources (e.g. thermal radiators, stoves and ovens). Consider installing a fire-extinguishing system in the battery location.	2D	
PHA-15	Mechanical abuse	External impact, e.g. from piercing and crushing	Damage to electrolyte separators, leading to internal circuit shorting.	All phases	2C	Design of the battery should prevent thermal runaway phenomenon. Do not use batteries that have suffered mechanical damage.	2D	
PHA-16	Electrical abuse	Overcharging; Excessive rate of charging or discharging, external short-circuiting, over-discharge and subsequent re-charging.	Can trigger the onset of overheating	Use	2C	Design of the battery should prevent thermal runaway phenomenon.	2D	Higher battery capacity and sizes also lead to a higher likelihood of internal impedance heating

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
PHA-17	Poor cell electrochemical design	Incomplete or poor understanding of electrochemical interactions occurring in the cell components.	Triggers the onset of overheating	Use	2C	Design of the battery should prevent thermal runaway phenomenon.	2D	
PHA-18	Internal cell faults due to manufacturing defects	Manufacturing defects introduced and not detected during the cell production, assembly and handling	Triggers the onset of overheating	Production	2C	See check-list of good lithium battery design features. Use batteries supplied by reputable manufacturers and have been certified and tested according to relevant standards.	2D	
PHA-19	Leakage of electrolyte	Internal corrosion or mechanical damage to the casing	Solvents and salts in the electrolyte are volatile and toxic to humans	All phases	2C	Ensure a leak-proof packaging is used, especially if a soft-pouch cell is used.	2D	

Vanadium redox-flow battery (VRB) system

System: VRB system	Analyst: Chua Eu Chieh	Date: 24 April 2020

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
PHA-20	Deflagration	Not possible; the aqueous electrolyte is not flammable	none	Use	3F	Hazard can be considered eliminated. No further action required	3F	
PHA-21	Overheating	Internal and external short-circuiting effects on electrolytes	Leakage of electrolyte due to high-temperature degradation of containment (e.g. tanks and seals)	Use	3E	Ability to warn and automatically discontinue the battery operation in a short-circuiting event or at an abnormal elevated operating temperature.	3F	The thermal mass of electrolyte tanks is sufficient to absorb any temperature increases caused by internal and external short-circuiting scenarios.
PHA-22	Corrosion	Sulphuric acid is a strong acid and has pH < 1.	Degradation of containment; harm to environment and personnel	Production, Use, Dispose	3C	Use corrosion-resistant materials for containment, such as stainless steel 316L. Install a means to detect leaks. Perform periodic maintenance and inspections. Prevent pumps from dry-running,	3D	

						to avoid seal damage and subsequent leakage		
PHA-23	Toxicity	Material characteristics. Vanadium is possibly carcinogenic. It is hazardous to health when in powder form, before being mixed into liquid form in the battery electrolyte. When the acidic electrolyte is exposed to high heat, toxic fumes of sulphur oxides is emitted.	Harmful if swallowed; Upon contact with personnel, causes severe skin burns, eye damage and respiratory problems.	Production	3C	Use personnel protective equipment (PPE) when handling electrolyte. Ensure material Safety Data Sheet is available on-site for easy reference. Ensure sufficient ventilation at the storage area	3D	
PHA-23	Electrical injury	Contact with electrical energy stored in cells, or with electricity powering the pumps	Injury to personnel	Use	2D	Ensure that only trained personnel can access and maintain batteries. Batteries should be de-energised before attempting any handling.	2E	

Appendix 5 N² / Design Structure Matrix (DSM)

		Hum 1	Hum 2	Hum 3	Hum 4	Hum 5	Env 1	Env 2	Civ 1	Ele 1.1	Ele 1.2	Ele 1.3	Ele 1.4	Ele 1.5	Ele 1.6	Ele 1.7	Hea 1	Hea 2	Hea 3	Hea 4	Hea 5	Wat 1	Wat 2
Hum 1	House occupant	**Hum 1**								**3**		**37,127, 129, 135, 145**	**151, 128**	**149, 135 - 137**						**151, 98**			
Hum 2	Home owner	**152**	**Hum 2**									**136,149**	**151**	**149, 136**						**151, 98**			
Hum 3	Members of public			**Hum 3**								**15,127, 142, 129, 135**	**128**	**150, 135**									
Hum 4	Project Partner / Supplier		**153**		**Hum 4**						**156**	**42,156**		**156, 142**						**151, 98**			
Hum 5	House constructor					**Hum 5**				**97**	**97**	**42-47,97**	**97**	**97**	**97**	**97**	**97**	**97**	**97**	**97**	**97**	**97**	**97**
Env 1	Weather elements						**Env 1**					**125, 126, 130**											
Env 2	Ambient temperatures							**Env 2**				**143**											
Civ 1	House and civil structure								**Civ 1**														
Ele 1.1	Import electricity									**Ele 1.1**						**1**							
Ele 1.2	Generate electricity										**Ele 1.2**					**1,131**							
Ele 1.3	Electro-chemical energy storage system	**33**										**Ele 1.3**				**1,131**							
Ele 1.4	Consume electricity									**1**			**Ele 1.4**			**1,131**							
Ele 1.5	Chemical energy storage system	**35-37**		**37**	**35,36**									**Ele 1.5**		**1,131**							
Ele 1.6	Home power distribution system													**11**	**Ele 1.6**	**1,131**							
Ele 1.7	Home Energy Management System											**131**	**131**			**Ele 1.7**			**1**				
Hea 1	Collect heat															**1**	**Hea 1**						
Hea 2	Store heat															**1**		**Hea 2**					
Hea 3	Increase heat															**1**			**Hea 3**				
Hea 4	Consume heat															**1**			**1**	**Hea 4**			
Hea 5	Recover heat															**1**					**Hea 5**		
Wat 1	Import grid water											**141**		**140 , 141**								**Wat 1**	
Wat 2	Collect rain water																						**Wat 2**

		Wat 3	Wat 4	Wat 5	Wat 6	Wat 7	Wat 8	SoS 1	SOS 2	SoS 3	SoS 4	SoS 5	SoS 6	ST 1	ST 2	ST 3	ST 4	P 1	P 2	P 3	P 4	P 5	P6	RG 1	RG 2	RG 3	RG 4
Wat 3	Filter and store rain water	**Wat 3**																									
Wat 4	Treat rain water		**Wat 4**																								
Wat 5	Use treated water			**Wat 5**																							
Wat 6	Treat used water				**Wat 6**																						
Wat 7	Use re-treated water					**Wat 7**																					
Wat 8	Sewage discharge						**Wat 8**																				
SoS 1	Spatial planning							**SoS 1**																			
SoS 2	Electricity supply grid								**SOS 2**																		
SoS 3	Water supply grid									**SoS 3**																	
SoS 4	Sewage grid										**SoS 4**																
SoS 5	University of Twente's fire-fighting response system											**SoS 5**		**36**		**36**											
SoS 6	Road and transport system												**SoS 6**														
ST 1	Regional fire-fighting organisation													**ST 1**		**36**											
ST 2	Public security														**ST 2**												
ST 3	Human resources development											**36**		**36**		**ST 3**											
ST 4	Research and innovation																**ST 4**										
P 1	Carbon and emission targets																	**P 1**									
P 2	Housing policies																		**P 2**								
P 3	Energy policies																			**P 3**							
P 4	Building insurance policies																				**P 4**						
P 5	Financing systems																					**P 5**					
P 6	National regulations																						**P 6**				
RG 1	Technical codes and standards																							**RG 1**			
RG 2	Paris Climate Agreement 2016																								**RG 2**		
RG 3	Resource supply chains																									**RG 3**	
RG 4	Inter-operability																										**RG 4**

Appendix 6 System Hazards Assessment (SHA)

The headers used in the SHA spreadsheet are:

- Safety-related functions: derived from the main category of hazards
- The other fields, such as the Analyst, Date, ID, Causes, Effects, Lifecycle, Initial risk score, Recommended action for the system integrator, Final risk score, and Comments, have the same definition as used in the Preliminary hazards analysis (PHA) spreadsheet.

System Hazards Assessment			**Analyst: Chua Eu Chieh**			**Date: 5 May 2020**		
ID	**Hazard**	**Causes**	**Effects**	**Lifecycle**	**Initial risk score**	**Recommended action for system integrator**	**Final risk score**	**Comments**
Safety-critical item: Battery ambient temperature control								
SHA-1	Battery charges at low temperatures (below 0°C)	Charge controller does not stop the charging process at low temperatures	Anode plating, increasing the risk of thermal runaway initiation	Use	3C	To ensure this scenario is taken into consideration when designing the battery charge controllers	3D	
Safety-critical item: Battery siting/location								
SHA-2	Flooding	Heavy rains and capacity of the drainage system is exceeded	External short-circuiting of batteries and electrical shock hazards	Use	2C	Place the battery systems at a safe height beyond the historical water flood level.	2D	Historical water-level heights/flooding data are available

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
SHA-3	Mechanical impact	Accidental collision by vehicles, falling of overhead tree branches, or collapse of the housing structure	The onset of lithium battery internal thermal runaway	Use	3C	Locate the battery away from heavy traffic flow (e.g. cars, etc.), and out of reach of falling tree trunks, with collision-protection barriers.	3D	
Safety-critical item: Civil structure integrity								
SHA-4	The high release rate of hydrogen into an indoor atmosphere	Loss of containment from the indoor hydrogen system	Pressure-peaking phenomena, leading to roof blowout, or structural collapse of the building containing hydrogen systems.	Use	1C	Design the building capable of withstanding the pressure-peaking phenomena, for indoor hydrogen systems.	1D	
SHA-23	Weight of battery	LIFE: 18.5kg per pack x 48 packs per house = 888 kg?	Building structure unable to bear the load, leading to structure failure	Install; Use	2C	To consider the load-bearing capacity of battery room	2E	

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
Safety-critical item: Containment and disposal of VRB electrolyte								
SHA-5	Significant release of electrolyte from the containment system	Mechanical impact	Harm to personnel when in contact and inhalation due to strong acidity of electrolyte. Negligible eco-toxicity	Use	3D	No further action necessary, as a built-in sensor to detect and warn of primary containment leak is sufficient to mitigate the hazard	3D	Refer to Safety Data Sheet for VRB electrolyte
Safety-critical item: Electrical safety								
SHA-6	Frequent inverter on/off occurrence during the day	Insufficient sun-light, power outage/ disruption, inverter failure, and high voltage output at the inverter.	Intermittent charging of batteries and hydrogen production (frequent on/off operations). Potential inverter/controller circuitry damage?	Use	4B	Presumably, the intermittent nature of battery charging and discharging does not result in a safety hazard. To check with Partners on possible effects. Any impact on the condition of batteries?	4B	
SHA-7	Emergency power-down of batteries and hydrogen systems	The development of hazardous conditions triggers safe-	Safety-related systems lose power and do not provide the	Use	2C	To ensure that safety-related systems - such as forced ventilation, gas detectors, alarms and emergency lighting, gas-	2D	

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
		shutdown of EES	required functions			flooding system - has an alternate power supply, and will still function during an emergency		
Safety-critical item: Gas and fire detection system; Ventilation system								
SHA-8	Detection and/or ventilation system malfunctions	Malfunction or failure of any one of the equipment or components;	Decreased ability to mitigate a potentially catastrophic event (e.g. fire and explosion)	Use	3C	Perform a Bow-tie analysis to a more detailed study on the preventive and reactive barriers to prevent catastrophic events from occurring. If feasible, use natural ventilation as opposed to induced ventilation. Implement an inspection and maintenance programme for the gas detection and ventilation equipment	3D	The initial risk score is similar to that derived from PHA for the hydrogen system
SHA-9	Detection and/or ventilation system malfunctions	No power supply to the induced ventilation system	Decreased ability to mitigate a potentially catastrophic event (e.g. fire and explosion)	Use	3C	Incorporate a status-indicator to alert the user to the malfunctioning of safety protection equipment.	3D	Creating an interlocking relationship, i.e. malfunctioning of the gas detection and

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
								ventilation system would result in the shutdown of the hydrogen and battery systems, might cause a nuisance to the users.
SHA-10	The user intentionally disables the system	Human error	Similar to the above	Use	3C	As above	3D	
Safety-critical item General systems								
SHA-11	Intentional abuse/vandalism electrical components of energy storage systems	Components are physically exposed, coupled with malicious intentions	Potential electrical injury by the perpetrator, malfunction of energy storage systems	Use	3D	Limit the accessibility of battery and hydrogen systems in a secured place to only authorised personnel (e.g. home inhabitants and maintenance personnel). Minimise exposure of components (e.g. wiring) to external elements—for example, use of cable conduits.	3D	To check with UT's campus housing management on what types (if any) acts of vandalism is prevalent in the campus or

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
								accommodation
Safety-critical item: Hydrogen production and storage								
SHA-12	Capacity or purpose of the area in the vicinity of hydrogen production and storage is changed (e.g. Addition of buildings/installations in the vicinity)	Planned changes in the surrounding layout	Safety distance is compromised	Use	1C	Ensure proper zoning for material storage and siting. Implement a Management of Change process to take into account such changes.	1D	The initial risk score is similar to that derived from PHA for the hydrogen system
SHA-13	Storage/siting of flammable materials in the vicinity of hydrogen storage and production	Intentional or unintentional material storage	Increased risk of fire and explosion	Use	1D	As above	1D	Procedural measures is not a reliable barrier
SHA-14	Addition of hydrogen production and storage capacity	Increased demand for hydrogen/electricity	Increased risk of fire and explosion	Use	1C	Ensure that the threshold of hydrogen production and storage, as calculated in the qualitative risk	1D	

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
						assessment (QRA), is not exceeded. If an exceedance is unavoidable, re-evaluate the QRA.		
SHA-15	Electrolyser and fuel-cell cooling system malfunction	To be investigated in sub-system design	Hydrogen system shutdown, leading to loss of production	Use	4F	In the hydrogen system design, the occurrence of the hazard should trigger an automatic shutdown of hydrogen production	-	Safe system shutdown has negligible safety risks. Should have been considered under the sub-system safety hazard assessment or HAZOP
SHA-16	Water supply disruption	To be investigated in sub-system design	Hydrogen system shutdown, leading to loss of production	Use	4F	As above	-	As above
SHA-17	Incoming water quality out of specifications	Incoming water contains, or exceeds the level of contaminants that can be	More load is exerted on the water treatment (Reverse osmosis / electrodesionis	Use	4D	To find out what specific input water quality specifications are needed. No additional actions required, as negligible operational safety hazard is	-	Not a safety concern

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
		conditioned by the water treatment system	ation - RO/EDI) system, and could result in more frequent maintenance and potential operational disruptions.			expected. Routine maintenance safety precautions to be undertaken.		
SHA-18	Hydrogen gas ignite during maintenance or upkeep operations	Hot-work is performed in the presence of combustible gas, wrong commissioning after maintenance, leak caused by poor maintenance and electrical failures	Introduction of the hazardous situation leading to injury, loss of life and asset damage	Use	1C	The threat is mitigated if the hydrogen system is purged-free from hydrogen gas before the start of maintenance, either through procedural or hardware means. Only trained personnel should perform maintenance. Maintenance procedure should emphasize safety measures during all stages of maintenance operations.	1D	Based on industry statistics, ARIA
Safety-critical item: Lithium battery ambient temperature controls								
SHA-19	System malfunction	Malfunction or failure of any one of the equipment or components;	Temperatures not maintained within the operating range of batteries.	Use	4C	Outside the operating temperature range, the charge controller should stop the charging and discharging process. The decision to install	4C	

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
		or interrupted power supply				ambient temperature controls depends on the purpose of batteries and seasonal operating modes, and the expected ambient temperature (based on historical values and future projections). To consider installing a back-up power supply to the ambient temperature control system, if the functionality is required throughout the year.		
SHA-20	BMS malfunctions resulting in its inability to monitor the charging and discharging rate of the battery pack	Malfunction or failure of any one of the electronic components	Potential electrical abuse on battery cells, resulting in the onset of internal thermal runaway	Use	3C	Incorporate a status-indicator to alert the user to the malfunctioning of safety protection equipment. An automatic halt of battery operations until the functionality of BMS has been restored.	3D	
SHA-21	The system is intentionally disabled by the user	Human error	Similar to the above	Use	4C	The automatic halt of battery operations until the functionality of BMS has been restored.	4C	
Safety-critical item: Oxygen production								

ID	Hazard	Causes	Effects	Lifecycle	Initial risk score	Recommended action for system integrator	Final risk score	Comments
SHA-22	Pure oxygen	Oxygen is directed to an unsafe location	Oxidizing agent; causes violent reactions or fires with materials such as oil and grease. Some materials will combust spontaneously in the presence of pure oxygen.	Use	1D	In the absence of an oxygen storage capability, the pure oxygen should be routed to a safe location in the atmosphere, where contact with flammable material or humans is avoided.	1E	High-pressure oxygen can cause nausea, dizziness, loss of muscle control, fits or loss of consciousness. However, the LIFE system does not produce pressurised oxygen.

Appendix 7 Hazards tracking database – as of 1 October 2020, with 'Open' status

The fields of the database are very similar to that used in the PHA and SHA spreadsheets, with the addition of the following:

- Hazard status: if the hazard entry is still pending resolution (i.e. Open), or has been resolved to a satisfactory manner (i.e. Closed). Only hazards with 'Open' status are listed here.
- Reason for closure: a short description to explain the reasons for no longer tracking a specific hazard
- Action and responsible party: A brief description of the required activities and the responsible party to carry out those actions

Hydrogen system

Hazard ID	Source	Hazard	Initial risk score	Final risk score	Action and responsible party
101	PHA-1	Formation of a flammable gas mixture of hydrogen and oxygen	1C	2C	HyGear - provide input for QRA
104	PHA-4	Unintended release of hydrogen	1C	1D	HyGear - design, maintenance recommendations
128	SHA-4	The high release rate of hydrogen into an indoor atmosphere	1C	1D	HyGear - recommendations for ventilation system requirements
136	SHA-12	Capacity or purpose of the area in the vicinity of hydrogen production and storage is changed (e.g. Addition of buildings/installations in the vicinity)	1C	1D	Utwente - verify if the management of change procedure is in place
138	SHA-14	Addition of hydrogen production and storage capacity	1C	1D	Utwente - verify if the management of change procedure is in place
142	SHA-18	Hydrogen gas ignite during maintenance or upkeep operations	1C	1D	HyGear - design for maintenance, and recommendations for safe maintenance
149	PHL-102	Operation: User misoperate, or unintentionally abuse the system	1C	Tbd	HyGear - conduct HAZOP study
102	PHA-2	Formation of a flammable gas mixture of hydrogen and oxygen – within the electrolyser	1D	1D	HyGear - conduct HAZOP study
105	PHA-5	Presence of hydrogen in the atmosphere is undetected	1D	1E	HyGear - design

Hazard ID	Source	Hazard	Initial risk score	Final risk score	Action and responsible party
106	PHA-6	Hydrogen fire is undetected	1D	1E	HyGear - design
107	PHA-7	Hydrogen fire	1D	1E	HyGear - design Utwente - emergency response guidelines
137	SHA-13	Storage/siting of flammable materials in the vicinity of hydrogen storage and production	1D	1D	Utwente - storage area management
146	SHA-22	Pure oxygen	1D	1E	HyGear - design considerations
147	PHL-101	High noise from the release of pressurised hydrogen from pressure-relief valve (PRV)	2C	2D	HyGear - design considerations
132	SHA-8	Detection and/or ventilation system malfunctions – due to malfunction or failure of any one of the equipment or components;	3C	3D	Utwente, SuperB, Volterion, HyGear - decide on safety-related systems and functional-safety aspects
133	SHA-9	Detection and/or ventilation system malfunctions – due to no power supply to the induced ventilation system	3C	3D	Utwente, SuperB, Volterion, HyGear - decide on safety-related systems and functional-safety aspects

Li-ion battery systems

Hazard ID	Source	Hazard	Initial risk score	Final risk score	Action and responsible party
43	PHL-43	Super-system: adjacent systems emit vibrations, causing connectors to loosen	2C	2D	Utwente - to check if any source of vibrations from adjacent systems (e.g. pumps)
44	PHL-44	Super-system: Battery disposed of not using proper channels	2C	2D	Utwente, HyGear, SuperB, Volterion - guidelines for safe disposal
45	PHL-45	Super-system: Battery-management system interface cables inadvertently is disconnected	2C	2D	SuperB - verify if design allows this to occur

Hazard ID	Source	Hazard	Initial risk score	Final risk score	Action and responsible party
47	PHL-47	Super-system: during transportation, connectors become loose	2C	2D	Utwente - To verify if post-installation checks include inspection for connection-tightness
65	PHL-65	System: Storage in a fully discharged state (< 2V/cell)	2C	2D	SuperB - design consideration
68	PHL-68	Use of second-life batteries	2C	2D	Utwente, SuperB - guidelines for second-life use
109	PHA-9	Electrical injury	1D	1E	SuperB - maintenance recommendations
110	PHA-10	Release of toxic gas, such as HCl, HF, CO, HCN, and potential SO2 and H2S	2C	2D	SuperB - assure the air-ventilation requirements
114	PHA-14	Thermal abuse	2C	2D	Utwente and SuperB - decide if the fire-extinguishing system is required
116	PHA-16	Electrical abuse	2C	2D	SuperB - assure design of electrical components and fittings
125	SHA-1	Battery charges at low temperatures (below 0*C)	3C	3D	SuperB - provide assurance on design
127	SHA-3	Mechanical impact	3C	3D	Utwente - battery siting
144	SHA-20	BMS malfunctions resulting in its inability to monitor the charging and discharging rate of the battery pack	3C	3D	SuperB - provide assurance on design

VRB systems

Hazard ID	Source	Hazard	Initial risk score	Final risk score	Action and responsible party
70	PHL-70	Corrosive electrolyte (sulfuric-acid based solution) leading to membrane failure	2D	2E	Volterion - confirmation on design feature
123	PHA-23	Toxicity	3C	3D	Utwente - ventilation design

Hazard ID	Source	Hazard	Initial risk score	Final risk score	Action and responsible party
124	PHA-24	Electrical injury	2D	2E	SuperB and Volterion - user interface design and de-energising features

All other hazards, not explicitly related to hydrogen and battery systems

Hazard ID	Source	System	Hazard	Initial risk score	Final risk score	Action and responsible party
80	PHL-80	House structure	Emergency response vehicles not able to be in proximity of houses due to narrow access, blocked access, or soft ground	1D	2D	Utwente- produce guideline for safe disposal of PV panels
100	PHL-100	PV electricity generation	Material recycling and disposal	1D	tbd	Utwente, SuperB, Volterion, HyGear - decide on safety-related systems and the need for back-up power supply for these systems
131	SHA-7	Electrical system	Emergency power-down of batteries and hydrogen systems	2C	tbd	Utwente, SuperB, Volterion and HyGear - to analyse Operational hazards
150	PHL-103	Overall system	Operation: User misoperate, or unintentially abuse the system	2C	tbd	Utwente - identify impact of HEMS on ESS safety
1	PHL-1	Home energy management system, HEMS	To explore further effects of HEMS failing to operate, operating incorrectly, receiving or sending erroneous information.	3C	tbd	Utwente - ensure worksite safety procedures are available and adhered to.
97	PHL-97	Overall system	Worksite safety hazards due to civil, earthwork and structure construction. See See Table B.3 in ISO 12100.	3D	3D	Utwente and project partners - ensure clear responsibilities for equipment and integrated system, throughout the

Hazard ID	Source	System	Hazard	Initial risk score	Final risk score	Action and responsible party
						design, installation and testing
99	PHL-99	PV electricity generation	Electrical hazards, such as electrocution	3D	tbd	Utwente - access restriction
135	SHA-11	Overall system	Intentional abuse/vandalism electrical components of energy storage systems	3D	tbd	Utwente, SuperB, Volterion and HyGear - to analyse Operational hazards
152	PHL-105	Overall system	House dweller unaware, or lack basic understanding on operation of EESS installed in the building	3C	2D	Utwente, SuperB, Volterion and HyGear - to analyse Operational hazards
153	PHL-106	Overall system	Home owner unaware, or lack basic understanding on operation of EESS installed in the building	3C	tbd	Utwente- produce guideline for safe disposal of PV panels
100	PHL-100	PV electricity generation	Emergency response vehicles not able to be in proximity of houses due to narrow access, blocked access, or soft ground	1D	tbd	Utwente, SuperB, Volterion, HyGear - decide on safety-related systems and the need for back-up power supply for these systems

Appendix 8 Qualitative risk calculations

Formulas used

An explanation of the formulas used to calculate the initial (unmitigated) and residual (mitigated) risks is as follows. A number of the formulas was referenced from the LOPA handbook published by the CCPS in 2001 [159].

