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Abstract

During the energy evolution currently undertaken, hydrogen has emerged as a potential energy carrier among others in transportation sector. However, assuring safety of the relevant infrastructure is a prerequisite to the adoption of hydrogen as a day-to-day road fuel. This thesis reviews risk assessments in hydrogen storage and distribution infrastructure, focusing in specific in hydrogen refueling stations, and sets as ulterior goal to suggest a risk assessment framework for the design and operation of the latter. Traditional risk assessments with their limitations are reviewed. Focus is placed on recent perspectives in risk, combining the probability based thinking anticipated in traditional risk assessments with qualitative approaches.

One such framework is introduced and its practical features summarized in strength of knowledge characterizations and consideration of surprises, are presented and further analyzed. Using a case study stressing the limitations of existent methodologies, reflected in ISO/TS 19880-1: 2016, a new approach while assessing risks in hydrogen refueling stations is suggested. That is the implementation of the new integrative framework. In the rationale of cautious thinking, it is suggested that risk evaluation and treatment, currently based in probabilistic RAC alone, is changed such that it also reflects on the strength of knowledge upon which those criteria are based. The operation of an exclusive hydrogen database is awaited to contribute to the characterization of the knowledge the overall analysis is based on, and therefore the knowledge supporting risk acceptance as well. The contribution of this type of database in hydrogen refueling station risk assessments can be summarized in two broad dimensions; enabling statistical calculations on one hand, and providing the risk analysts with valuable input for the strength of knowledge characterization and the surprise assessment on the other.

Key words: Quantitative risk assessment, Hydrogen refueling stations, Knowledge dimensions, Surprises, Risk management, Risk perspectives, Risk acceptance criteria

Preface and acknowledgements

This master thesis has been written to fulfill the graduation requirements to the Offshore Technology master's program at the university of Stavanger, in the Risk Management specialization. The work was carried out throughout the spring semester of 2017 under the expert guidance of Roger Flage as the faculty's supervisor.

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Furthermore, I need to express my gratitude to friends and colleagues, supporting each other throughout our studies, and my family for providing me the opportunity to study abroad. This thesis is dedicated to Michalis, Agni and especially my father Athanasios who has always been supportive by my side.

Efthymia Derempouka

June 2017, Stavanger

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List of abbreviations

CGH2   Compressed gaseous hydrogen

CHIC   Clean Hydrogen in European Cities

EIGA   European Industrial Gases Association

ETA   Event Tree Analysis

FRAM   Functional Resonance Analysis Method

FTA   Fault Tree Analysis

FCEV   Fuel Cell Electric Vehicles

H2   Hydrogen

HRS   Hydrogen Refueling Station

LPG   Liquid Petroleum Gas

NUSAP   Numerical Unit Spread Assessment Pedigree

PRA   Probabilistic Risk Assessment

QRA   Quantitative Risk Assessment

R&D   Research and Development

RAC   Risk Acceptance Criteria

SAA   Systemic Accident Analysis

SMR   Steam Methane Reforming

SoK   Strength of Knowledge

1. Introduction

1.1. Motivation

A worldwide shift towards news forms of energy, with renewable ones prevailing, is recently evolving. Environmental incentives, such as Global warming but also aspects related to the energy crisis of traditional fuels including petroleum and coal are just few of the reasons triggering this shift (Dunn, 2002). Hydrogen on the other side can be produced based on a variety of feedstock, under different production streams, some of which producing totally 'green' energy, and at the same time it can be widely cost efficient (Dunn, 2002, Godula-Jopek et al., 2012).

A broad network of countries is already embracing the new energy carrier. In Germany, a hydrogen motorway is already in use and the launch of Hydrail, i.e. a hydrogen powered train, officially released as 'Coradia iLint' is expected to realize towards the end of 2017 (Telegraph, 2016). Another example derives from South Korea this time, where Hyundai Motor Co., the largest company in automobile sector in the country is the leading company in hydrogen driven cars worldwide. A cooperation between South Korea and Norway, combining the engine technology of the former with hydrogen production 'know how' and relevant infrastructure from the latter could potentially open the road for a massive introduction of hydrogen powered cars and the adoption of hydrogen as a wide transport energy carrier (Yohap News Agency, 2016). Yet, in order to allow for such an evolution, assuring the safety of the relevant infrastructures remains critical requirement and a challenge to achieve this is reducing the uncertainties within the risk assessment methodology (Moonis et al., 2010).

According to Hafver et al. (2016) though, in contexts where weak phenomenological knowledge or restricted experience applies, methodologies traditionally adopted in the engineering field, viewing risk primarily as the combination of probabilities and consequences, may fail in exposing all hidden risks. New technologies and applications areas given the restricted experience arguably fall within this category. Therefore, raises the question whether this traditional risk assessment framework is considered adequate for managing uncertainties when it comes to hydrogen related applications where new or modified technologies, to produce, store and distribute hydrogen are utilized.

In the following we aim to shed some light on this behalf such that this study contributes to the development of a robust risk assessment framework on the relevant applications, and the introduction of the new energy carrier is facilitated.