The **initial (or unmitigated) frequency of fatality** refers to the probability of a fatality occurring if there had been no safeguards or independent protection layers in place. In reality, this is not possible as practical systems inevitably have safeguards built-in. Nevertheless, this measure gives a rough indication of the raw risk that is present and if this risk is deemed acceptable. The term 'Likelihood' and 'frequency' both refers to the probability and can be used interchangeably. The unit for the likelihood is in 'per opportunity per year', as in '1 in 10 000 pieces per year' or '1 in 1 million operating hours per year'. The initial frequency of fatality is also used to represent the initial/unmitigated risk since the frequency is defined for a very specific consequence (i.e. fatality).

$$Initial\ likelihood\ of\ fatality, F_o = IEF \times P_H \times P_F \quad (1)$$

Where

IEF is the initiating event frequency;

P_H is the probability of human presence, or the average human exposure hours in a year to the analysed hazard

P_F is the probability of immediate fatality, different from F_o, is the probability that the unsafe event can cause instant fatality to human is present near the equipment or system.

For a single initiating event, the **frequency of top event due to the *i*-th initiating event** is obtained by:

$$f_i^T = IEF_i \times PFD_{i1} \times PFD_{i2} \times \ldots \times PFD_{ij} \quad (2)$$

IEF_i is the initiating event frequency for the *i*-th cause;

PFD_{ij} is the Probability of Failure on Demand for the *j*-th proactive independent protective layer, for a related to the *i*-th cause. The derivation of PFD is further explained in (6)

When there are multiple initiating events commonly seen in a Bowtie diagramme, the **frequency of the top event for aggregated initiating events** is obtained by summing up the frequencies of all the different causes:

$$Aggregate\ top\ event\ frequency, f^T = \sum_{i=1}^{I} f_i^T$$
$$= f_1^T + f_2^T + \cdots + f_I^T \tag{3}$$

Where

f_i^T is the frequency for top event T for *i*-th initiating event

The f**requency of a consequence** refers to the probability of a consequence occurring, taking into consideration the safeguards or barriers that are in place. The consequence is focused on the probability of having a human fatality. This definition is taken from[184].

$$f_i^C = f^T \times PFD_{i1} \times PFD_{i2} \times \ldots \times PFD_{ij} \tag{4}$$

Where

f_i^C is the frequency for consequence *C* for *i*-th consequence

f^T is the frequency of the top event for aggregated initiating events, calculated from (3)

PFD_{ij} is the Probability of Failure on Demand of the *j*-th reactive (or, mitigative) IPL that protects against consequence *C* for initiating event *i*

Finally, the **mitigated frequency** (and risk) **of a single fatality occurring**, after taking into account the independent protective layers and safeguards that are put in place, is obtained from:

$$f_{mit.} = f_i^C \times P_H \times P_F \tag{5}$$

Where

f_i^C is the frequency of the i-th consequence, obtained from (4)

P_H and P_F are both the same values as used in (1), where

P_H is the probability of human presence, or the average human exposure hours in a year to the analysed hazard

P_F is the probability of fatality in the scenario where human is present near the equipment or system when the consequence occurs, The **Probability of Failure on Demand (PFD)** of a safety-system refers to the likelihood that a system fails to work when it is required to perform its safety function. IEC 61508 contains several formulas for several component configurations, and most were derived from [185]:

$$PFD_{avg} = \lambda_D t \tag{6}$$

Where

λ_D is the frequency of dangerous and undetected failure

t is the mean downtime of the system

The average value of PFD is taken as the reliability of a system is time-dependent. Since the effectiveness of safeguard-type barriers cannot be quantified, its Probability of Failure on Demand (PFD) is assigned as '1'.

Calculation of risks for the hydrogen system

Note: In the following calculations, data, especially for the Initiating event frequency (IEF) and the Probability of Failure on Demand (PFD) were compiled from several sources. For brevity, the frequently-cited ones would be denoted by the following, with the full reference as given below:

- *CCPS LOPA (2001): Center for Chemical Process Safety (CCPS), Layer of protection analysis: simplified process risk assessment. New York: Wiley, 2001, p. 292.*
- *CCPS LOPA (2007): Center for Chemical Process Safety (CCPS), "Protection Layers," in Guidelines for Safe and Reliable Instrumented Protective Systems: American Institute of Chemical Engineers, 2007, pp. 267-299.*
- *CCPS LOPA (2015): Center for Chemical Process Safety (CCPS), Guidelines for Initiating Events and Independent Protection Layers in Layer of Protection Analysis (LOPA): VitalSource Bookshelf, 2015. [Online]*

Other less-cited sources are cited and referenced typically.

Bowtie scenario:

Hazard: Formation of a flammable gas mixture of hydrogen and oxygen indoors and outdoors
Top Event: Indoor or outdoor release of hydrogen from containment

The Bowtie diagram has six threats and ten consequences.

Threats / Causes:

1. Corrosion (Hydrogen embrittlement)
2. Leaking at joints
3. Outdoor storage tank rupture due to external impact

4. Outdoor storage tank rupture due to heat from external fires (less likely to occur if steel tanks are used, as was proposed for use in the LIFE project)
5. Gas separation membrane failure within the electrolyser
6. Maintenance personnel mistake (assumed to be the most likely cause of top event occurring)

Consequences:

1. The displacement of oxygen in an indoor environment, leading to a person's asphyxiation
2. The displacement of oxygen in an outdoor environment, leading to a person's asphyxiation
3. A delayed ignition for indoor systems
4. The immediate or spontaneous ignition/deflagration of mixture
5. Hydrogen mixture detonation, resulting in shock waves (worst-case consequence)
6. Hydrogen flame propagation leading to an indoor secondary fire
7. Routing of indoor hydrogen to outdoors, leading to an outdoor secondary fire
8. Human exposure to the flame's high temperature/thermal radiation
9. Pressure-peaking phenomenon leading to the structural collapse of the enclosure
10. Ignition during maintenance (most likely consequence)

Two versions were created for each Top Event. Version 1 is the 'idealised scenario' where every possible barrier is included. Version 2 represents the 'LIFE conceptual design' scenario, where only the barriers specified in the conceptual design project specifications are included.

Version 1 Bowtie – idealised scenario

The causes and the adopted initiating event frequencies in the corresponding Bowtie are shown below, to help the understanding of the calculations.

Initial risks

The scenario used is the loss of containment of hydrogen gas, leading to explosion and fire.

Using Equation (1), the initial risk of a single fatality is obtained. For the individual, two types of profile have been defined: the building resident and the maintenance personnel. The difference between the two lay in the exposure hours. The public refers to passersby or an adjacent neighbour who could be at home at all time.

Table 37 Version 1 Hydrogen system Bowtie: Adopted Initiating Event Frequencies (IEF) for identified causes/threats

No.	Cause	IEF (y^{-1})	Remarks / Source
1	Corrosion	1×10^{-4}	Pressure vessel residual failure, Table 5.1, CCPS LOPA (2001) [159]. Use conservative number, corresponding to the failure rate of small leaks (Purple Book, VROM 2005) [62]
2	Leaking at joints	1×10^{-3}	EU/Ineris/Air Liquide study (initiating event I8, from HP fittings, valves or piping connections)
3	Storage tank rupture due to mechanical impact	1×10^{-2}	Third-party intervention, Table 5.1, CCPS LOPA (2001)
4	Storage tank rupture due to external fire	1×10^{-2}	Large fire from aggregate causes, Table 5.1 (CCPS 2001)
5	Electrolyser membrane leak	1×10^{-5}	PFD data is unavailable. Worst case scenario for membrane leak, Table 5, Psara et al. [163] is 1×10^{-7}
6	Maintenance personnel mistake	1×10^{-3}	Lock-out-tag-out mistake Table 5.1, CCPS LOPA (2001)

The assumptions used:

- **Human exposure**
  - of the building resident: The average Dutch household size was 2.2 in 2019. The assumption used was that three residents would be in the house 16 out of 24 hours per day, on average in a week. The higher number takes into account any visitors, and family members staying at home in the weekends.
  - of the maintenance personnel: Maintenance is done once a year, lasting a total of 24 hours (i.e. 8 hours x 3 days)
  - of the public or adjacent neighbour: always assume that a person is exposed at any time of the day
- **The initiating event frequency (IEF)**: The cause with the most conservative of initiating event frequency (IEF) from the identified causes is used. From Table 37 these were Cause #3 and Cause #4 with the value 1×10^{-2}.
- **The probability of immediate fatality**: The value of '1' was used for hydrogen explosion and fire, based on the premise that it is almost impossible to avoid the direct impact of a hydrogen explosion or fire when it occurs in the immediate surrounding of the person (e.g. up to 5 meters).

The outcome is shown in Table 38. The calculated likelihood value is rounded to the nearest non-zero decimal number.

Table 38 Version 1 Hydrogen system Bowtie: Initial risk calculation hydrogen top event bowtie

	Initiating Event Frequency (y^{-1}), *IEF*	**Human exposure** (y^{-1}), P_H	**Probability immediate fatality,** P_F	**Likelihood of fatality** (y^{-1}), $F_o = IEF \times P_H \times P_F$
Individual (resident)	1×10^{-2}	6.7×10^{-1}	1	7×10^{-3}
Individual (maintenance personnel)	1×10^{-2}	2.7×10^{-3}	1	3×10^{-5}
Societal (public)	1×10^{-2}	1	1	1×10^{-2}

The acceptability criteria that were selected:

Table 39 The chosen acceptability risk criteria

	Acceptability value (y^{-1})
Individual	Less than 1×10^{-6}
Society	Less than 1×10^{-3}

The worst-case likelihood, i.e. risk for the Individual (resident), is used to represent the Individual risk. When the outcome is compared with the selected acceptability values, the initial risks for Individuals and the Society are shown to be unacceptable.

Risk mitigation

The adopted values of the Probability of Failure on Demand (PFD) of the identified Independent Protection Layers (IPLs) are shown below.

Preventive IPLs:

Table 40 Version 1 Hydrogen system Bowtie: Preventive IPLs

No.	Independent Protection Layer	PFD (y^{-1})	Remarks / Source
1	Pipe and vessel outer casing	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001)
2	Joint design, e.g. compression joints	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001)
3	In-line shut-off valves to cut off flow when the higher-than-normal flow is detected within the piping	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001)
4	Siting of vessels	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001). Also, Guideline for safe and reliable instrumented protective systems, CCPS (2007)[171]
5	Physical anti-collision barrier	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001)
6	Relief valve	1×10^{-2}	Active IPL, Table 6.4, CCPS LOPA (2001)
7	Fire-proofing	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001) Relevant only if composite tanks are used. In the LIFE project, steel tanks are used, and thus fire-proofing materials are not applied to it.
8	Design basis – more robust electrolyser	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001)
9	Design basis – maintenance mode	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001)
10	Behavioural barriers	1×10^{-1}	Only applicable to a scenario involving maintenance activities. Risk-reduction can be credited if there are proper maintenance procedures, training and validation of competency, William Bridges [166]

Table 41 Version 1 Hydrogen system Bowtie: Mitigative IPLs

No.	Independent Protection Layer	PFD (y^{-1})	Remarks / Source
1	Safety Instrumented Function: Emergency shut-down of hydrogen production	1×10^{-2}	consider as SIL-1, Table 6.4, CCPS LOPA (2001)
2	Siting of storage tanks outdoors	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001)
3	Design basis: use of EX-rated equipment,	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001)

No.	Independent Protection Layer	PFD (y^{-1})	Remarks / Source
	lightning protection devices		
4	Blast walls and flame barrier walls	1×10^{-2}	Blast walls/bunker, Table 6.3, CCPS LOPA(2001)
5	Use of fire-proofing materials	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001)
6	Design basis: positioning of indoor ventilation exhaust points outside the building	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA(2001)
7	Use of flame arrestors	1×10^{-2}	Flame/Detonation Arrestors, Table 6.3, CCPS LOPA (2001)
8	Design basis: removal of possible mechanical and thermal ignition sources	1×10^{-2}	Only take the credit if it is due to the inherent safe design, Table 6.3, CCPS LOPA (2001)
9	Design basis: the strength of civil structures	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA (2001)
10	Indoor natural ventilation for explosion venting	1×10^{-1}	Cannot be used as IPL for fire consequences, but only for asphyxiation and pressure-peaking consequences; Similar PFD as forced-ventilation. Table B5, CCPS LOPA (2007) [171]
11	Use of proper personnel protection equipment (PPE)	1×10^{-1}	Table 5.49, Guidelines for initiating events and IPLs in LOPA, CCPS LOPA (2015) [160]. Only credited if used in conjunction with a portable hydrogen detector and proper execution of operational / maintenance procedures

Table 42 Version 1 Hydrogen system Bowtie: Identified safeguards, which are not be considered as Independent Protection Layers (IPLs)

No.	Safeguard	PFD (y^{-1})	Remarks / Source
1	Indoor hydrogen detectors and alarm - portable or fixed	1	Reliability of hydrogen detectors are generally low, and effectiveness is influenced by the type, placement location and quantity used. Risk-reduction credit can be credited if such detection systems are connected to safety instrumented functions
2	Use of flame detectors and warning system	1	Only provides warning without further fire-quenching response
3	Indoor induced-draft ventilation	1	The system can be disabled due to fire, explosion or power outage. The constant functionality should not be assumed unless it is a passive type, or if there is continuous validation of its functionality.
4	Indoor fire suppression system / automatic deluge	1	Water does not extinguish hydrogen fires and can only act as a cooling agent for adjacent equipment. Credit may be taken for secondary-fire cases, and only if the deluge system is connected to safety-instrumented functions. Note that the hydrogen storage system used in the LIFE project does not have a fire-suppression system installed.
5	Community emergency response and evacuation procedures, including working from a safe distance	1	Not typically regarded as IPL as its implementation is highly dependent on local conditions; CCPS LOPA (2015)
6	Behavioural barriers where a human response is required for system consequences	1	For residential buildings, it is assumed that the inhabitants do not have the necessary competency to provide the correct response. Credit can be taken only if all related sub-systems operate correctly and promptly; CCPS LOPA (2007).
7	Proper house-keeping to keep area uncongested	1	Is a behavioural barrier and cannot be assured; CCPS LOPA (2001).

Mitigated risk

Using Equation (2), the **top event frequencies due** to a particular initiating event, f_i^T, is calculated after taking into account the IEF of all the potential initiating event/causes, and the PFD of all the potential Independent Protection Layers/safety barriers. The illustration of how f_i^T is obtained for Cause #6 – 'maintenance personnel mistake' - can be seen in the Bowtie Figure 30 and the accompanying calculation. f_i^T is similarly calculated for all the causes and is shown in Table 43.

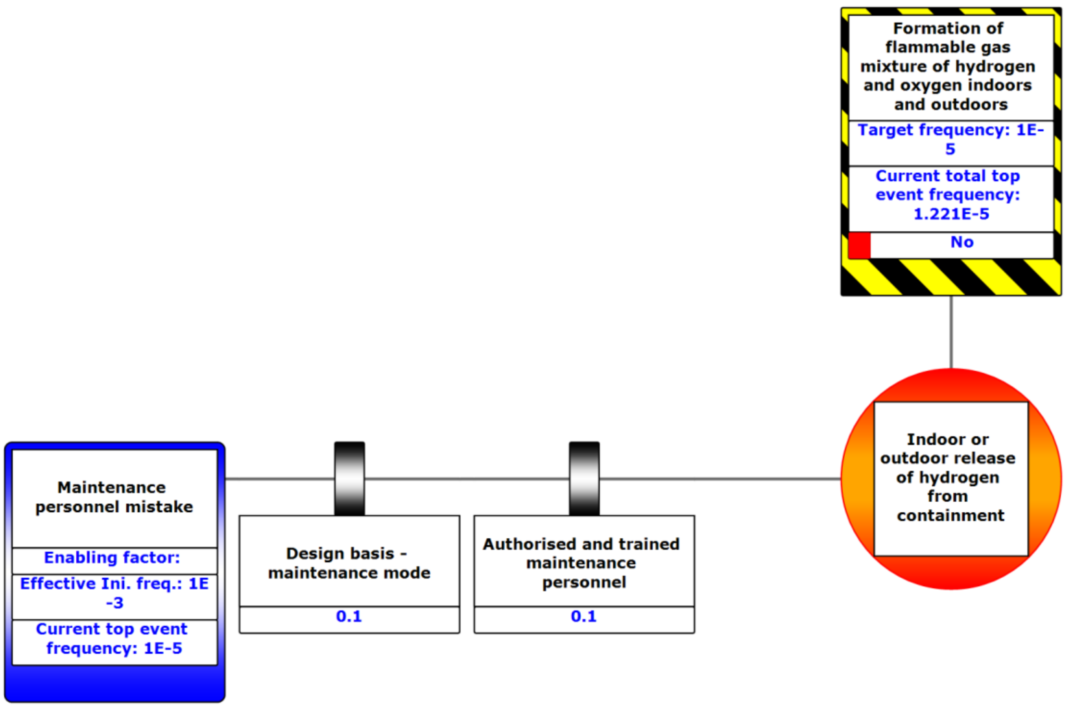


Figure 30 Bowtie diagram: Cause-branch for 'Maintenance personnel mistake'

The top event frequency for Cause #6,

$$\begin{aligned} f_6^T &= IEF_6 \times PFD_{6-1} \times PFD_{6-2} \\ &= (1 \times 10^{-3}) \times (0.1) \times (0.1) \\ &= 1 \times 10^{-5} \end{aligned}$$

Next, by using Equation (3), the **frequency of the top event for the aggregated initiating events**, f^T, is obtained by a simple summation of f_i^T of all causes, rounded up to the most significant decimal value.

The outcome is tabulated below.

Table 43 Version 1 Hydrogen system Bowtie: Top Event Frequencies for all causes after applying preventive mitigation

Initiating Event #	Description	Top event frequencies, f_i^T (y⁻¹)
1	Corrosion (Hydrogen embrittlement)	1×10^{-6}
2	Leaking at joints	1×10^{-7}
3	Outdoor storage tank rupture due to external impact	1×10^{-6}
4	Outdoor storage tank rupture due to heat from external fires	1×10^{-8}
5	Gas separation membrane failure within the electrolyser	1×10^{-7}
6	Maintenance personnel mistake	1×10^{-5}
Frequency of the top event for aggregated initiating events, f^T		1×10^{-5}

Using Equation (4), **the frequency of consequence**, f_i^C, was calculated for each consequence. The illustration of how f_i^C is obtained for Consequence #10 – 'Ignition during maintenance' can be seen in the Bowtie (Figure 31).

As it turns out, there was only one Independent Protection Layer (IPL); while all the other barriers are considered safeguards. Arguably, the use of personal protective equipment (PPE) cannot be fully assured as it is also highly dependent on human behaviours for compliance. Nevertheless, HyGear noted that their maintenance personnel are issued with standard PPE for their duties, and it is expected that the PPE is used whenever carrying out maintenance work.

The frequency of Consequence #10,

$$\begin{aligned} f_{10}^C &= f^T \times PFD_{10-1} \times PFD_{10-2} \times PFD_{10-3} \times PFD_{10-4} \\ &= (1 \times 10^{-5}) \times 1 \times 1 \times 0.1 \times 1 \\ &= 1 \times 10^{-6} \end{aligned}$$

The f_i^C for all the consequences are shown in

Table 44.

The consequence with the highest likelihood value is Consequence #10 – 'Ignition during maintenance', which outweighs the likelihood of the other consequences by order of magnitudes. The likelihood for the consequence with the most severe outcome[161] is Consequence #5 –' Hydrogen mixture detonation, resulting in shock waves' – is one million times smaller. Therefore, the frequency of consequence for Consequence #10 was used to calculate the mitigated risk for the hazard.

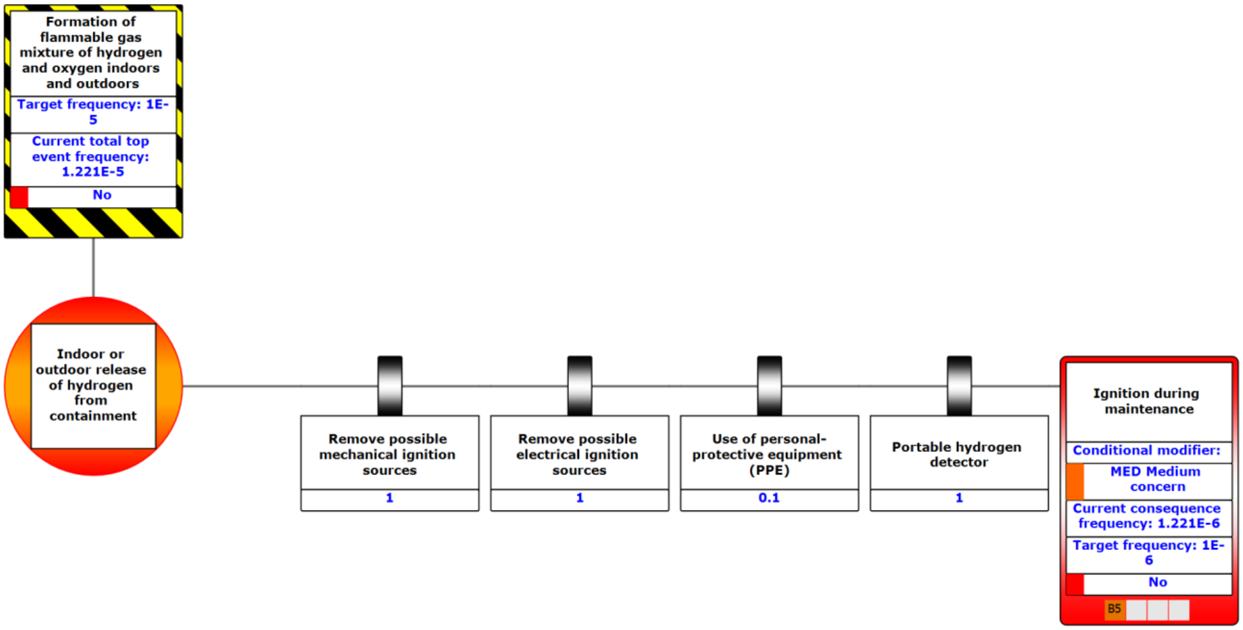


Figure 31 Bowtie diagram: Consequence-branch for 'Ignition during maintenance.

Table 44 Version 1 Hydrogen system Bowtie: Mitigated frequency of consequences

Consequence	**Description**	**frequency of consequence** (y^{-1}), f_i^C
1	Indoor oxygen displacement leading to asphyxiation	1×10^{-8}
2	Outdoor oxygen displacement leading to asphyxiation	1×10^{-9}
3	Indoor systems: delayed ignition	1×10^{-9}
4	Immediate / spontaneous ignition (deflagration) of mixture	1×10^{-7}
5	Detonation resulting in shock waves	1×10^{-12}
6	Indoor flame propagation, leading to secondary fire	1×10^{-7}
7	Routing of indoor hydrogen to outdoors, leading to an outdoor secondary fire	1×10^{-9}
8	Human exposure to high flame temperature / thermal radiation	1×10^{-10}
9	Pressure-peaking phenomenon leading to the structural collapse of the enclosure	1×10^{-8}
10	Ignition during maintenance	1×10^{-6}

Using Equation (5), the mitigated frequency, $f_{mit.}$, is calculated. The probability of human exposure and the probability of fatality, P_H and P_F respectively, is similar to that used in the calculation for the initial risk. The unmitigated and mitigated risks for the individual and society is shown in Table 45.

The mitigated risks for the individual and society are now within the acceptability limits.

Table 45 Version 1 Hydrogen system Bowtie: Mitigated risk of one fatality occurring

	Frequency of consequence (y^{-1}), f_i^C	**Human exposure x Probability of fatality** (y^{-1}), $P_H \times P_F$	**Frequency of mitigated risk** (y^{-1}), $f_{mit.} = f_i^C \times P_H \times P_F$
Individual (resident)	1×10^{-6}	6.7×10^{-1}	8×10^{-7}
Individual (maintenance personnel)	1×10^{-6}	2.7×10^{-3}	3×10^{-9}
Societal (public)	1×10^{-6}	1	1×10^{-6}

Version 2 Bowtie - Conceptual design scenario

The Bowtie and LOPA techniques are applied again for the same hazard and top event, this time using the details that are known at the conceptual design phase of the LIFE project. The Analyst discussed with HyGear the potential causes, consequences and the barriers that would most likely be relevant in the envisioned constructed hydrogen system. As a result, the following changes are made to the Bowtie:

- Removed causes that have a very low likelihood of occurring:
    - Storage tank rupture due to heat from external fire; because HyGear's proposed tank designs are made of carbon steel which has higher tolerability to external fire compared to composite materials
- Removed barriers which would have a low likelihood of existing
    - In-line shut-off valves; because HyGear's design typically does not incorporate these
    - Use of fire-resistant materials on adjacent equipment; because the hydrogen storage area for the LIFE project is conceptually co-located with the High-Pressure Lab's existing gas storage area. As yet, there is no plan to make modifications to improve the fire-resistance of adjacent equipment.
    - Design considerations for electrolyser; because HyGear plans to source the electrolyser from a 3rd-party supplier and thus would not have the responsibility of its detailed design.

The Initiating Event Frequencies (IEFs) remain unchanged from that of Version 1.

With the reduced set of parameters, the re-calculated values are as below. The details of the calculations are now omitted for brevity of reporting. Only changes by a factor of 10 or more to a larger or smaller value are noted; else the frequency value is assumed to remain the same as in Version 1.

Table 46 Hydrogen system Bowtie: Changes to the top event frequencies in Version 2 compared to Version 1

Initiating Event #	Description	Top event frequencies, f_i^T (y⁻¹)	Note
1	Corrosion (Hydrogen embrittlement)	1×10^{-6}	No change
2	Leaking at joints	1×10^{-5}	Was 1×10^{-7}
3	Outdoor storage tank rupture due to external impact	1×10^{-6}	No change
4	Outdoor storage tank rupture due to heat from external fires	-	Removed as a potential cause
5	Gas separation membrane failure within the electrolyser	1×10^{-5}	Was 1×10^{-7}
6	Maintenance personnel mistake	1×10^{-5}	No change
Frequency of the top event for aggregated initiating events, f^T		3×10^{-5}	Was 1×10^{-5}

Followed by the frequency of consequences:

Table 47 Changes to the frequencies of consequence in Version 2, compared to Version 1

Consequence	Description	frequency of consequence (y⁻¹), f_i^C	Note
1	Indoor oxygen displacement leading to asphyxiation	3×10^{-7}	Was 1×10^{-8}
2	Outdoor oxygen displacement leading to asphyxiation	3×10^{-9}	Was 1×10^{-9}
3	Indoor systems: delayed ignition	3×10^{-9}	Was 1×10^{-9}
4	Immediate / spontaneous ignition (deflagration) of mixture	3×10^{-7}	Was 1×10^{-7}
5	Detonation resulting in shock waves	3×10^{-12}	Was 1×10^{-12}
6	Indoor flame propagation, leading to secondary fire	3×10^{-7}	Was 1×10^{-7}
7	Routing of indoor hydrogen to outdoors, leading to an outdoor secondary fire	3×10^{-9}	Was 1×10^{-9}
8	Human exposure to high flame temperature / thermal radiation	3×10^{-9}	Was 1×10^{-9}
9	Pressure-peaking phenomenon leading to the structural collapse of the enclosure	3×10^{-8}	Was 1×10^{-8}
10	Ignition during maintenance	3×10^{-6}	Was 1×10^{-6}

The consequence with the highest likelihood value remains to be Consequence #10 – 'Ignition during maintenance', and thus is selected for use in the calculation of the mitigated risk, with no significant change in its frequency value.

Thus finally, the mitigated risk of a single fatality occurring:

Table 48 Version 2 of Hydrogen system Bowtie - frequency of mitigated risk

	Frequency of consequence (y^{-1}), f_i^C	**Human exposure x Probability of fatality** (y^{-1}), $P_H \times P_F$	**Frequency of mitigated risk** (y^{-1}), $f_{mit.} = f_i^C \times P_H \times P_F$
Individual (resident)	3×10^{-6}	6.7×10^{-1}	2×10^{-6}
Individual (maintenance personnel)	3×10^{-6}	2.7×10^{-3}	9×10^{-9}
Societal (public)	3×10^{-6}	1	3×10^{-6}

The calculated risks for Version 1 and Version 2 can be compared in Table 49.

Table 49 Values of the initial/unmitigated risks, and the mitigated risks for Version 1 and 2 of the hydrogen bowtie scenarios

	Acceptability value (y^{-1})	**Calculated value** (y^{-1})	**Acceptable risk?**
Individual risk			
Initial/unmitigated	Less than 1×10^{-6}	7×10^{-3}	No
Mitigated – Version 1		8×10^{-7}	Borderline Yes
Mitigated – Version 2		2×10^{-6}	Borderline No
Societal risk			
Initial/unmitigated	Less than 1×10^{-3}	1×10^{-2}	No
Mitigated - Version 1		1×10^{-6}	Yes
Mitigated - Version 2		3×10^{-6}	Yes

Version 1: 'idealised scenario' where every possible barrier is included. Version 2: 'LIFE conceptual design' scenario, where only the barriers specified in the conceptual design project specifications are included

To summarise, the initial risks for individuals and the society (public) were calculated to be in the unacceptable region**,** corresponding with the outcome from the qualitative risk assessments**.**

For the Individual risk, the mitigated risk for Version 1 of the analysis cleared the acceptability criteria by a small margin. Similarly, in Version 2 of the analysis, the mitigated risk for the Individual failed to meet the acceptability criteria also by a tiny margin. For both versions, it is then recommended to demonstrate if the ALARP principle has been achieved.

For the Societal risk, the mitigated risks for both Versions 1 and 2 were successfully reduced to an acceptable level with a comfortable margin. The reduction was almost by a factor of 1000 times smaller than the threshold value.

Calculation of risks for the Li-ion battery system

Note: In the following calculations, data, especially for the Initiating event frequency (IEF) and the Probability of failure on demand (PFD) were compiled from several sources. For brevity, the frequently-cited ones would be denoted by the following, with the full reference as given below:

- *CCPS LOPA (2001): Center for Chemical Process Safety (CCPS), Layer of protection analysis: simplified process risk assessment. New York: Wiley, 2001, p. 292.*
- *CCPS LOPA (2007): Center for Chemical Process Safety (CCPS), "Protection Layers," in Guidelines for Safe and Reliable Instrumented Protective Systems: American Institute of Chemical Engineers, 2007, pp. 267-299.*
- *CCPS LOPA (2015): Center for Chemical Process Safety (CCPS), Guidelines for Initiating Events and Independent Protection Layers in Layer of Protection Analysis (LOPA): VitalSource Bookshelf, 2015. [Online]*
- *DNV GL(2019): M. Pierce, "Quantitative Risk Analysis for Battery Energy Storage Sites," DNV GL, 2019. [Online]. Available: https://www.dnvgl.com/*

Other less-cited sources are cited and referenced typically.

Bowtie scenario:

Hazard: Chemical reactions within the electrolyte of general-type lithium-ion battery
Top Event: Onset of Lithium-battery cell thermal runaway

The Bowtie diagram has eight threat branches and three consequence branches.

Threats/Causes:

1. The battery exposed to external fire
2. The battery ambient temperature is higher than 70 degrees C (low likelihood).
3. The battery subjected to piercing, impact, crushing or vibration and then put into operation, i.e. charged and discharged
4. The battery is overcharging, i.e. the charging current or voltage exceeds that of the cell's rating
5. The battery is over-discharged.

6. External short-circuiting during transportation (not a likely cause during the use-phase in the LIFE project)
7. External short-circuiting due to a lightning strike (low likelihood)
8. Internal cell defects from the manufacturing processes

Consequences:

1. Combustion of adjacent battery cells and equipment
2. Toxic fume emission and personnel injury
3. Toxic water/chemical hazard following fire-extinguishment actions

Two versions were created for each Top Event. Version 1 is the 'idealised scenario' where every possible barrier is included. Version 2 represents the 'LIFE conceptual design' scenario, where only the barriers specified in the conceptual design project specifications are included.

Version 1 Bowtie – idealised scenario

The causes and the adopted initiating event frequencies in the corresponding Bowtie are shown in Table 50 to help the understanding of the calculations.

Initial risks

The scenario used is that of a battery incurring a thermal runaway due to an aggregate of causes, leading to a battery fire.

Using Equation (1), the initial risk of a single fatality is obtained. For the individual, two types of profile have been defined: the building resident and the maintenance personnel. The difference between the two lay in the exposure hours. The public refers to passersby or an adjacent neighbour who could be at home at all time.

The assumptions used:

- **Human exposure**
  - of the building resident: The average Dutch household size was 2.2 in 2019. The assumption used was that three residents would be in the house 16 out of 24 hours per day, on average in a week. The higher number takes into account any visitors and all family members who are staying at home during the weekends.
  - of the maintenance personnel: Maintenance is done once a year, lasting a total of 24 hours (i.e. 8 hours x 3 days)
  - of the public or adjacent neighbour: always assume that a person is exposed at any time of the day
- **The initiating event frequency (IEF)**: The cause with the most conservative of initiating event frequency (IEF) from the identified causes is used. The causes were Causes #1, 3, 4, 5, 6 and 8, all with the IEF of 1×10^{-2}

- **The probability of immediate fatality:** 1% is used, based on the approximate number of fatality resulting from the number of residential fires in the Netherlands [186]. Furthermore, [187] mentions that in 90% of the time, people can evacuate safely (i.e. without fatality) when smoke is visibly seen.

Table 50 Version 1 Li-ion battery Bowtie: Adopted Initiating Event Frequencies (IEF) for identified causes/threats

No.	Cause	IEF	Remarks / Source
1	Battery exposed to external fire	1×10^{-2}	Aggregate small fire (Table 5.1), CCPS LOPA (2001)
2	Battery exposed to external temperature > 70*C	4×10^{-3}	Based on the possibility of the number of days in a year outside temperature can rise above 30 ^{o}C in Enschede, over ten years (2010 - 2019), as shown in Appendix 12, pg 233
3	External impact	1×10^{-2}	Third-party intervention (Table 5.1), CCPS LOPA (2001) [172]
4	Cell over-charging	1×10^{-2}	QRA for battery storage sites, DNV GL (2019)[172]
5	Cell over-discharging	1×10^{-2}	QRA for battery storage sites, DNV GL (2019)
6	External short-circuiting from transportation	1×10^{-2}	Assumed to be similar to cell over-charging and discharging
7	External short-circuiting from lightning strikes	1×10^{-3}	Lightning strikes (Table 5.1), CCPS LOPA (2001). Also, verified by calculations using average flash-density of 1.5 per km^2 in the Netherlands [188], and a 30m by 30m area surrounding the battery house.
8	Internal cell defects from manufacturing processes	1×10^{-2}	QRA for battery storage sites (Table 4-1), DNV GL (2019)

The outcome is shown in Table 51. The likelihood value is rounded to the nearest non-zero decimal number.

The initial risks for individual building resident were calculated to be **unacceptable**, whereas, for the individual maintenance personnel and society, the risk was **acceptable**. Despite the acceptable risk to the public, it was decided to be more conservative and apply safety barriers anyway to achieve bigger safety buffer due to the novelty factor of using Li-ion batteries in residential buildings.

Table 51 Version 1 Li-ion battery Bowtie: Initial risk calculation

	Initiating Event Frequency (y^{-1}), IEF	**Human exposure** (y^{-1}), P_H	**Probability immediate fatality,** P_F	**Likelihood of fatality** (y^{-1}), $F_o = IEF \times P_H \times P_F$
Individual (resident)	1×10^{-2}	6.7×10^{-1}	1×10^{-2}	7×10^{-5}
Individual (maintenance personnel)	1×10^{-2}	1.8×10^{-3}	1×10^{-2}	2×10^{-7}
Societal (public)	1×10^{-2}	1	1×10^{-2}	1×10^{-4}

Risk mitigation

The adopted values of the Probability of Failure on Demand (PFD) of the identified Independent Protection Layers (IPLs) are shown below.

Table 52 Version 1 Li-ion battery LOPA: Preventive IPLs

No.	**Independent Protection Layer**	**PFD** (y^{-1})	**Remarks / Source**
1	Cell design considerations	1×10^{-1}	Inherently safe design, Table 6.3, CCPS LOPA(2001). Some of these considerations were listed in Table 13, page 54. A conservative figure is used since battery design can vary from one manufacturer to another
2	Gas and fire detection, warning and suppression system for storage room	1×10^{-1}	Table 5.44, CCPS LOPA (2014)
3	Room with active cooling/ temperature controls (HVAC) between 5 - 50 degrees C	1×10^{-1}	QRA for battery storage sites (Table 4-2), DNV GL (2019). The HVAC system should produce an alarm if a malfunction occurs
4	Safe design of electrical systems to prevent electrical fire	1×10^{-1}	QRA for battery storage sites (Table 4-2), DNV GL (2019)
5	Cell design – robust outer casing	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA (2001)
6	Battery Management System (BMS) to detect an internal fault or shorting	1×10^{-2}	QRA for battery storage sites (Table 4-2), DNV GL (2019)

No.	Independent Protection Layer	PFD (y^{-1})	Remarks / Source
7	Siting of battery: in low traffic and also flood-free zones	1×10^{-2}	Inherent safe design, Table 6.3, CCPS LOPA (2001)
8	Battery Management System (BMS) to regulate charging and discharging	1×10^{-2}	QRA for battery storage sites (Table 4-2), DNV GL (2019)
9	Electrical protection against ground faults, short circuits and surges (e.g. fuse and circuit breakers), and including electrical surge protection devices	1×10^{-1}	QRA for battery storage sites (Table 4-2), DNV GL (2019)
10	Design considerations: resistance to heating due to external short-circuiting	1×10^{-2}	Inherent safe design, Table 6.3, CPS LOPA (2001). Some of these considerations were listed in Table 13, page 54. Assumes conformity to UL1642, IEC 62133 and UN 38.3 test requirements for air transport.
11	Factory test on battery assembly before final packaging	1×10^{-4}	Based on SuperB's experience, the number of cell failures due to manufacturing defects can be even lower, i.e. at 1 in 100 000 (1×10^{-5})

Table 53 Version 1 Li-ion battery Bowtie: Mitigative IPLs

No.	Independent Protection Layer	PFD (y^{-1})	Remarks / Source
1	Cell design considerations – better heat insulation between cells	1×10^{-1}	Inherent safe design, Table 6.3, CCPS LOPA (2001). Use a conservative number as cell design may vary from one manufacturer to another
2	Automatic suspension of battery operations upon detection of thermal runaway	1×10^{-1}	Safety systems, Table 4-2 DNV GL (2019). Use a conservative number as cell design may vary from one manufacturer to another
3	Continuous air ventilation system for the battery room	1×10^{-1}	QRA for battery storage sites (Table 4-2), DNV GL (2019). Credit is given if it meets the air-flow requirement to avoid built-up of toxic gases (namely HCl) and has an indication of failure alarm.
4	Human response to abnormal condition with multiple indicators and sensors and the operator has > 24 hours to accomplish the required response action	1×10^{-2}	Data table 5.47, CCPS LOPA (2015)
5	The battery is placed in a water containment feature	1×10^{-2}	Dike - Table 6.3, CCPS LOPA (2015)

Table 54 Version 1 Li-ion battery Bowtie: Identified safeguards, which are not be considered as Independent Protection Layers (IPLs)

No.	Safeguard	PFD (y^{-1})	Remarks / Source
1	Cell packaging during transportation and proper handling	1	Procedural and behavioural safeguard. Table 6.1, CCPS LOPA (2001)
2	Avoid long-term storage at 0% state-of-charge	1	Considered a manual task, unless the batteries are connected to a charging system that prevents self-discharge below 0% state-of-charge
3	Inspection and replacement of aged battery cells	1	This is typically a manufacturer's recommendation but is challenging to enforce. Furthermore, CCPS LOPA recognises maintenance activities as a safeguard only. Table 6.1, CCPS LOPA (2001)

No.	Safeguard	PFD (y^{-1})	Remarks / Source
4	Community emergency response and evacuation procedures	1	Not typically regarded as IPL as its implementation is highly dependent on local conditions; CCPS LOPA (2014)
5	Fire detection, alarm and suppression system	1	Considered as a safeguard only if fire-detector and alarm are present; Table 6.1 CCPS LOPA (2001). A risk-reduction factor of 0.1 may be given if the system is linked to an instrumented protective systems and automatic deluge, and is tested regularly.
6	Toxic gas (CO, HCl and NO2) detectors and alarm	1	Detects the onset of thermal runaway. However, it is considered a safeguard because it does not trigger any additional safety systems (e.g. automatic battery shutdown, or increased air circulation)
7	Disposal of contaminated water by experts	1	Considered a management process. The availability of experts in the region should not be assumed

Mitigated risk

Using Equation (2), the **top event frequencies** due to a particular initiating event, f_i^T, is calculated after taking into account the IEF of all the potential initiating event/causes, and the PFD of all the potential Independent Protection Layers/safety barriers.

Using Equation (3), the **frequency of the top event for the aggregated initiating events**, f^T, is obtained by a simple summation. The outcome is shown in Table 55.

Table 55 Version 1 Li-ion battery Bowtie: Top event frequencies after applying preventive mitigation

Initiating Event #	Description	Top event frequencies, f_i^T (y⁻¹)
1	The battery exposed to external fire	1×10^{-4}
2	The battery ambient temperature is higher than 70 degrees C (less likely cause).	4×10^{-8}
3	The battery subjected to piercing, impact, crushing or vibration and then put into operation, i.e. charged and discharged	1×10^{-8}
4	The battery is overcharging, i.e. the charging current or voltage exceeds that of cell's rating	1×10^{-5}
5	The battery is over-discharged.	1×10^{-4}
6	External short-circuiting during transportation	1×10^{-7}
7	External short-circuiting due to a lightning strike (low likelihood)	1×10^{-4}
8	Internal cell defects from the manufacturing processes	1×10^{-6}
	Frequency of the top event for aggregated initiating events, f^T	3×10^{-4}

Using Equation (4), the **frequency of consequence**, f_i^C, for the respective outcomes are as follow:

Table 56 Version 1 Li-ion battery Bowtie: Mitigated frequency of consequence

Consequence #	Description	frequency of consequence, f_i^C
1	Combustion of adjacent battery cells and equipment	3×10^{-6}
2	Toxic fumes emission and personnel injury	3×10^{-7}
3	Toxic water from fire-extinguishment	1×10^{-11}

Using Equation (5), the mitigated risk of a single fatality occurring, $f_{mit.}$, is calculated. The value of the highest fatality likelihood, $\mathrm{f_i^C}$, namely from Consequences #1 is used. The probability of human exposure and the probability of fatality, P_H and P_F respectively, is similar to that used in the calculation for the initial risk. The outcome is shown in Table 57.

Table 57 Version 1 Li-ion battery system Bowtie: mitigated risk:

	Frequency of consequence (y^{-1}), f_i^C	**Human exposure x Probability of fatality** (y^{-1}), $P_H \times P_F$	**Frequency of mitigated risk** (y^{-1}), $f_{mit} = f_i^C \times P_H \times P_F$
Individual (resident)	3×10^{-6}	6.7×10^{-3}	2×10^{-8}
Individual (maintenance personnel)	3×10^{-6}	1.8×10^{-5}	6×10^{-11}
Societal (public)	3×10^{-6}	1×10^{-2}	3×10^{-8}

The mitigated risks for the society are now within the acceptability limits.

Version 2 Bowtie - Conceptual design scenario

The Bowtie and LOPA techniques are applied again for the same hazard and top event, this time using the details that are known at the conceptual design phase of the LIFE project. The Analyst discussed with SuperB the potential causes, consequences and the barriers that would most likely be relevant in the envisioned constructed Li-ion battery system. As a result, the following changes are made to the Bowtie:

- Enhanced probability of failure on demand (PFD) of a barrier:
    - Cell design considerations; because a lithium iron phosphate type is used, thus enhancing the cell's thermal stability. The PFD is decreased by a factor of 10.
- Removed causes that have a very low likelihood of occurring:
    - Battery ambient temperature > 70°C; because the ambient temperature has a larger impact on the battery longevity, rather than on the safety. Furthermore, it is highly unlikely that the ambient temperature can go above 70°C, based on historical data and future projections where the average winter and summer is predicted to be warmer by only 2-3°C in 2050 [165].
    - External short-circuiting conditions that lead to Li-ion battery thermal runaway only occur during transportation and battery storage.
- Removed barriers which would have a low likelihood of existing
    - The battery is placed in a water containment feature; because it is conceptually envisioned that such a facility is not required due to the low likelihood of a lithium iron phosphate battery fire occurring
    - Design considerations - Better heat insulation in between cells; because SuperB does not have the responsibility of the battery cell design, and thus is unable to assure that this feature exists.

    - There is no fire-suppression system installed, either as a preventive barrier (gas-flooding system to suppress electrical fires), or mitigative barrier (water-sprinkler system to suppress battery fires). This is on the basis that using CO gas monitor is used to detect both electrical fires and also the out-gassing battery phenomena.
- Remove a consequence which has a very low likelihood of occurring
    - Toxic water from fire-extinguishment; because the battery shed is not designed for on-site water submersion

The Initiating Event Frequencies (IEFs) remain unchanged from that of Version 1.

With the reduced set of parameters, the re-calculated values are as below. The details of the calculations are now omitted for brevity of reporting. Only changes by a factor of 10 or more to a larger or smaller value are noted; else the frequency value is assumed to remain the same as in Version 1.

Table 58 Li-ion battery system Bowtie: Changes to the top event frequencies in Version 2 compared to Version 1

Initiating Event #	Description	Top event frequencies, f_i^T (y^{-1})	Note
1	The battery exposed to external fire	1×10^{-5}	Was 1×10^{-4}
2	The battery ambient temperature is higher than 70 degrees C (less likely cause).	-	Removed as a potential cause
3	The battery subjected to piercing, impact, crushing or vibration and then put into operation, i.e. charged and discharged	1×10^{-8}	No change
4	The battery is overcharging, i.e. the charging current or voltage exceeds that of the cell's rating	1×10^{-5}	No change
5	The battery is over-discharged.	1×10^{-4}	No change
6	External short-circuiting during transportation	-	Removed as a potential cause
7	External short-circuiting due to a lightning strike (low likelihood)	1×10^{-4}	No change
8	Internal cell defects from the manufacturing processes	1×10^{-6}	No change
	Frequency of the top event for aggregated initiating events, f^T	2×10^{-4}	Was 3×10^{-4}

Followed by the frequency of consequences:

Table 59 Li-ion battery system Bowtie: Changes to the frequency of consequence in Version 2 compared to Version 1

Consequence #	Description	frequency of consequence, f_i^C	Note
1	Combustion of adjacent battery cells and equipment	3×10^{-5}	Was 3×10^{-6}
2	Toxic fumes emission and personnel injury	2×10^{-7}	Was 3×10^{-7}
3	Toxic water from fire-extinguishment	-	Removed as a potential consequence

The value of the highest fatality likelihood, $\mathrm{f_i^C}$, similar to that in Version 1, is still from Consequences #1. Thus finally, the mitigated risk of a single fatality occurring:

Table 60 Version 2 Li-ion battery system Bowtie: Frequency of mitigated risk

	Frequency of consequence (y^{-1}), $\mathrm{f_i^C}$	**Human exposure x Probability of fatality** (y^{-1}), $P_H \times P_F$	**Frequency of mitigated risk** (y^{-1}), $f_{\mathrm{mit}} = f_i^C \times P_H \times P_F$
Individual (resident)	3×10^{-5}	6.7×10^{-3}	2×10^{-7}
Individual (maintenance personnel)	3×10^{-5}	1.8×10^{-5}	6×10^{-10}
Societal (public)	3×10^{-5}	1×10^{-2}	3×10^{-7}

To summarise the analysis results, it can now be seen that the initial risk for the Individual was unacceptable, whereas the risk for the Society was in the acceptable region. Following the application of relevant barriers, the mitigated risks in Versions 1 and 2, were reduced to within the acceptability range. This is shown in Table 61.

Table 61 Values of the initial/unmitigated risks, and the mitigated risks for Version 1 and 2 of the Li-ion battery system

	Acceptability value (y^{-1})	**Calculated value (y^{-1})**	**Acceptable risk?**
Individual risk			
Initial/unmitigated		7×10^{-5}	No
Mitigated – Version 1	Less than 1×10^{-6}	2×10^{-8}	Yes
Mitigated – Version 2		2×10^{-7}	Yes
Societal risk			
Initial/unmitigated		1×10^{-4}	Yes
Mitigated - Version 1	Less than 1×10^{-3}	3×10^{-8}	Yes
Mitigated - Version 2		3×10^{-7}	Yes

Bowtie diagrams (embedded pdf files)

Hydrogen Bowtie diagrams – (left) Version 1; (right) Version 2

Hydrogen Bowtie V1 - 20201029.pdf   Hydrogen Bowtie V2 - 20201029.pdf

Li-ion Bowtie diagrams - (left) Version 1; (right) Version 2

Li-ion Bowtie V1 - 20201029.pdf   Li-ion Bowtie V2 - 20201029.pdf

Appendix 9 Li-ion battery room air-flow rate requirement

DNV-GL collected data from their experiments to estimate the required air ventilation during a battery fire scenario [130]. One of the outcomes is a probabilistic analysis of the required water flow rates [gallons-per-minute, or GPM] and airflow rate [cubic-feet-per-minute, or CFM], found in Table 9 of the report. The table is replicated in Table 62.

The biggest determinant for the required airflow is the room volume and the battery mass, or specifically the amount of energy stored in a unit of battery mass. The latter can differ from one battery type to another.

Table 62 Table 9 from [130]: Required water flow rates (gallons per minute, GPM) and air flow rates (cubic-feet per minute, CFM) per energy system (kWh) or mass (kg). The values were derived from a probabilistic analysis.

Scalable Metrics for Systems based on Electrochemical Battery Mass and Energy Content

	25th Percentile	Mean	75th Percentile
Water Flow Rate GPM/kg	0.07	0.10	0.20
Water Flow Rate GPM/kWh	0.70	0.99	2.09
Air Flow Rate CFM/kg	0.01	0.02	0.03
Air Flow Rate CFM/kWh	0.11	0.18	0.31

Air flow rate calculations.

Convert ft^3/m to m^3/h, as is the commonly-used unit in the Netherlands. Then, the air change-per-hour (ACH) will be determined.

Use conversion formula: 1 cubic feet = 0.0283168 cubic meter

Therefore, the equivalent required air-change per kWh is:

- Minimum (25^{th} Percentile): 0.11 ft^3/m = 3.11E-3 m^3/m = 6.6 CF/hr = 0.187 m^3/h
- Maximum (75^{th} Percentile) : 0.31 ft^3/m = 8.78E-3 m^3/m = 18.6 CF/hr = 0.53 m^3/h

Scenario:

Battery rooms:

- Lower ceiling in older houses: Typical room. Area: 12m^2 (3 m x 4 m), ceiling 2.4 m: Volume = 28.8 m^3 (1017 ft^3)
- Higher ceiling in newer houses. Area: 12 ^{2} (30 m x 4 m), ceiling 2.6 m: Volume = 31.2 m^3 (1102 ft^3)
- LIFE Battery shed. Area: 9.9 m^2 (2.2 m x 4.5m) and ceiling height is 2.5m. Volume = 24.8 m^3 (875 ft^3)

The maximum battery capacities installed in the LIFE battery shed are:

1. VRB: 27 kWh
2. Li-ion battery: 92 kWh

The required ACH is $= \frac{\text{required air change rate [m}^3\text{per hour]}}{\text{room volume [m}^3\text{]}} \times \text{battery capacity[kWh]}$

When calculated and tabled using the minimum ACH (25th Percentile) from Table 62:

		Room area (m³)		
		Low ceiling	High ceiling	LIFE battery shed
Battery Capacity (kWh)		28.8	31.2	24.8
VRB	27	0.18	0.16	0.20
Li-ion	92	0.60	0.55	0.69
Li-ion and VRB	119	0.77	0.71	0.90

For maximum ACH (75th Percentile), the values are:

		Room area (m³)		
		Low ceiling	High ceiling	LIFE battery shed
Battery Capacity (kWh)		28.8	31.2	24.8
VRB	27	0.50	0.46	0.58
Li-ion	92	1.69	1.56	1.97
Li-ion and VRB	119	2.19	2.02	2.54

Appendix 10 Considerations and checklist of Li-ion battery installation in homes

IET's Code of Practice for EES Systems [93] contains guidelines to aid a residential building owner or designer when considering to install a Li-ion battery in their property. This guide is non-exhaustive and is not meant to be a substitute for specialist advice. The guidelines are shown below.

Considerations when locating a battery and power-conditioning equipment (PCE)

1. Manufacturer's instructions and safety data sheets
2. Limits on the length of cable between battery and charger/inverter if these are located in separate enclosures
3. Space of cables and containment to be routed, such as limitations for the maximum bend radii
4. Access to the workspace is adequate for installation, repairs and decommissioning
5. Means of energy isolation is clearly identifiable and accessible
6. Ventilation requirements
7. Ambient temperatures
8. Presence of and the distance to heat sources
9. Fire and escape routes
10. Fire detection systems
11. Presence of sources of ignition (e.g. gas boilers, heating elements)
12. Weight of battery and the ability of the workspace to support it
13. Flood risks

Power-conditioning equipment / charge controller

14. Environmental aspects against the ingress protection (IP) rating. If the inverter is located outdoors, it must have a suitable rating such as IPF 44 or IP54
15. The impact of noise that could be generated. Some PCEs have audible noise from fans and electronic components which can be a nuisance to humans and animals
16. Proximity to batteries (the further the inverter is from the battery, the higher the voltage drop).
17. The orientation that can impact ventilation and cooling, e.g. close to the wall
18. In buildings or locations that have audio frequency induction loop system (AFILS) for people with hearing aids, PCEs may cause disturbances through excessive audio-frequency, ultra-sonic and electromagnetic noise

Requirements for all types of rooms: Air ventilation; CO, HCl and NO_2 detector; and access-restriction for only authorised personnel.

Checklist 1: Safety functions of Li-ion battery systems

A lithium-ion energy storage system is unique to a particular instllallation or project. For instance, the battery energy capacity and lithium-ion chemistry could vary from one installation to another. During the design phase, the system integrator and the battery supplier should discuss and agree if a specific safety barrier is applicable (or, necessary), and if so, which party is responsible for implementing the safety barrier. The end-objective is to create a safe system, balancing safety with practicality.

Note: The author wishes to thank SuperB for their contribution in reviewing this form and for proposing appropriate changes.

For each safety barrier, there are three columns:

Applicability: if a particular safety barrier is required for the installed system. If the concern is applicable, then proceed to identify the responsibility to manage the issue

End responsibility: action party to design and implement the solution. Sup. = battery supplier; Int. = Integrator

Remarks: add additional remarks or comments

No.	Safety barrier	Applicability		Responsibility		Remarks / Notes
		No	Yes	Sup.	Int.	
General certification						
1	CE label for the battery pack/module	☐	☒	☒	☐	
2	CE label for the complete battery installation, including external protection circuits, charge controllers, etc.	☐	☒	☐	☒	Implies also compliance with the following: 1. Low Voltage Directive (2014/35/EU) 2. EMC Directive (2014/30/EU) 3. Radio equipment directive (covers 1. and 2.; only applicable if there is an intended radio transmitter)
3	Compliance to IEC 62933 Electrical energy storage (EES) systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical-based systems	☐	☐	☐	☐	Only if the battery is to be integrated with the grid-connection for charging and discharging. The responsibility is with the system integrator.

No.	Safety barrier	Applicability		Responsibility		Remarks / Notes
		No	Yes	Sup.	Int.	
						There are currently no Notified Bodies yet in the Netherlands who have this standard in their scope.
Compliance to future standards:						
a	NEN 4288 *Bedrijfsvoering van batterijen energieopslagsystemen* (Operation of battery energy storage systems)	☐	☐	☐	☒	The expected release date: end 2020
b	IEC 62485-Part 5. Safety requirements for secondary batteries and battery installations - Part 5: Safe operation of stationary lithium-ion batteries for the battery installation	☐	☐	☐	☒	The expected release date: 2021. The system integrator should bear responsibility
	PGS 37 *Lithium-ion accu's: opslag en buurtbatterijen* (Li-ion batteries: storage and neighborhood batteries)	☐	☐	☐	☒	The expected release date: end 2021. The system integrator should bear responsibility
Battery siting/location						
4	Flood risk	☒	☐	☐	☒	
5	Battery capacity storage limit	☒	☐	☐	☐	Currently no legal limits in NL
6	Battery room size	☐	☒	☐	☐	Currently no legal requirement on gap/space between batteries
7	Battery room load-bearing capability	☐	☒	☐	☒	18.5kg per pack x 48 packs per house = 888 kg?
8	Cable length between battery, inverter and charger (system efficiency issue, rather than safety)	☐	☒	☐	☒	
9	Room accessibility for installation, maintenance and decommissioning	☐	☒	☐	☒	
10	Means of energy isolation: accessibility and visibility	☐	☐	☐	☐	
11	Proximity to fire ignition and heat sources	☐	☒	☐	☒	

No.	Safety barrier	Applicability		Responsibility		Remarks / Notes
		No	Yes	Sup.	Int.	
12	Does not compromise indoor fire escape routes and exits	☐	☒	☐	☒	
13	If placed outdoors: Components have suitable ingress protection (IP) ratings. Usually, IP54 is sufficient.	☒	☐	☒	☐	Not applicable. Batteries and systems will be placed indoors in a battery house
14	Noise generation from batteries and components – i.e. inverter	☒	☐	☐	☐	
Safety systems for battery room / work-space						
15	Ambient temperature controls	☐	☒	☐	☒	Winter season charging
16	Battery Management System (see Checklist 2)	☐	☒	☒	☐	
17	Air ventilation system	☐	☒	☒	☒	Very important for safety! Proposal and specs, by SuperB; Installation, by UT
18	Fixed fire-suppression system	☐	☒	☐	☒	
19	Fire detection system and alarm	☐	☒	☐	☒	
20	Gas detection system and alarm	☐	☒	☐	☒	Gas detection is important! For LIFE: LFP batteries mainly vent and causes the release of flammable and toxic gases
21	Fire resistance enclosure: 1-hour minimum	☐	☒	☐	☐	
22	Noise generation related to safety systems – e.g. ventilation systems	☐	☐	☐	☐	Bouwbesluit 2012, Article 3.8. Should be less than 30 dB
23	Use of explosion-proof (EX) equipment -	☐	☐	☐	☐	It depends on if the battery shares space with other equipment. If only Li-ion battery stored, then off-gas explosion-proof should be T2 temperature class, and IIC gas group (as per IEC 60079)
24	Back-up power supply for safety systems	☐	☐	☐	☐	
Battery room access during use						

No.	Safety barrier	Applicability		Responsibility		Remarks / Notes
		No	Yes	Sup.	Int.	
25	Restricted access to for only authorised personnel (except for the ordinary-user interface)	☐	☒	☐	☒	Very important! To establish who would be an 'authorised personnel.'
26	Warning signage	☐	☒	☐	☒	
Emergency response during use						
27	External/outdoor ease of accessibility for fire brigade for emergency response	☐	☒	☐	☒	
28	Emergency response guidelines	☐	☒	☐	☒	
29	Post-fire clean up (burnt cells, or water bath)	☐	☒	☐	☒	
Installation, use, maintenance and decommissioning activities						
30	System commissioning tests	☐	☒	☐	☒	
31	Minimum system documentation (to be discussed) – Basic data, Operations and maintenance manual	☐	☒	☒	☒	Joint responsibility. To-be-released NEN 4288 addresses the requirements
32	Implementation of maintenance and inspection	☐	☒	☒	☒	Joint responsibility.
33	System decommissioning and disposal; second life usage	☐	☒	☒	☒	To-be-released NEN 4288 addresses the requirements

Checklist 2: Battery Management System

The Battery Management Systems (BMS) is the battery cell protection electronics. The features of a BMS can vary from one Li-ion product to another. The purpose of this checklist is to provide clarity on the Battery Management System features used in the LIFE project that aims to prevent thermal-runaway phenomena from occurring. If a specific protection feature is not included, then the asset owner (i.e. the University of Twente) will need to decide if it is necessary to incorporate additional safety barriers.

No.	**Safety protection features**	**Included?**		**Remarks**
		No	**Yes**	
1	Monitoring of cell voltage	☐	☒	
2	Monitoring of cell current	☐	☒	
3	Monitoring of internal cell temperature	☐	☒	
4	Indication of the state of charge	☐	☒	
5	Protection against overcharging	☐	☒	
6	Protection against low-temperature charging, e.g. low ambient temperature shut-off	☐	☒	
7	Monitoring of even/balanced voltage across cells	☐	☒	
8	Smoke or fire detection shut-off	☒	☐	To be integrated at the system level
9	High ambient temperature shut-off (less of safety, but to maintain battery lifespan)	☐	☒	
10	Indicates the state of health (battery longevity, rather than a safety issue)	☐	☒	This feature is available, but currently is not made visible for the ordinary users

Other concerns for the system integrator to manage (please add):

Appendix 11 Possible pictograms for hydrogen, Li-ion battery and VRB installations

Hydrogen

Figure 32 (left) Pictograms for transportation or storage. International Maritime Dangerous Goods Code (IMDG) denotes the number '2' for flammable gas and number '3' for flammable liquid. (right) Pictogram for compressed gas. From [117].

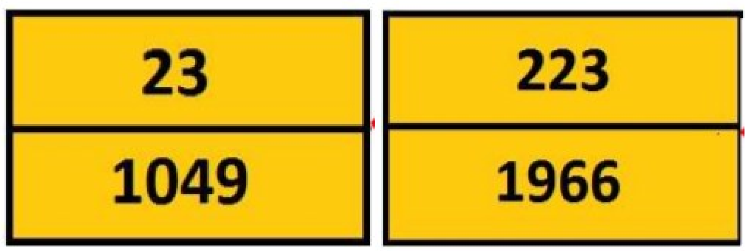


Figure 33 International Carriage of Dangerous Goods by Road (ADR)'s labels for transportation of hydrogen gas (left) and liquid (right). This consist of the hazard identification number at the upper section, and the United Nations Model Regulations number (UN number) at the lower section, a four-digit code indicating the hazardous material or article [189].

Figure 34 Warning placards can be used for a reminder at hydrogen storage areas. From [95].

Li-ion batteries

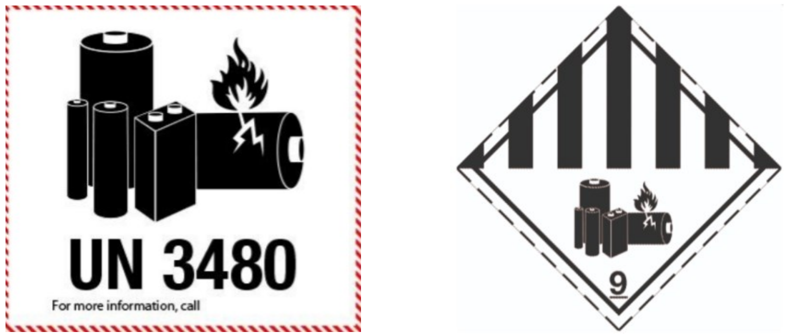


Figure 35 Examples of pictograms for use during transportation: (left) *UN 3480*; (right) *Lithium-ion ADR Class 9 combined with UN 3480.*

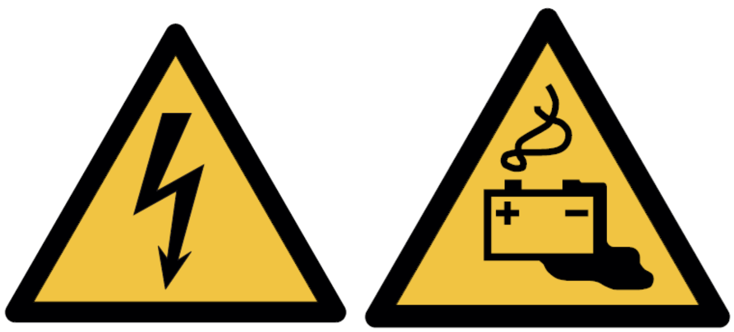


Figure 36 Pictograms at battery storage areas: (left) electric shock W012, from [190]; (right) battery charge area typically for lead-acid battery (from EN ISO 7010)

Figure 37 More possible pictograms for battery storage areas: (left) for a general battery; (centre) for Li-ion battery; (right) for non-Li-ion battery. From [66]

VRB

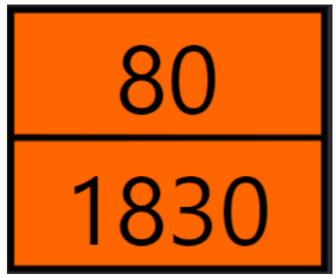


Figure 38 Only for sulphuric acid with higher than 51% content. (left) IMDG's class '8' is for corrosive products; (right) ADR's hazard identification number is '80', and the UN's number for sulphuric acid is '1830'.

Figure 39 CLP's pictograms that can be used where VRBs are located: (left) Corrosive symbol; (right) Health hazard

Appendix 12 Information and data used in the safety hazards assessments

LIFE Electrical Energy Storage (EES) system specifications

Source: LIFE project documents

Hydrogen system

Proposed capacity for the LIFE:

Product	HyGear Hydrogen storage
Type of storage	3* 10 m pipes (Ø 1m) with 200 bar pressure
Max. storage capacity	7000 kWh
Max. storage H_2	210 kg (3*70 kg) with 200 bar pressure

Fuel cells:

- Power: 6 kW
- Voltage: 72 – 120 V_{DC} (depends on final configuration)
- Current: 0 - 85 A (depends on final configuration)

Electrolyser

- Power: 12 kW
- Voltage: 72 – 116 V_{DC}
- Current: 0 – 100 A
- Gas flow: 2.4 Nm^3/h
- Gas pressure: 30 bar

Storage

- Intermediate: 250 L @ 30 bar
- High pressure: 11500 L @ 210 kg @ 200 bar
- Choice of:
    a) Bottle racks: 230 x 50L bottles @ 210 kg, 200 bar
    b) Tubes:

The process flow diagram of the entire hydrogen system is not published in this report as it is proprietary information of HyGear.

SuperB Li-ion battery

Proposed capacity for the LIFE:

Product	Super-B Lithium-ion
Amount of batteries	48
Power – charge	61 kW
Power – discharge	210 kW
Current – charge	100 A
Current – discharge	300 A
Max. storage capacity	48*1.92 = 92 kWh

General product specifications:

Super B – product	
Name of product	SB12V100E-ZC is a Lithium Iron Phosphate rechargeable battery
Height	0,31 m
Width	0,41 m
Length	0,22 m
Weight	18,5 kg

Super B - battery	
Voltage – charge	12,8 V_{dc}
Voltage – discharge	14,6 V_{dc}
Capacity	1,92kWh
Max. charge current	100 A
Max. discharge current	300 A
Cycles (typical)	N/A
Battery chemicals	Lithium Iron Phosphate (LiFePO4):
Charge method	CCCV

Super B – external safety	
Operational temperature	0 to 45 °C
Humidity	max. 95%
Safety	Non-flammable and non-explosive

Volterion Redox-flow batteries

Proposed capacity for the LIFE:

Product	Volterion Redox-flow
Amount of batteries	2
Power	5 kW (max. 7.5 kW for 30 min.)
Voltage - charge	40 V_{DC}
Voltage - discharge	63 V_{DC}
Max. storage capacity	2*13.5 = 27 kWh

General product specifications:

Volterion – product	
Full product name	Volterion Power RFB
Height	1,95 m
Width	0,80 m
Length	1,20 m
Volume (electrolyte)	700 l
Weight (incl. electrolyte)	1550 kg
Material (covering)	Housing: aluminium frame with stainless steel (RVS) covering
Tanks	2 PE tanks incl. water safety tray and splash protection
IP-class	IP-56

Volterion – battery	
Voltage	40-63 V_{dc}
Power (constant)	5 kW
Current	80 – 110 A
Capacity - electrolyte	13,5 kWh
Capacity - discharge	10 kWh
Cycles (typical)	> 20.000 cycles
Lifespan	20 years
Electrolyte	all-vanadium (1.6 mol/l)
Stack technology	volterion compact sealless stack
Battery management	Volterion battery management
Connections (DC)	3 * 350A
Auxiliary supply	110-230 V_{ac} (50-60Hz)
Certification	CE-certified

Volterion – external safety	
Operational temperature	0 – 40 °C
Humidity	max. 95%
Safety	Non-flammable and non-explosive
Ventilation	Required

Indentured equipment list

Source: Constructed based on LIFE project documents

System ID	Level 1	Level 2	Level 3	Partner	Type
1	House and civil structure			EcoCabins	
1.1		Three pre-fab houses		As above	
2	Home Energy Management System (HEMS)			-	
2.1		Decentralized Energy Management toolkit (*DEMKit*)		Utwente	
2.2		Sensors		tbd	
2.3		*PQube Power Analyser*		tbd	
3	Electrochemical energy storage system				
3.1		Redox-flow battery		Volterion	Electrochemical storage
3.1.2			Electrolyte	As above	
3.1.3			Electrical circuits	As above	
3.1.4			Packaging	As above	
3.1.5			Battery management system	As above	
3.2		Lithium-ion battery		Super B	Electrochemical storage
3.2.1			Battery management system	As above	
3.2.2			Cell	As above	
3.2.3			User interface	As above	
3.2.4			Outer packaging	As above	
4	Chemical energy storage system				
4.1		Hydrogen system		HyGear	Chemical storage
4.1.1			Electrolyser	As above	
4.1.2			Hydrogen intermediate storage tanks	As above	
4.1.3			Hydrogen high-pressure storage tanks	As above	
4.1.4			Hydrogen fuel cell	As above	
4.1.5			Heat exchanger	As above	
4.1.6			Water treatment system and storage	As above	
4.1.7			H2 Detection and warning system	As above	
4.1.8			Compressor	As above	
4.1.9			Water / Air separators	As above	
4.1.10			Air blower	As above	

System ID	Level 1	Level 2	Level 3	Partner	Type
5	Thermal energy system			Solar Freezer	Latent heat storage, Phase-change material type
5.1		PVT panel: 12 thermic collectors		As above	
5.1		1 heat pump (*NIBE*)		As above	
5.1		3 electro boilers (*NIBE*)		As above	
5.1		Heat transfer unit for GEP water buffer		As above	
5.1		Circulation regulation system		As above	
5.1		SolarFreezer Controller		As above	
5.1		Buffer bag		As above	
5.1		Floor heating system		As above	
6	Electrical energy generation				
6.1		PV panel and charging station		AmperaPark	
6.1.1			Double glass solar panels	As above	
6.1.2			Electrical distribution system	As above	
6.1.3			EV car charging poles	As above	
6.1.4			Parking and roof structure	As above	
6.2		DC-AC inverter		tbd	
6.3		AC-DC inverter		tbd	
7	Water system				
7.1		Bluewater circuit (Rainwater)		-	
7.1.1			Rainwater filtration	NX Filtration	
7.1.2			Rainwater storage	GEP	
7.1.3			Blue water treater (SmartBox)	Jotem	
7.1.4			Rainwater pump	GEP	
7.2		Greywater circuit		-	
7.2.1			Greywater supply (incoming)	-	
7.2.2			Greywater treatment (*Grey Box*)	Jotem	
7.2.3			Greywater storage	Jotem	
7.3		Blackwater circuit		-	
7.3.1			Blackwater supply (incoming)	-	
7.3.2			Blackwater treatment (*Black Box*)	Jotem	
7.4		Grid supply		tbd	

System ID	Level 1	Level 2	Level 3	Partner	Type
8	Electrical system			tbd	
8.1		Electrical wiring		tbd	
8.2		Meter		tbd	
8.3		Grid supply		tbd	

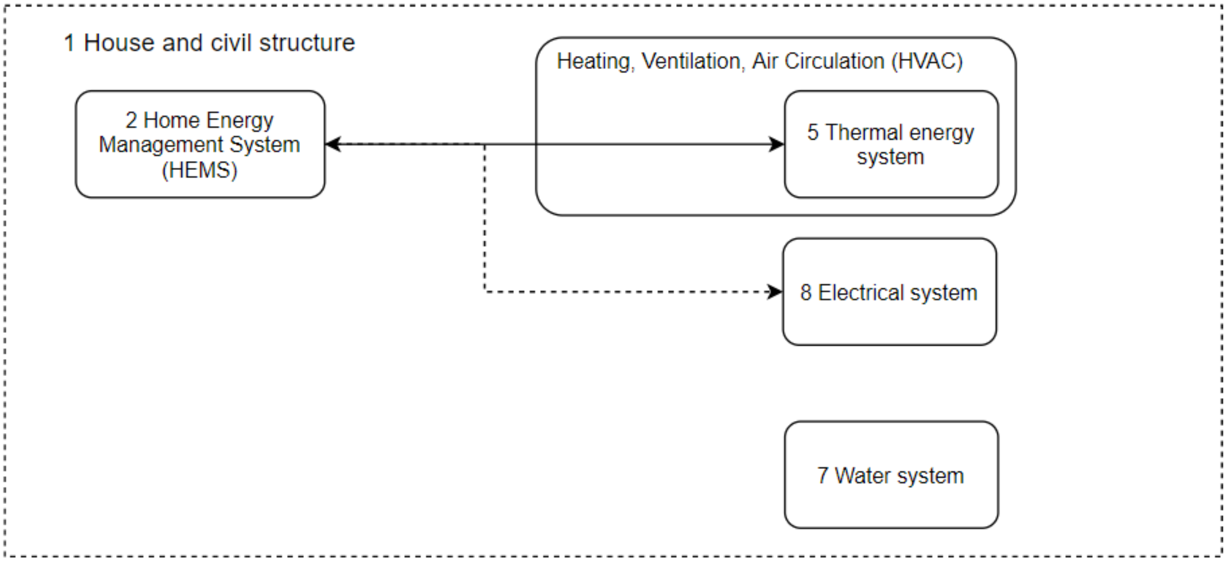
Functional flow block diagrams

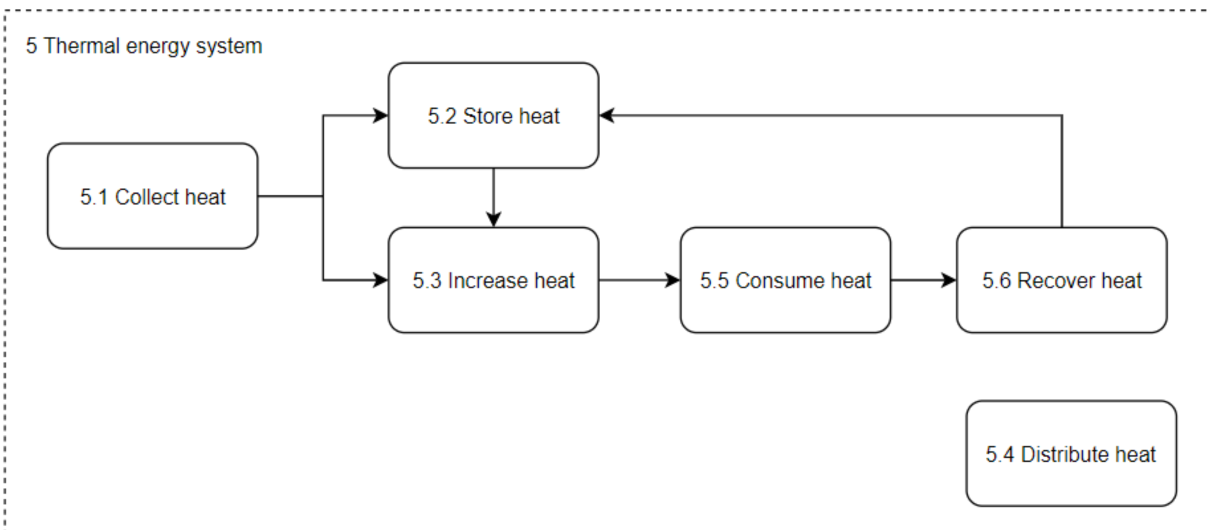
Source: Created based on LIFE project documents

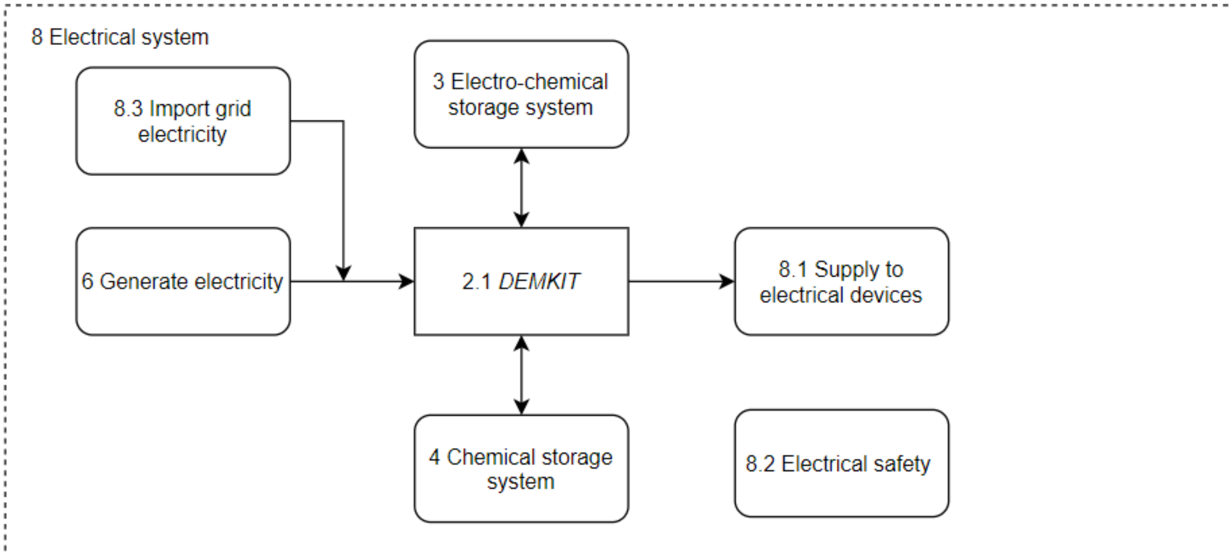
The identified functions:

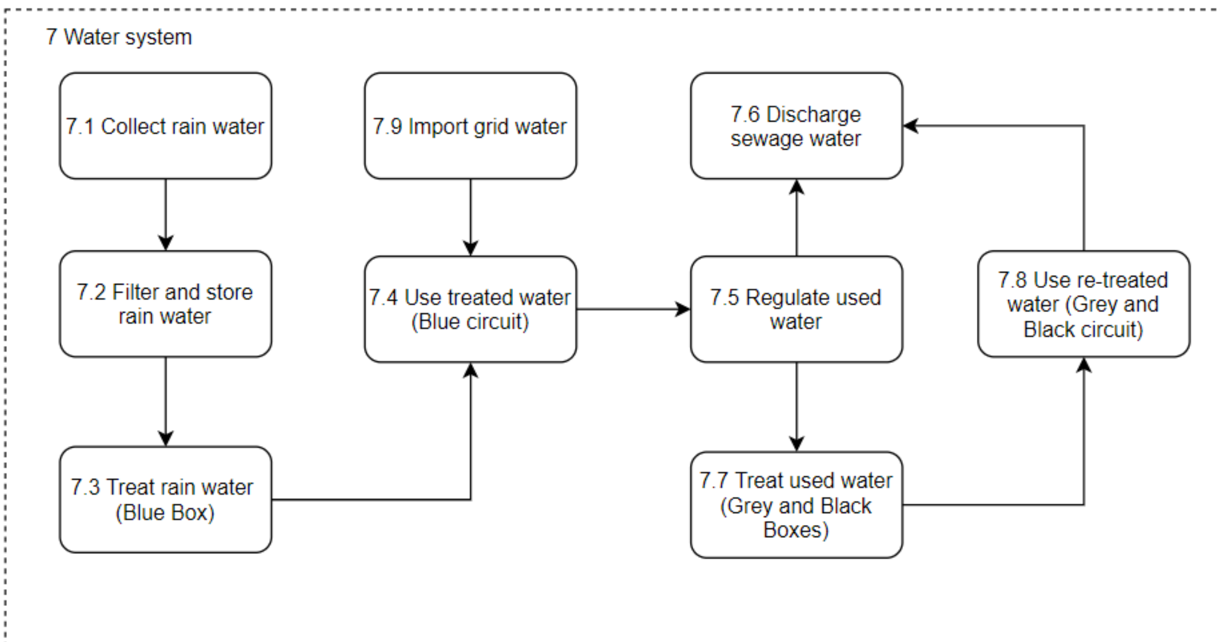
System ID	Level 1 of the indentured equipment list	Function ID	System function
1	House and civil structure	1	Provide a safe and secure living space for the 1,2 or 3 inhabitant(s)
2	Home Energy Management System (HEMS)	2.1	Measure energy usage
		2.2	Regulate energy usage
3	Electrochemical energy system	3.1	Charge battery
		3.2	Discharge battery
		3.3	Regulate charge and discharging
4	Chemical energy system	4.1	Treat water
		4.2	Electrolyse water
		4.3	Store hydrogen
		4.4	Convert hydrogen into electricity
5	Thermal energy system	5.1	Collect thermal energy
		5.2	Store thermal energy
		5.3	Increase thermal energy
		5.4	Distribute thermal energy
		5.5	Consume thermal energy
		5.6	Recover thermal energy
6	Electrical energy generation	6.1	Generate DC current
		6.2	Convert DC to AC
7	Water system	7.1	Collect rainwater
		7.2	Filter and store rainwater
		7.3	Treat rainwater (Blue box)
		7.4	Consume treated water
		7.5	Regulate used water
		7.6	Discharge sewage water
		7.7	Treat used water (Grey and Black boxes)
		7.8	Consume re-treated water
		7.9	Import from grid
8	Electrical system	8.1	Supply to electrical devices
		8.2	Protect against electricity hazards
		8.3	Import from grid

The identified functions are then mapped out in functional flow block diagrams to show the relationship between each function. The levels for each function can be expanded to see the subsequent level of details. Not all functional flow block diagrams are shown here.



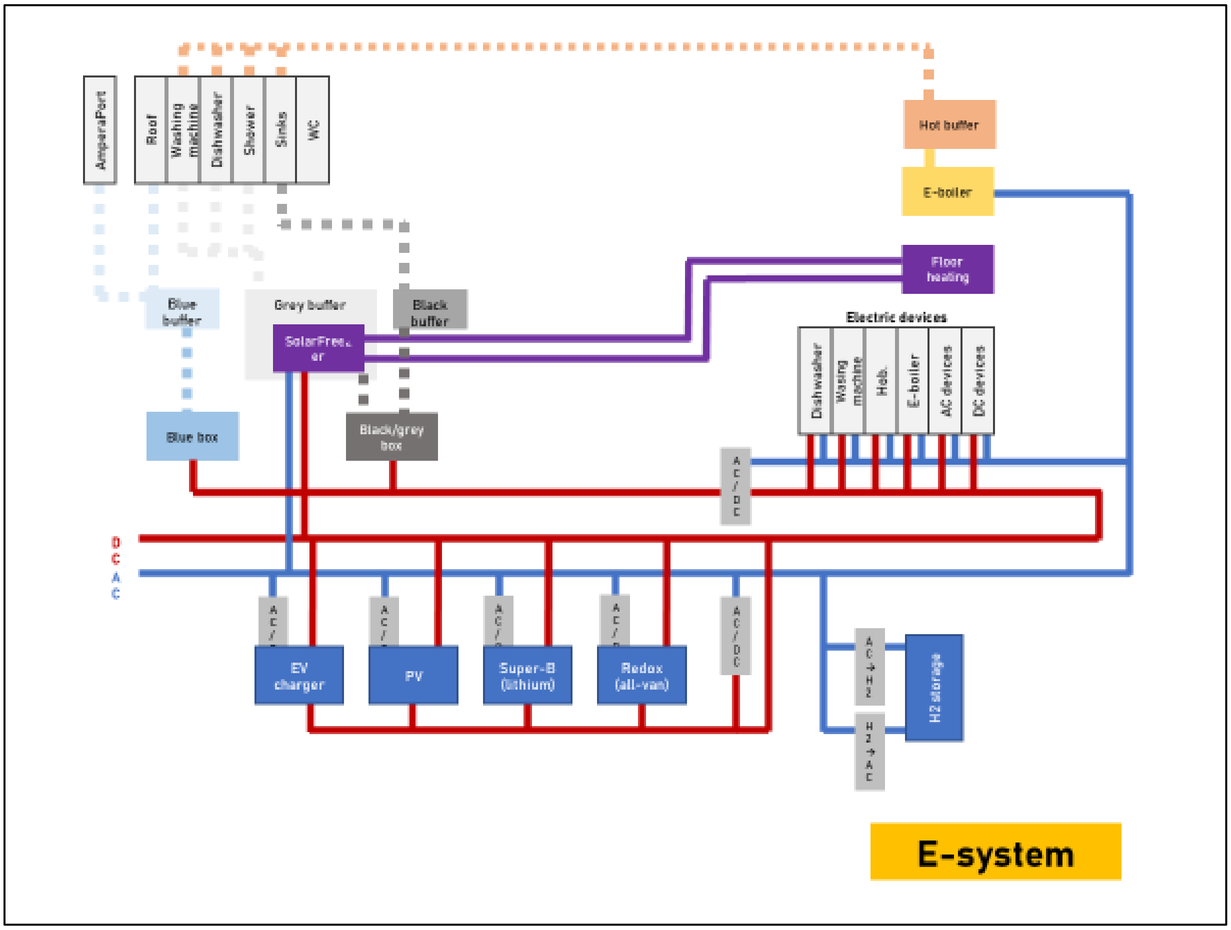



8 Electrical system
8.3 Import grid electricity
3 Electro-chemical storage system
6 Generate electricity
2.1 *DEMKIT*
8.1 Supply to electrical devices
4 Chemical storage system
8.2 Electrical safety


7 Water system
7.1 Collect rain water
7.9 Import grid water
7.6 Discharge sewage water
7.2 Filter and store rain water
7.4 Use treated water (Blue circuit)
7.5 Regulate used water
7.8 Use re-treated water (Grey and Black circuit)
7.3 Treat rain water (Blue Box)
7.7 Treat used water (Grey and Black Boxes)

Water and electricity scheme for LIFE

Source: LIFE project documents



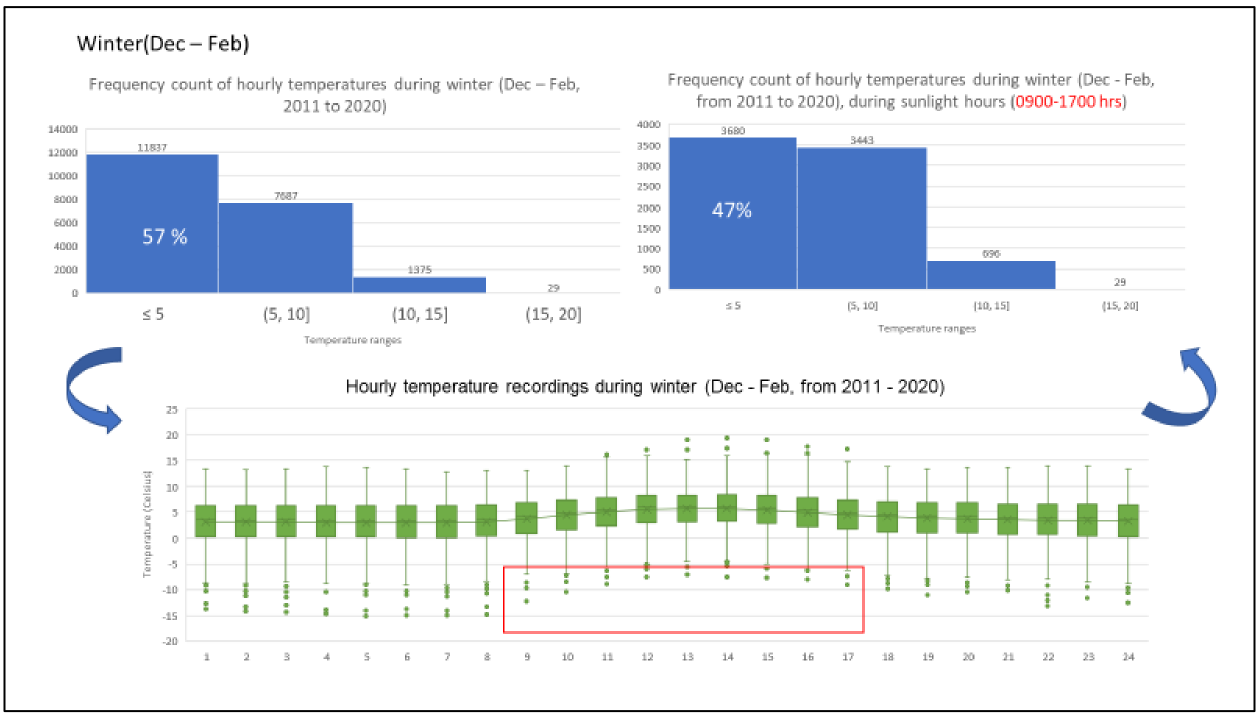
Temperature data in Enschede

Source: https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens

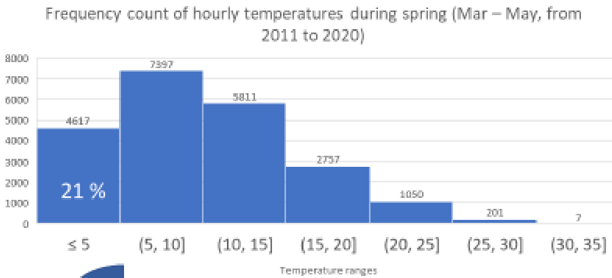
Hourly outside temperature recordings from the Twenthe weather station (number 290) from 1 January 2011 until 21 May 2020.

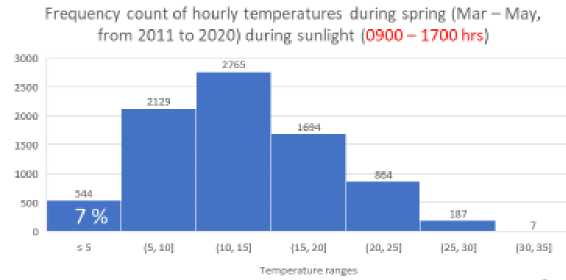
The data were converted into charts for the four seasons of the year, to indicate the temperature fluctuations over ten years. The interest is in estimating the amount of time the temperature goes below 5^{o}C and above 40 ^{o}C, which are outside the operating ranges of the Li-ion and VRB batteries. The conclusion from these charts are:

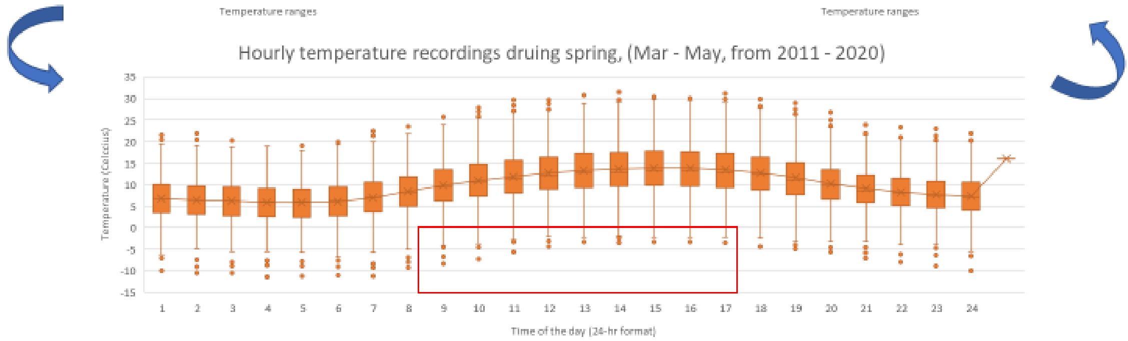
- During winter and autumn, there are substantial periods when the outside temperature can get lower than 5^{o}C.
  - In the winter, the average is around 47% of the hourly-recording during daylight (0900 – 1700 hrs) and 57% of the hourly-recording during the entire 24 hour period
  - In the autumn, the corresponding hourly-recording is around 8% and 16% respectively.
- There is negligible frequency, around 0.1% when the outside temperature rises above 40^{o}C



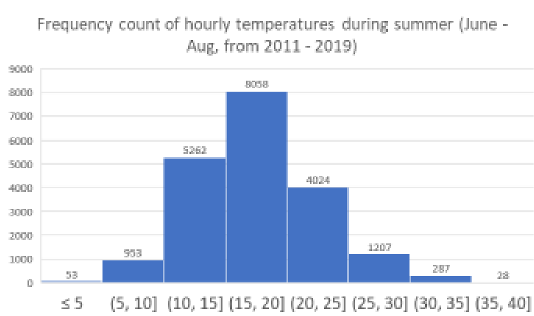
Spring (Mar – May)





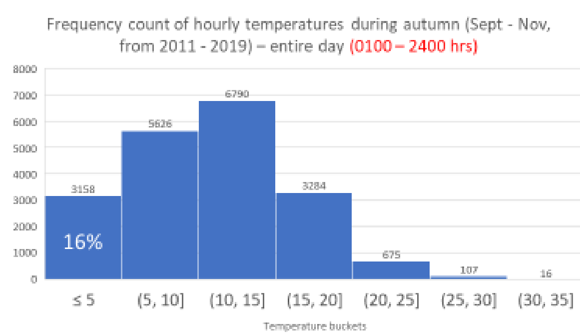


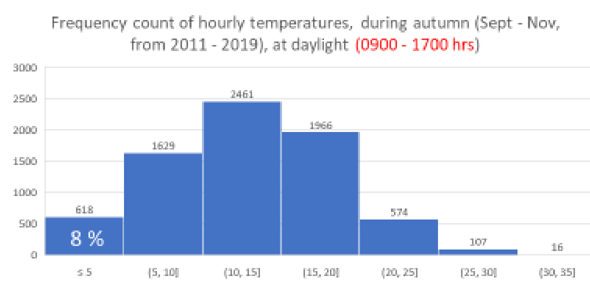
Summer (June – Aug)



No issues during the summer.

Autumn (Sept - Nov)





Hazards List

NEN-EN-ISO 12100:2010 Safety of machinery - General principles for design - Risk assessment and risk reduction

Table B.1 – Types of hazards. This table contain ten types of hazards to consider (Mechanical, Electrical, Thermal, etc.), its possible origins and the potential consequences of these hazards.

Table B.3: List of tasks that can result in hazardous situations. This table contains seven types of tasks (e.g. Transport, Assembly, etc.) and examples of such tasks (lifting, loading, etc.)

Safety data sheets (SDS)

Three safety data sheets were used as references.

1. Lithium iron phosphate battery. Source: Sonnen [142]

2. Compressed hydrogen gas. Source: Air Liquide [117]

3. Vanadium electrolyte solution. Source: courtesy of Volterion. The SDS is appended to this report, as it is not available online.

OXKEM Limited

Since 1978 manufacturer and blender of speciality pigments and chemicals

SAFETY DATA SHEET

VANADIUM ELECTROLYTE SOLUTION

Compilation date: 20/03/2017

Revision No: 1

Section 1: Identification of the substance/mixture and of the company/undertaking

1.1. Product identifier

1.2. Relevant identified uses of the substance or mixture and uses advised against

Product name: VANADIUM ELECTROLYTE SOLUTION

Use of substance / mixture: Research. Vanadium redox batteries.

1.3. Details of the supplier of the safety data sheet

Company name: Oxkem Ltd

117 Loverock Road

Reading

Berkshire

RG30 1DZ

UK

Tel: +44 (0) 118 952 2929

Fax: +44 (0) 118 952 2959

Email: info@oxkem.co.uk

1.4. Emergency telephone number

Emergency tel: +44 (0) 118 952 2929

(office hours only)

Section 2: Hazards identification

2.1. Classification of the substance or mixture

Classification under CLP: Acute Tox. 4: H302; Skin Corr. 1A: H314

Classification under CHIP: Xn: R22; C: R35

Most important adverse effects: Harmful if swallowed. Causes severe skin burns and eye damage.

2.2. Label elements

Label elements under CLP:

Hazard statements: H302: Harmful if swallowed.

H314: Causes severe skin burns and eye damage.

Signal words: Danger

Hazard pictograms: GHS05: Corrosion

GHS07: Exclamation mark

Precautionary statements: P280: Wear protective gloves/protective clothing/eye protection/face protection.

[cont...]

P303+361+353: IF ON SKIN (or hair): Remove immediately all contaminated clothing. Rinse skin with water/shower.

P305+351+338: IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing.

P301+330+331: IF SWALLOWED: rinse mouth. Do NOT induce vomiting.

P312: Call a POISON CENTER or doctor if you feel unwell.

P403+233: Store in a well-ventilated place. Keep container tightly closed.

P501: Dispose of contents/container to hazardous or special waste collection point.

2.3. Other hazards

Section 3: Composition/information on ingredients

3.2. Mixtures

PBT: This product is not identified as a PBT/vPvB substance.

Hazardous ingredients:

SULPHURIC ACID - REACH registered number(s): 01-2119458838-20-XXXX

EINECS	CAS	CHIP Classification	CLP Classification	Percent
231-639-5	7664-93-9	-	Skin Corr. 1A: H314	10-20%

VANADIUM OXIDE SULPHATE

248-652-7	27774-13-6	-	Acute Tox. 4: H302; Skin Irrit. 2: H315; Eye Irrit. 2: H319; STOT SE 3: H335	10-20%

DIVANADIUM TRIS(SULPHATE)

237-226-6	13701-70-7	-	Acute Tox. 4: H302; Skin Irrit. 2: H315; Eye Irrit. 2: H319; STOT SE 3: H335	10-20%

ORTHOPHOSPHORIC ACID

231-633-2	7664-38-2	-	Skin Corr. 1B: H314	1-10%

Section 4: First aid measures

4.1. Description of first aid measures

Skin contact: Remove all contaminated clothes and footwear immediately unless stuck to skin. Drench the affected skin with running water for 10 minutes or longer if substance is still on skin. Transfer to hospital if there are burns or symptoms of poisoning.

Eye contact: Bathe the eye with running water for 15 minutes. Transfer to hospital for specialist examination.

Ingestion: Wash out mouth with water. Do not induce vomiting. Give 1 cup of water to drink every 10 minutes. If unconscious, check for breathing and apply artificial respiration if necessary. If unconscious and breathing is OK, place in the recovery position. Transfer to hospital as soon as possible.

Inhalation: Remove casualty from exposure ensuring one's own safety whilst doing so. If

[cont...]

unconscious and breathing is OK, place in the recovery position. If conscious, ensure the casualty sits or lies down. If breathing becomes bubbly, have the casualty sit and provide oxygen if available. Transfer to hospital as soon as possible.

4.2. Most important symptoms and effects, both acute and delayed

Skin contact: Blistering may occur. Progressive ulceration will occur if treatment is not immediate.

Eye contact: Corneal burns may occur. May cause permanent damage.

Ingestion: Corrosive burns may appear around the lips. Blood may be vomited. There may be bleeding from the mouth or nose.

Inhalation: There may be shortness of breath with a burning sensation in the throat. Exposure may cause coughing or wheezing.

Delayed / immediate effects: Immediate effects can be expected after short-term exposure.

4.3. Indication of any immediate medical attention and special treatment needed

Section 5: Fire-fighting measures

5.1. Extinguishing media

Immediate / special treatment: Eye bathing equipment should be available on the premises.

Extinguishing media: Suitable extinguishing media for the surrounding fire should be used. Use water spray to cool containers.

5.2. Special hazards arising from the substance or mixture

Exposure hazards: Corrosive. In combustion emits toxic fumes of sulphur oxides.

5.3. Advice for fire-fighters

Advice for fire-fighters: Wear self-contained breathing apparatus. Wear protective clothing to prevent contact with skin and eyes.

Section 6: Accidental release measures

6.1. Personal precautions, protective equipment and emergency procedures

Personal precautions: Mark out the contaminated area with signs and prevent access to unauthorised personnel. Do not attempt to take action without suitable protective clothing - see section 8 of SDS. Turn leaking containers leak-side up to prevent the escape of liquid.

6.2. Environmental precautions

Environmental precautions: Do not discharge into drains or rivers. Contain the spillage using bunding.

6.3. Methods and material for containment and cleaning up

Clean-up procedures: Clean-up should be dealt with only by qualified personnel familiar with the specific substance. Absorb into dry earth or sand. Transfer to a closable, labelled salvage container for disposal by an appropriate method.

[cont...]

6.4. Reference to other sections

Reference to other sections: Refer to section 8 of SDS. Refer to section 13 of SDS.

Section 7: Handling and storage

7.1. Precautions for safe handling

Handling requirements: Avoid direct contact with the substance. Ensure there is sufficient ventilation of the area. Do not handle in a confined space. Avoid the formation or spread of mists in the air.

7.2. Conditions for safe storage, including any incompatibilities

Storage conditions: Store in cool, well ventilated area. Keep container tightly closed. Avoid incompatible materials and conditions - see section 10 of SDS.

7.3. Specific end use(s)

Specific end use(s): No data available.

Section 8: Exposure controls/personal protection

8.1. Control parameters

Hazardous ingredients:

SULPHURIC ACID...100%

Workplace exposure limits / OELV: **Respirable dust**

State	8 hour TWA	15 min. STEL	8 hour TWA	15 min. STEL
UK / IRE	0.05 mg/m3	-	-	-

ORTHOPHOSPHORIC ACID...100%

UK / IRE	1 mg/m3	2 mg/m3	-	-

8.1. DNEL/PNEC Values

DNEL / PNEC No data available.

8.2. Exposure controls

Engineering measures: Ensure there is sufficient ventilation of the area.

Respiratory protection: Respiratory protective device with particle filter. Gas/vapour filter, type B: inorganic vapours excl. CO (EN141).

Hand protection: Butyl gloves. Nitrile gloves.

Eye protection: Tightly fitting safety goggles. Ensure eye bath is to hand.

Skin protection: Acid-resistant protective clothing.

Environmental: Refer to specific Member State legislation for requirements under Community environmental legislation.

Section 9: Physical and chemical properties

[cont...]

9.1. Information on basic physical and chemical properties

State: Liquid

Colour: Green-blue

Odour: Odourless

Oxidising: Non-oxidising (by EC criteria)

Solubility in water: Miscible in all proportions

Boiling point/range°C: >100 **Melting point/range°C:** <-15

Relative density: 1.4 **pH:** <1

9.2. Other information

Section 10: Stability and reactivity

10.1. Reactivity

Other information: No data available.

Reactivity: Stable under recommended transport or storage conditions.

10.2. Chemical stability

10.3. Possibility of hazardous reactions

Chemical stability: Stable under normal conditions.

Hazardous reactions: Hazardous reactions will not occur under normal transport or storage conditions.

Decomposition may occur on exposure to conditions or materials listed below.

10.4. Conditions to avoid

Conditions to avoid: Heat.

10.5. Incompatible materials

10.6. Hazardous decomposition products

Materials to avoid: Strong bases. Strong oxidising agents. Metals.

Haz. decomp. products: In combustion emits toxic fumes of sulphur oxides.

Section 11: Toxicological information

11.1. Information on toxicological effects

Hazardous ingredients:

SULPHURIC ACID...100%

ORL	RAT	LD50	2140	mg/kg

[cont...]

ORTHOPHOSPHORIC ACID...100%

ORL	RAT	LD50	1530	mg/kg

Relevant effects for mixture:

Effect	Route	Basis
Acute toxicity (harmful)	ING	Hazardous: calculated
Corrosivity	OPT INH DRM	Hazardous: calculated

Symptoms / routes of exposure

Skin contact: Blistering may occur. Progressive ulceration will occur if treatment is not immediate.

Eye contact: Corneal burns may occur. May cause permanent damage.

Ingestion: Corrosive burns may appear around the lips. Blood may be vomited. There may be bleeding from the mouth or nose.

Inhalation: There may be shortness of breath with a burning sensation in the throat. Exposure may cause coughing or wheezing.

Delayed / immediate effects: Immediate effects can be expected after short-term exposure.

Other information: Not applicable.

Section 12: Ecological information

12.1. Toxicity

12.2. Persistence and degradability

Ecotoxicity values: No data available.

Persistence and degradability: No data available.

12.3. Bioaccumulative potential

12.4. Mobility in soil

Bioaccumulative potential: No data available.

Mobility: Readily absorbed into soil.

12.5. Results of PBT and vPvB assessment

12.6. Other adverse effects

PBT identification: This product is not identified as a PBT/vPvB substance.

Other adverse effects: Negligible ecotoxicity.

Section 13: Disposal considerations

13.1. Waste treatment methods

Disposal operations: Transfer to a suitable container and arrange for collection by specialised disposal company.

Disposal of packaging: Dispose of in a regulated landfill site or other method for hazardous or toxic wastes.

[cont...]

NB: The user's attention is drawn to the possible existence of regional or national regulations regarding disposal.

Section 14: Transport information

14.1. UN number

UN number: UN3264

14.2. UN proper shipping name

Shipping name: CORROSIVE LIQUID, ACIDIC, INORGANIC, N.O.S. (SULPHURIC ACID)

14.3. Transport hazard class(es)

Transport class: 8

14.4. Packing group

14.5. Environmental hazards

Packing group: II

Environmentally hazardous: No

Marine pollutant: No

14.6. Special precautions for user

Special precautions: No special precautions.

Tunnel code: E

Transport category: 2

Section 15: Regulatory information

15.1. Safety, health and environmental regulations/legislation specific for the substance or mixture

15.2. Chemical Safety Assessment

Specific regulations: Not applicable.

Chemical safety assessment: A chemical safety assessment has not been carried out for the substance or the mixture by the supplier.

Section 16: Other information

Other information

Other information: This safety data sheet is prepared in accordance with Commission Regulation (EU) No 453/2010.

* indicates text in the SDS which has changed since the last revision.

Phrases used in s.2 and 3: H302: Harmful if swallowed.

H314: Causes severe skin burns and eye damage.

H315: Causes skin irritation.

H319: Causes serious eye irritation.

H335: May cause respiratory irritation.

[cont...]

R22: Harmful if swallowed.

R35: Causes severe burns.

Legal disclaimer: The above information is believed to be correct but does not purport to be all inclusive and shall be used only as a guide. This company shall not be held liable for any damage resulting from handling or from contact with the above product.

Appendix 13 Approximation of safety/hazard distance for ignited hydrogen jet

An example of using a nomogram to determine the flame length of the ignited jet is shown in Figure 40.

The nomogram can be used to determine the flame length of an ignited hydrogen jet or the distance to a certain hydrogen concentration in the air for an un-ignited jet. Steps in using the nomogram:

1. Approximate the hole diameter of the leak source. Start at the lower chart, reading from the vertical axis.
2. Approximate the hydrogen system pressure, typically the normal operating pressure. On the lower chart, trace the horizontal line until it meets the slops for the relevant system pressure
3. Approximate the hydrogen content in the atmosphere. In the lower chart, trace a vertical line to the upper chart until it meets the relevant slope. For unignited release, the slope could be for the 2% case (typically the set-point for hydrogen detector alarms, at which below this point no alarm has been sounded yet) or the 4% case (alarm has been sounded) or the case when there is a visible flame.
4. Approximate the safe distance. Trace the line horizontally from the slope to the left vertical axis.

In the example above, a 1mm diameter leak is assumed. System pressure of 200 bar is considered. For an ignited jet, the SD is approximated to be between 1 to 2 meters away from the leak source.

It can be observed that the hazard distance is affected by both the leak diameter and the system pressure.

Other methods:

Molkov, in this book ‘Fundamentals of Hydrogen Safety Engineering’, has developed nomograms for unignited jet and ignited jet fires. These monograms allow for a broader range for the independent variables such as the hydrogen concentration (volumetric fraction) in the air, and the tank storage temperatures. Refer to [118].

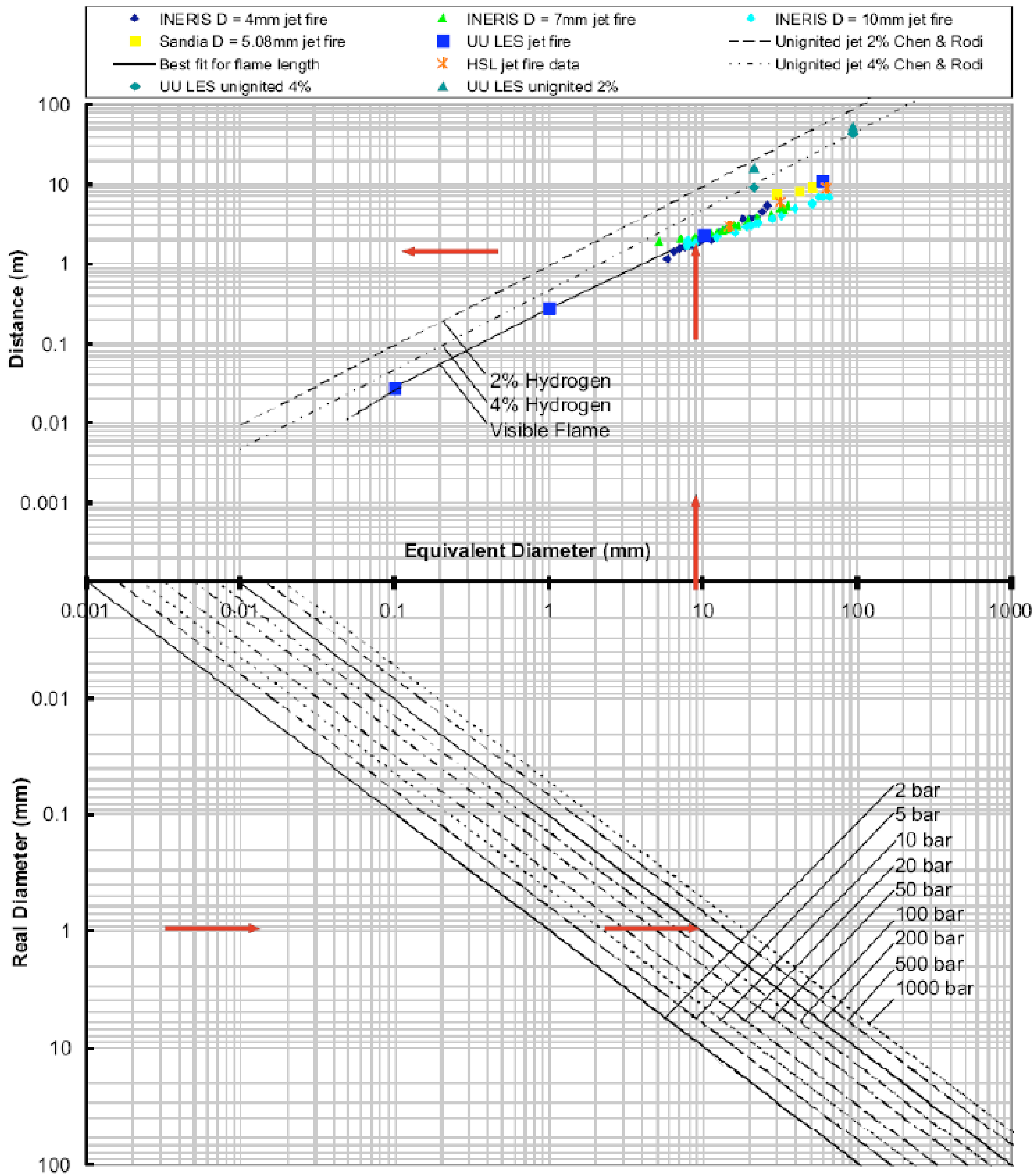


Figure 40 Nomogram for calculation of the flame length of high momentum jet fire by the physical size of leak and pressure in storage. From [109].

Appendix 14 Electrical energy storage (EES) technology, hydrogen systems and batteries

An overview of EES is described here, with a focus on hydrogen system, Li-ion battery and VRB technology.

Overview of electrical energy storage technology

Energy is the capacity for doing work. The SI unit for energy is either Joule (J) or watt-hour (Wh). There is a generally acceptable categorisation of energy into two broad categories, namely primary and secondary energy [191]. 'Primary energy' is the energy embodied in sources which involve human-induced extraction or capture, that may include separation from contiguous material, cleaning or grading to make the energy available for trade, use or transformation. Secondary energy is the energy embodied in commodities that have undergone human-induced transformation or conversion. 'Secondary energy' types are sometimes called energy carriers. Figure 41 shows this categorisation. Both electricity and hydrogen are considered as energy carriers. It can also be seen that some forms of energy, such as crude oil, coal and petroleum products, are easier and cost-effective to store and distribute.

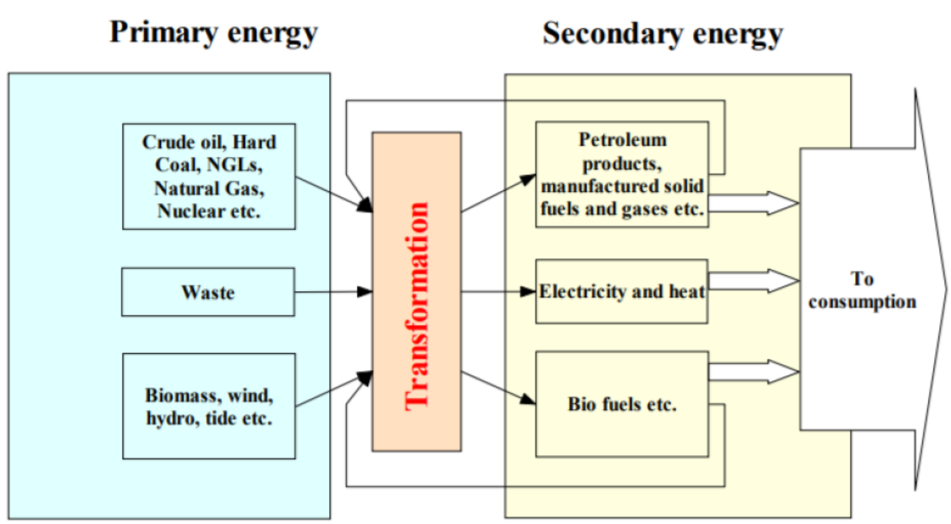


Figure 41 Primary and secondary energy, as presented by Øvergaard [191]

The contribution of energy storage technology to the energy transition is immense. Two types of storage systems are typically referred to in this regard: electrical energy storage (EES) and thermal energy storage. Figure 42 shows one possible manner to classify the various types of energy storage technologies.

In line with the research objective, some useful aspects of EES technology will be discussed to gain an understanding of the respective advantages, limitations and applicability between the different technology types. More in-depth details of the individual technologies can be found in other literature.

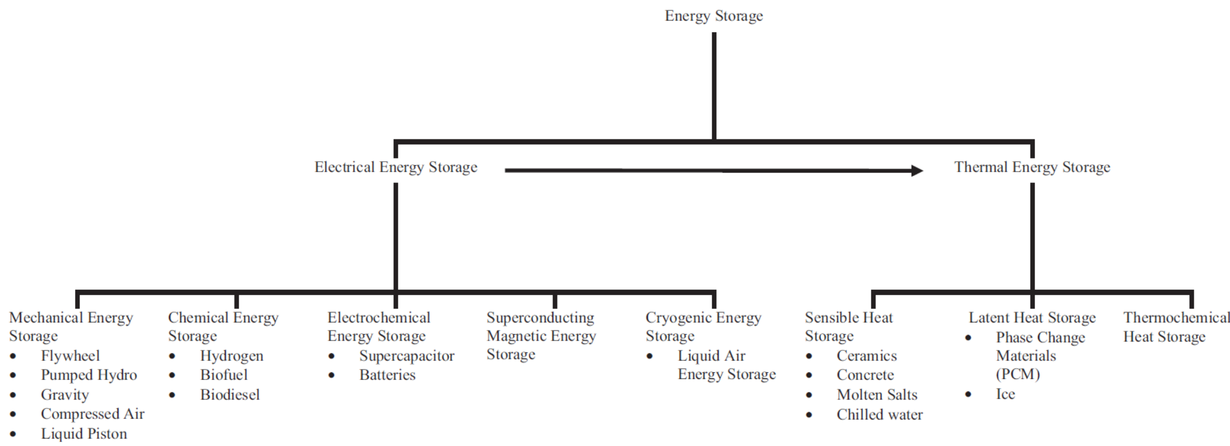


Figure 42 Classification of energy storage technology, from Aneke and Wang [8].

Power rating and storage capacity: Power rating refers to the amount of instantaneous energy a device is able to withdraw/inject from/into the electricity grid, with the unit kW, or MW. The storage capacity, with the unit kWh or MWh, determines the discharge time, which is obtained by dividing the energy capacity with the power rating [192]. In combination, both characteristics determine the suitability of application of the various technology types, as shown in Figure 44.

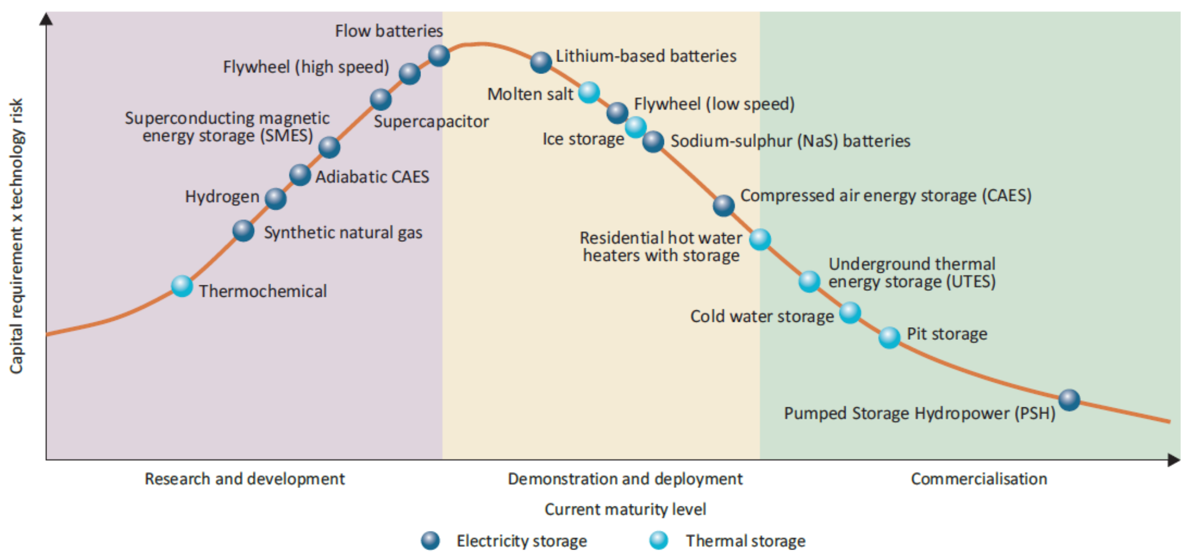


Figure 43 Maturity curve of EES in 2014, from IEA [193]

Figure 44 shows the position on the maturity curve as of 2014. Except for pumped hydro storage (PHS), most of the electrical storage technologies are clustered to the left of the 'valley of death'. This is a phase when a particular product has not yet begun generating revenue, and yet a large amount of cash is burned to keep operations going, typically during the initial development stage or where it needs to demonstrate its practical and commercial viability [194].

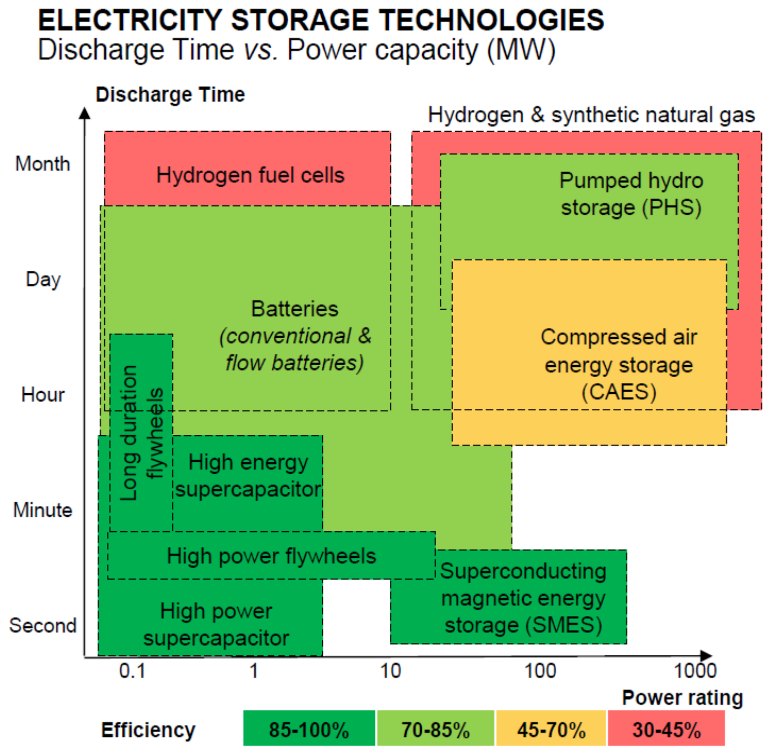
Accordingly, PHS makes up 98% of the currently installed large/utility-scale energy storage global capacity, as of 2017 [8, 195].

Excluding PHS, Li-ion batteries make up the majority of newly-installed capacity, a trend that is already noticeable since 2011 [196].

Economics and pricing: Attractive economics can help to enable widespread adoption of energy storage technology.

However, Decourt and Romain noted in their report in 2013 that it is difficult to compare the different technologies due to the multiple application and technical factors that can affect the economic assessments. Capital cost is the easiest to compare while operating cost is dependent on the operating company. Electricity prices are not easy to compute as it is dependent factors such as end application, market factors and regulations [192].

Two commonly-used units when to the cost of energy storage technology are price per unit power ($/kW) and price per unit capacity ($/kWh). Schmidt et al. projected that the capital costs for some of the EES would fall with the increase of installed capacity [197]. The installed capacity of 1 TWh would indicate that a particular technology has become mature. Based on this 'experience curves', see Figure 45, there is still room for the capital cost of residential hydrogen fuel-cell,



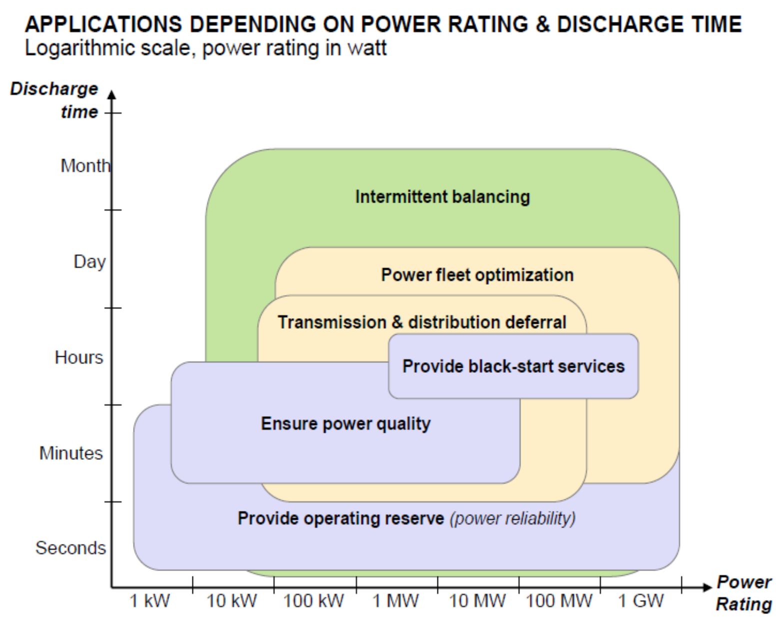


Figure 44 Power rating and discharge time determines application type of electrical storage technologies [33].

Li-ion batteries and VRB to become more attractive as the installed capacity was estimated to be only around 1 GWh in 2015.

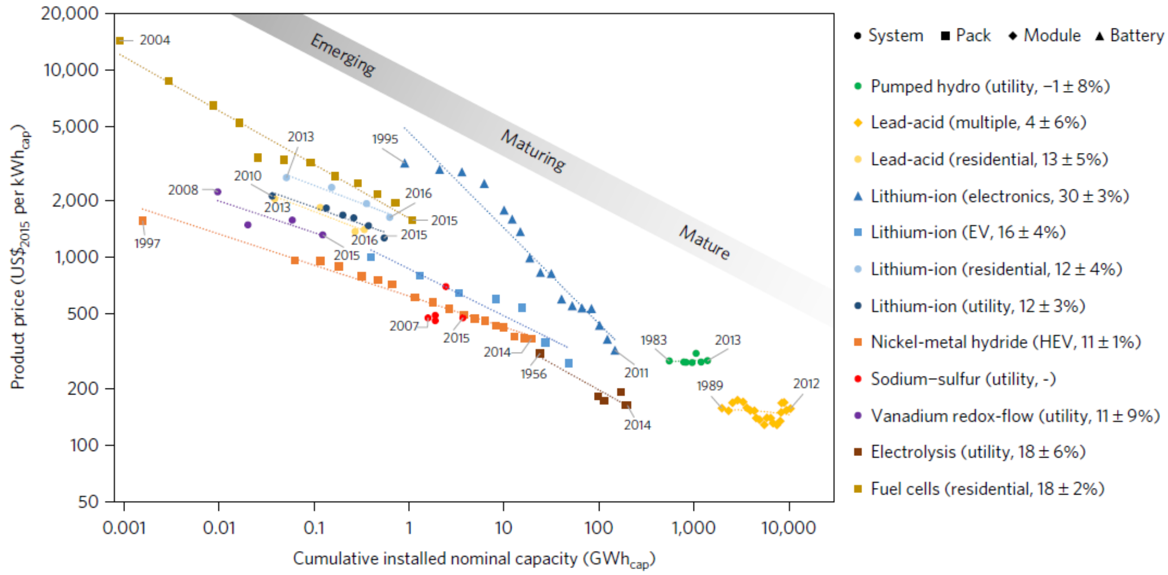


Figure 45 The future cost of electrical energy storage based on experience rates [197].

Environmental impact: Although EES technologies are enablers for more sustainable energy usage, these also harm the environment. Factors that need to be assessed include some greenhouse gas (GHG) emissions, land use, water use, and energy intensity [192]. For example, PHS has a high land footprint for dam-building and also uses a substantial amount of water, which has an impact on the ecosystem.

A means to compare energy intensity is the use of Energy stored on invested (ESOI), introduced by Barnhart and Benson [198]. ESOI is the ratio of electrical energy stored over the lifetime of a storage device to the amount of primary embodied energy required to build the device. Embodied energy is the amount of energy for resource acquisition, transportation, fabrication, delivery, operation and maintenance and disposal required in the building of a storage device. In other words, the higher the ESOI, the less energy-intensive a particular EES technology. Batteries had ESOI ranging from 2-10, while PHS and compressed air energy storage (CAES) has ESOI just above 200. Barnhart and Benson's study supports the point that improvements are required to improve the cycling life of battery technology to achieve more affordable batteries and lessen the harm to the environment.

Table 63 gives an overview of the advantages and disadvantages of the various electrical energy storage technology.

Table 63 Advantages and disadvantages of the various electrical energy storage technology [192]

	Advantages	Drawbacks
PHS[1]	Commercial, large scale, efficient	Low energy density, availability of sites, depends on availability of water
CAES[2]	Cost, flexible sizing, large scale	Lack of suitable geology, low energy density, need to heat the air with gas
Flywheels	Power density, efficient, scalable	Cost, low energy density
NaS battery[3]	Efficient, density (power & energy), cycling (*vs.* other battery)	Safety, discharge rate (*vs.* other battery), must be kept hot
Li-ion battery[4]	Efficient, density (energy & power), mature for mobility	Cost, safety
Flow battery	Independent energy & power sizing, scalable	Cost (more complex balance of system)
Supercapacitor	High power density, efficient and responsive	Low energy density, cost ($/kWh), voltage changes
SMES[5]	High power density, efficient and responsive	Low energy density, cost ($/kWh), not widely demonstrated
Molten salt	Commercial, large scale	Niche for concentrating solar power plants
Hydrogen	High energy density, versatility of hydrogen carrier	Low round-trip efficiency, cost, safety
SNG[6]	High energy density, leverage current infrastructure	Low round-trip efficiency, cost

Note: [1] PHS: pumped hydro storage; [2] CAES: compression air energy storage; [3] NaS: sodium-sulfur; [4] Li-ion: lithium-ion; [5] SMES: superconducting magnetic energy storage; [6] SNG: synthetic natural gas.

Hydrogen technology

Hydrogen is the smallest and lightest element known to humankind. It is the most abundant element in the universe [199, 200]. On Earth, hydrogen in its pure form is a diatomic molecule (H_2) in gaseous form at atmospheric (atm) pressure and at room temperature. Its boiling point at 1 atm is -253 °C. However, only 0.00005% of the atmosphere contains hydrogen in its pure form as most hydrogen are found in combination with other elements to make up compounds such as hydrocarbons and water (H_2O). Therefore, processing efforts are required to extract hydrogen from these compounds to create pure H2 gas.

Hydrogen's attractiveness as a fuel stems from the fact that it is found in relative abundance on Earth [201]. It produces no emissions when used in a fuel-cell, in ESS offers long discharge times ranging from days to months, and has one of the highest energy density by weight, as can be seen from Figure 46 [202]. It is also a very versatile energy carrier within what is termed as the 'hydrogen economy' [203]. Hydrogen can be used to generate electricity, i.e. Power to Power or P2P; blended into natural gas via methanation, i.e. Power to Gas or P2G; used as a vehicle and rocket fuel, i.e. Power to Mobility or P2M; and used in the production of petroleum products or fertiliser, i.e. Power to Chemical or P2C [82].

On the downside, hydrogen has a relatively low energy density by volume, thus needs a much bigger storage volume space at atmospheric pressure in ambient conditions for a corresponding amount of

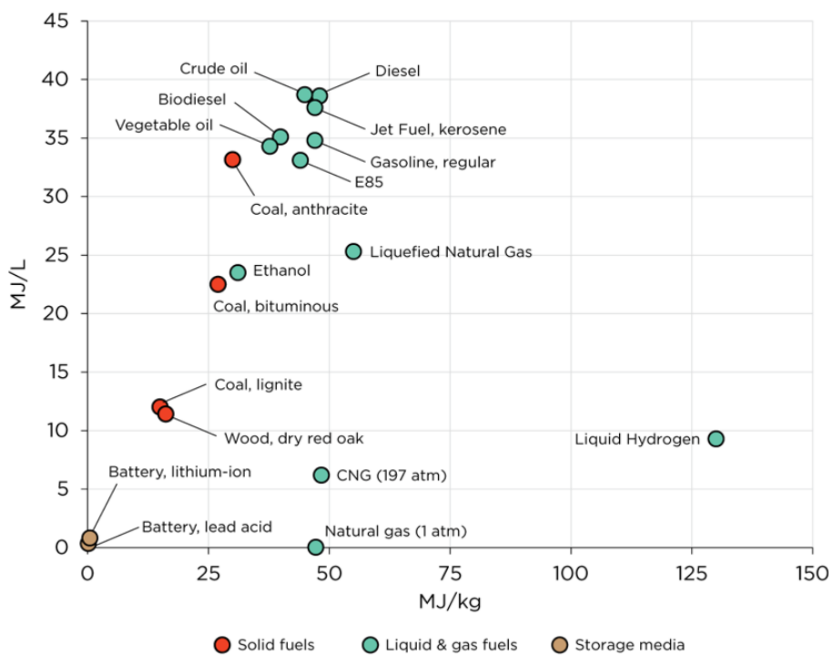


Figure 46 Volumetric and gravimetric density of fuels and energy storage medium. The unit on the vertical axis is sometimes called 'volumetric density' and on horizontal axis 'gravimetric density'. From [43].

energy of, for instance, gasoline. It also has a low round-trip efficiency of 35-45% and brings safety concerns [82].

Next, is a description of the main components of a hydrogen fuel-cell system.

Hydrogen production: Hydrogen can be produced using several methods. The US Department of Energy lists four general categories: thermochemical, electrolytic, i.e. using electricity for water splitting, photolytic, i.e. direct solar water splitting and biological, i.e. using microorganisms [2]. Steam methane reforming (SMR) is a thermochemical method which uses natural gas to produce 95% of hydrogen used in the USA today [77]. SMR is dominant due to its relative cheapness compared to other methods but is environmentally not sustainable since the hydrogen is still fossil-fuel-based and requires the sequestration of emitted CO_2 gas.

The electrolytic method is potentially a means for producing 'green hydrogen' if the electricity originates from renewable energy sources. 1 kg of water produces approximately 9 kg of hydrogen [204]. Other advantages include the ability for distributed production, reducing the need for gas transportation as opposed to centralised production. The hydrogen produced is also of greater purity compared to that from the SMR process, which is critical when using hydrogen in low-temperature fuel cells with polymer exchange membranes (PEMFC) [7]. Figure 47 shows a schematic configuration of an electrolyser and also the electrochemical reactions that occur at the anode and cathode electrodes. Voltage is imposed between two electrodes that exceed the electrolyte's thermodynamic stability range to enable the splitting of the electrolyte molecules, in the case of water, into hydrogen and oxygen molecules.

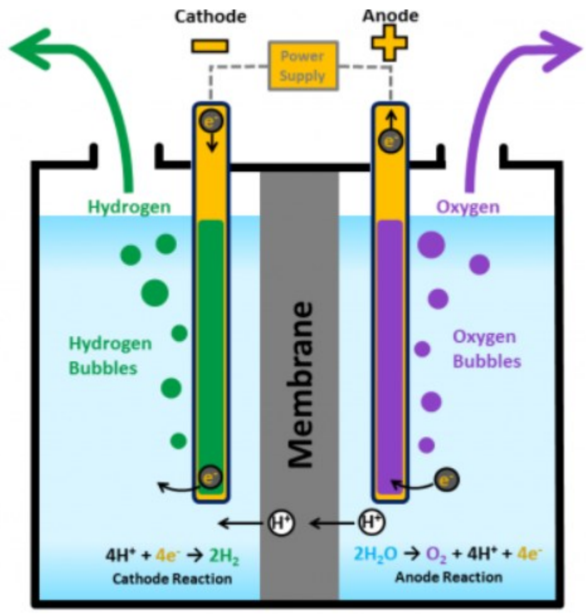


Figure 47 Schematic of water electrolysis in a single cell. From DOE EERE [43].

The types of electrolysers are made distinct by the electrolyte material used and the temperature at which they operate [205]. The notable types are alkaline electrolysis cells (AEC), proton exchange-membrane (PEM), anion exchange membrane (AEM, or also called alkaline PEM) and solid oxide electrolysis (SOE). The first three belong to the low-temperature category, while SOE is a high-temperature type.

AEC is the incumbent technology, is widely used for largescale industrial application, readily available, durable and has a relatively lower cost of capital. Its drawbacks are low current density, low operating pressure and also limited dynamic operation (frequent start-ups and varying power output). PEM is less matured than AEC and is used mostly for small-scale applications. Its advantages are high power density and cell efficiency, provision of highly compressed and pure hydrogen, and flexible operation. Its drawbacks include expensive platinum catalyst and fluorinated membrane materials, high system complexity and shorter lifetime than AEC at present. The PEM electrolysers also need water to be of a certain quality. The incoming water passes through a treatment system, typically consisting of pre-treatment, reverse osmosis and electro deionisation [204]. SOE has been demonstrated at laboratory scale and has the potential advantages of high electrical efficiency, low material cost and the options to operate in reverse mode as a fuel cell. It faces the challenge of severe material degradation due to its high operating temperatures [206].

Current research priorities are to improve the efficiency of the electrolyser system as a whole, along with its operating life, power density and stack size, reducing costs (primarily material costs), and also developing flexible systems adapted to an intermittent and fluctuating power supply. Besides, another objective is to integrate compression process into the electrolyser to avoid the cost of a separate hydrogen compressor needed to increase the hydrogen pressure for storage [205].

Fuel cell: At the heart of the hydrogen system, is the fuel cell. Fuel-cells generate electricity as long as there is fuel supplied. Several hydrogen fuel cells exist. Similar to electrolysers, fuel cells are differentiated based on the electrolyte used, which subsequently determines the catalyst type, operating temperature, dimensions, required purity of hydrogen fuel [2]. Table 64 shows a comparison of some key characteristics of the different type of hydrogen fuel cells.

Of these, PEMFC-type receives the most significant interest in the application of fuel-cell electric vehicles as well as small-scale stationary power generation. Its advantages are that it operates comparatively lower operating temperatures, from 60-80^oC, uses non-corrosive electrolytes and has a high power density, leading to compact and light-weight assemblies. Its drawbacks include the use of expensive platinum materials and it's susceptibility to CO gas poisoning. Thus, use of high-purity hydrogen is required, with a maximum limit of CO of 0.001%, or 10 ppm) [207].

Table 64 Comparisons among fuel cell types. From US DOE's Fuel Cells Technologies Office [49].

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluorosulfonic acid	<120°C	<1 kW - 100 kW	60% direct H_2;[i] 40% reformed fuel[ii]	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60%[iii]	• Military • Space • Backup power • Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40%[iv]	• Distributed generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50%[v]	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60%[vi]	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns

Storage: Three methods are currently used to store hydrogen molecules: applying high pressure, cooling to a very low temperature, or binding it with a solid material. The first method involves compressing hydrogen into a high-pressure vessel, cylinder or a human-made salt cavern. The advantages of this method compared to the other methods are that tank sizes are scalable to required energy content, has high charging and discharging rate and do not suffer from self-discharge, thus suitable for long-term storage [82]. Table 65 shows the four types of vessels currently available commercially, and the fifth type is still being developed. Type IV is the most commonly-used in fuel-cell electric vehicles (FCEV) [200].

The second storage method, cooling hydrogen cryogenically until it liquefies at its boiling point at approximately 253 °C. Figure 48 shows the density of hydrogen plotted against temperature, where it can be seen that cryogenic freezing can achieve even higher density than high-pressure compression at ambient temperatures [2].

Table 65 Hydrogen pressure vessels types. Adapted from Barthélémy [208] and Tretsiakova-McNally [91].

Type	Typical storage pressures	Description	Typical usage	Characteristics
I	150 - 300 barg	Made of metal	Industrial gas storage	Cheapest, most wide-spread use
II	Pressure not limited	Made of a thick metallic liner hoop wrapped with a fiber-resin composite.	Stationary applications such as back-up power supply or power generator for residential.	Compared to Type I, is ligher but more expensive
III	Technology mature for P ≤ 350 bar; 700 bar under development.	Made of a thick metallic liner hoop wrapped with a fiber-resin composite.	Portable applications such as fuel for transportation	More expensive than Type I and II, but is weight-saving. Less affected by hydrogen embrittlement.
IV	Technology mature for P ≤ 350 bar; 700 bar under development.	Made of all-polymeric liner fully-wrapped with a fiber-resin composite. The port is metallic and integrated in the structure (boss)		Similar to type III, but lighter and even more expensive. Has possibility of hydrogen permeating through the liners.
V	information not available	all-composite without liner	First prototype in 2014, but not yet approved for mobility applications	information not available

The process of liquefaction requires 30% - 40% of the final energy content of the hydrogen [7]. The approach is energy-intensive and expensive to cool down and maintain the hydrogen temperature [82]. The disadvantages, namely the high equipment cost to liquefy hydrogen, to keep it cool and also the associated safety hazards, makes it uncommon for fuel-cell vehicle and small-scale residential storage applications.

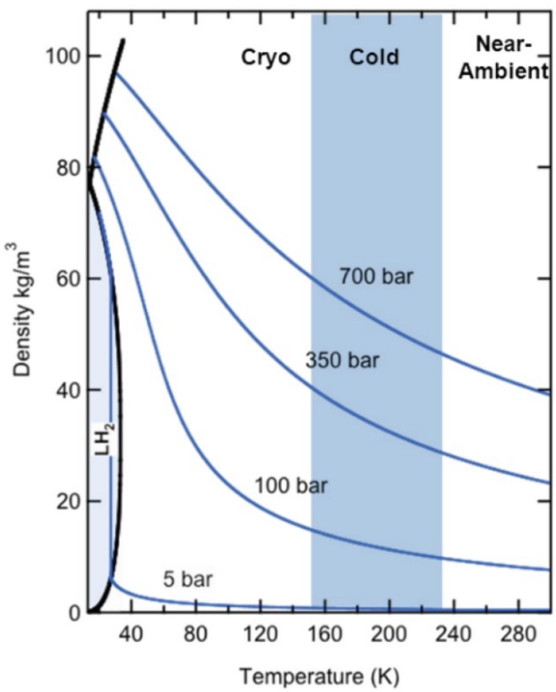


Figure 48 Density vs Temperature curves showing cold or cryogenic-compressed hydrogen enables higher onboard hydrogen storage. From [2].

The third method involves adsorption on the surfaces of solids, absorption within solids, or by chemical reaction. Of these options, absorption into metal hydrides is the most developed [91]. The advantage of this method is that it avoids energy losses incurred in the compression and liquefaction method. High volumetric density can be achieved, and since the reaction with hydrides occurs at atmospheric pressure, there are fewer safety concerns [82]. Disadvantages include long charge time and weight, making it still unsuitable for mobility applications [7].

Lithium-ion (Li-ion) batteries

Li-ion batteries are used in a wide range of applications, from personal homes electrical appliances such as in electric shavers, mobile phones, to electric-vehicles (EV) to electric-powered bikes, cars and buses, and as an energy storage medium in homes and grid-level electricity networks. Li-ion batteries belong to the electrochemical energy storage category and refer to an entire family of battery chemistries [129]. It is a secondary battery, meaning that it can be recharged. Lithium-ion is not to be confused with metal-lithium batteries, which are essentially primary batteries and is not rechargeable. Its main advantages compared to other battery types such as sodium-sulfur (NaS), nickel-cadmium (NiCd) and lead-acid (LA) are its high energy density, high cycle and calendar lifetimes, fast and efficient charging, low self-discharge rate, no need to be held upright, and is relatively maintenance-free [209].

Much research and development work is currently focused on reducing its relatively high price and also to increase its safety and performance [7]. Compared to hydrogen systems as an electrical energy storage system, Li-ion batteries have lower energy density and thus shorter storage duration for an equivalent mass. However, its round-trip efficiency of over 90% and portability makes it more attractive than hydrogen, especially for mobile applications. Self-discharge for hydrogen systems is about 0-4% per day, whereas for Li-ion batteries and flow batteries is only about 0.1-0.3% per day [192]. Li-ion batteries do not suffer from the ‘memory effect’, but deeper (higher) depth-of-discharge during charge/discharge cycles will reduce its cycle lifetime. Li-ion batteries are considered the leading future storage technology due to cost reductions and rapid scale-up of manufacturing capacities [196].

The major components of a lithium-ion battery are the electrodes, the electrolyte, the cell enclosure, and the separator [210]. The two **electrodes**, namely the anode and cathode, contain lithium which alternatingly releases and collects lithium ions during charging and discharging. The current collectors at both electrodes transfer current evenly throughout the cell to the active material, provides mechanical support and provides a point of mechanical connection to the leads that transfer current into the cell [129].

The negative electrode, or anode, is usually made of some form of carbon that allows the intercalation of lithium ions. This differs from metal-lithium batteries, where the anode is made of lithium metal or compounds [181]. Intercalation is the reversible process of inclusion or insertion of a molecule (or ion) into compounds with layered structures, a type of insertion reaction [7]. Non-graphite anodes such as titanate, used in lithium titanate oxide (LTO), have also been developed. The positive electrode, or cathode, is made from lithium metal oxide [129]. During charging, lithium ions flow from the oxide cathode and intercalate into the anode, while the reverse happens during discharging. Figure 49 explains this graphically [211].

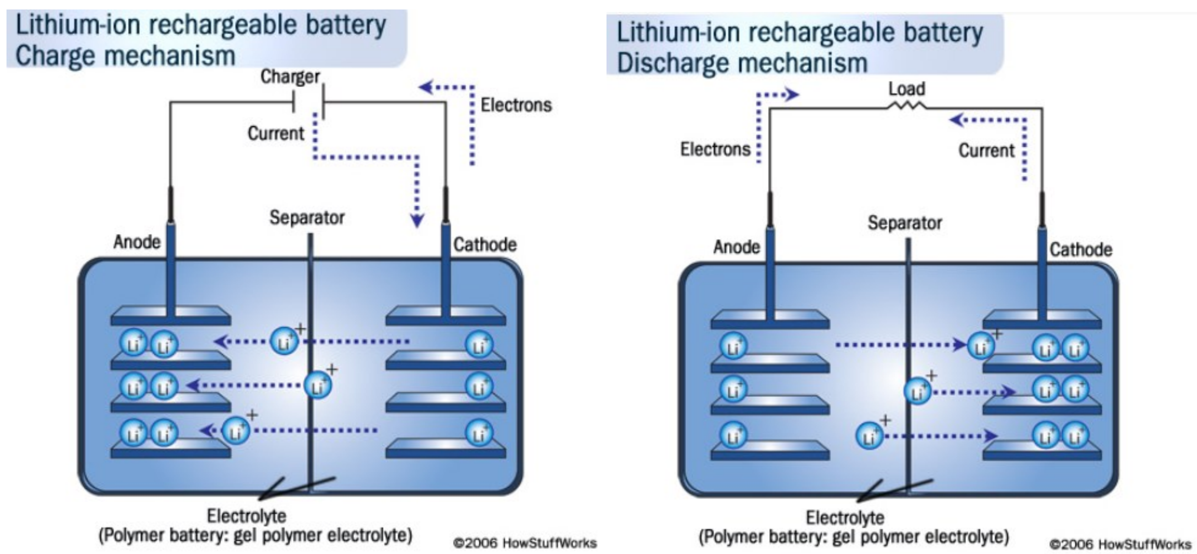


Figure 49 Charging and discharging operation in a Li-ion cell. Image from [211]

The behaviour of the different electrode materials affects the chemistry of each lithium-ion battery type, resulting in different properties such as the charge and discharge rate, it’s nominal cell voltage, stored energy density, the lifecycle and thermal stability. Table 66 compares some of the properties of the various types of Li-ion batteries, with data compiled from [120, 209, 212, 213]. The quoted figures do not take into consideration the exact specifications that can affect the values.

The **electrolyte** allows the transportation of lithium ions between the electrodes [210], and is typically a mixture of organic carbonates and solvents containing lithium salts [129]. According to Mikolajczak et al., the mixture ratio determines the desired cell properties. The chemistry of the electrolyte components determines, among other things, the thermal stability and also the flammability of the electrolyte. The **separator** is a thin film whose function is to prevent direct contact between the anode and cathode. It is porous, allowing the movement of lithium ions through diffusion during charge and discharge. The **enclosure** provides mechanical protection, and to contain the electrodes and electrolyte.

Li-ion batteries can come in various shapes, the major ones being cylindrical cells (looks like the AAA-sized batteries), hard-case prismatic pouches (looks like the mobile phone battery) and pouch polymer cells [129].

Vanadium redox flow batteries (VRB)

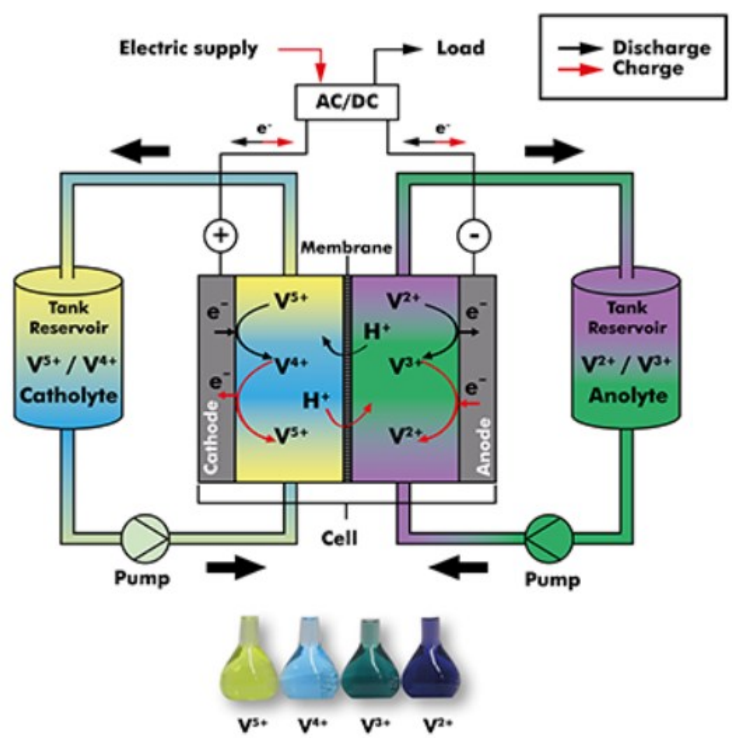


Figure 50 Schematic of VRB. Image from [1].

VRB belong to the group of flow batteries. The chemical composition of the electrolyte defines the sub-categories of this group of batteries, the other common type being Zinc-Bromine (Zn/Br). These type of batteries has the advantage of having independence between the power rating and the storage capacity [192, 214]. The power rating depends on the active area of the cell stack, which can be added to increase the output. Meanwhile, the storage capacity depends on the volume of electrolyte solutions stored in external tanks, which can be scaled to meet the requirements.

The round-trip efficiency is 65-80% and has a lifespan of 10 000 – 20 000 cycles [192], usually lasting 10-15 years [214]. VRB is also tolerant of overcharging and can undergo deep discharge without affecting the cycle life, unlike Li-ion batteries. On the downside, the need for pumps, sensors, power management, and secondary containment makes them unsuitable for small scale energy storage application [8]. Flow batteries typically have low energy densities (10-70 kWh/m^3). The self-discharge rate is quite similar to Li-ion, in the 0.1 – 0.4% range of losses per day.

Figure 50 shows a schematic diagramme of a VRB [1]. Two types of electrolytes are kept in separate loops, with V^{5+}/V^{4+} and V^{2+}/V^{3+}. When the battery is turned on, the pumps will move the respective electrolytes through a cell stack. Ionic exchange happens in the cell stack via a selective membrane, without the electrolytes cross-contaminating each other; thus, the electrolyte does not undergo degradation. During the charge cycle, V^{4+} becomes V^{5+} while releasing an electron at the cathode; at the anode, the V^{3+} gains an electron and is reduced to V^{2+}. These reactions absorb the electrical energy and convert it into chemical energy. During the discharge cycle, the reverse happens.

Table 66 Comparison of the different Li-ion battery types. Compiled from Battery University [212], Fire and Emergency New Zealand [120], [209, 213]

	LCO	LMO	LFP	NCA	NMC	LTO
Commercialised since	1991	1996	1996	1999	2008	2008
Current typical applications	Mobile phones, tablets, laptops, cameras	Power tools, medical devices, electric powertrains	Portable and stationary power supply needing high load currents and endurance	Medical devices, industrial, electric powertrain (Tesla)	E-bikes, medical devices, electric vehicles, industrial	UPS, electric powertrain (Mitsubishi i-MiEV, Honda Fit)
Charge	0.7 - 1C	0.7 - 1C	1C	0.7C	0.7 - 1C	1 - 5C
Discharge	1C	1C	1C	1C	1C	10C
Nominal voltage, V per cell	3.6 - 3.7	3.7	3.2 - 3.3	3.6	3.6 - 3.7	2.4
Specific energy, Wh/kg	150 - 200	100 - 150	90 - 120	200 - 260	150 - 220	50 - 80
Cost, $/kWh	Very expensive due to cobalt	Low	~ 580	~350	~ 420	~1005
Onset of thermal runaway, ^oC	150	250	400	150	210	inherently safe
Cycle lifetime	500 - 1000	300 - 700	> 2000	500	1000 - 2000	3000 - 7000
Remarks	Not relevant nowadays	Low life, less relevant today; mixed with NMC for better performance	One of the safest Li-ion battery	Shares many similarities with NMC	Leading system. Market share is increasing	Safe, long life, can ultra-fast charge, good low-temperature discharge. Low specific energy and expensive

Battery types: refers to the cathode material, except for LTO, which refers to the anode material. LCO - Lithium Cobalt Oxide, $LiCoO_2$; LMO - Lithium Manganese Oxide, $LiMn_2O_4$; LFP - Lithium iron phosphate, $LiFePO_4$; NCA - Lithium Nickel Cobalt Aluminum Oxide, $LiNiCoAlO_2$; NMC - Lithium Nickel Manganese Cobalt Oxide, $LiNiMnCoO_2$; LTO - Lithium Titanate Oxide, Li_2TiO