1.2. Objectives

The present study aims to recommend a framework for the risk assessment in hydrogen refueling stations enabling confidence in the produced risk picture. During the analysis, we set the following objectives, expecting that by meeting these the main goal will be achieved.

The objectives are:

- To establish the setting of hydrogen refueling stations, and identify how risk assessment is currently conducted in the specific applications.
- To identify weaknesses linked to the current methodology.
- To review recent advances in the risk field such that the latter provide us with critical input for our recommendations, and reflect on practical aspects of the new perspectives.

1.3. Limitations

The produced recommendations derive from a combined review of relevant literature and a case study introduced. The latter does not project to an existing hydrogen refueling station, instead it comprises a model one bearing typical representative units.

The source of this case has been a QRA under confidential status, and therefore, our access to data has been restricted to a certain degree. A hydrogen refueling station is realized as a system of interacting processes, yet given the limited access to information, we chose to focus only in a part of this system, that is the dispenser unit. The objective has been to evaluate safety distances with respect to the operation of the dispenser and therefore, our direct recommendations with respect to RAC are tailor made to safety distances determination. Yet, they can be stretched to encompass the overall rationale governing risk acceptance in HRS.

With respect to risk acceptance we acknowledge that care should be placed when using predefined RAC while aiming to ensure good arrangements, as argued in Aven and Vinnem (2005). This concern is partly reflected in the discussion of the limitations in the case study introduced. Yet given that the ISO standard allows that practice, and the certain extent of the analysis we are allowed in a master thesis, we accept this practice of predefined criteria and during our recommendations we focus on ways to assure that decisions on acceptable risk extend mere probabilistic risk considerations.

Finally, we wish to clarify that the new framework combining probability based thinking with qualitative approaches, is not to be confused with the semi-quantitative risk assessment as per ISO/TS 19880-1:2016, and therefore, to avoid this type of confusion throughout this thesis we refer to the new framework, as an integrative risk assessment framework or the new integrative framework.

1.4. Structure

Chapter 2 is a literature based chapter, identifying weaknesses linked to the traditional probability based approach in risk assessments, adopted as per se in well-established industries, illustrating thus the reasons that gradually led to a currently undertaken shift in the risk field.

Chapter 3 introduces the reader to traditional and recent perspectives in risk as per literature, and taking its point of departure from the weaknesses linked to the first, introduces a new integrative perspective combining traditional probability based thinking with more qualitative approaches. The knowledge dimension and the consideration of surprises, as the main features of this new perspective are defined and the context of emerging risk being relevant to new application areas is illustrated.

Chapter4 narrows down and focuses on hydrogen refueling stations. This chapter is built in two conceptual unities. First, the current level of development of the hydrogen refueling stations' network in Norway is presented and in a second level, the planning and permitting procedures for the operation of hydrogen refueling stations are placed on focus. As such the current Technical Specification ISO-standard is being reviewed, and the limitations stemming primarily from its probabilistic orientation when assessing risks are discussed.

Chapter 5 presents a case study. In specific a QRA of a representative gaseous hydrogen refueling station is conducted following the methodology as per ISO/TS 19880-1:2016 and the challenges faced and attributed to the young development level of such applications together with probability based orientation of the ISO/TS 19880-1 standard are discussed.

In chapter 6 we proceed to a set of recommendations with respect to hydrogen risk assessment. In specific the chapter reflects on how the integrative framework introduced in chapter 3 can practically be adopted in hydrogen refueling stations, extending thus the probabilistic risk assessment in the emergent application.

Chapter 7 reviews the basic points made in this thesis and summarizes the conclusions.

2. Risk assessment shifts towards a new perspective on risk

2.1. Weaknesses of traditional QRA frameworks

As risk assessment, we define the overall process of identifying and analyzing risks to humans, assets and/or the environment associated with specific activities, and assess as per cases how certain modifications can contribute to attaining and maintaining a predefined safety level meeting regulatory requirements and codes (DNVGL, 2017).

A risk assessment's main objective is to provide decision support. This latter means to provide decision makers and involved stakeholders awareness of the inherent risks and hazards related to the activities on focus, and therefore the basis to plan and prioritize over risk reducing measures (Funnemark and Engebø, 2005).

Depending both on the context of the risk management process and the methods being utilized; qualitative, semi-quantitative or quantitative, the form of the assessment varies as well (IEC, 2009). The availability of relevant and reliable data as well as legislation in specific applications are factors that may also prescribe the type of risk assessment to be conducted. Even in cases though where a full quantification of risk is considered fortunate, still caution should be placed not to attribute a level of accuracy and precision higher than it derives from the analysis, i.e. the accuracy of data and methods applied supports (IEC, 2009).

Quantitative risk assessments, called for short hereinafter QRAs, as have been conducted for the last 3-4 decades, in several industries, provide a systematic approach to estimate the likelihood of hazardous events and their consequences, and express those results quantitatively as risk to human, assets and/or environment (DNVGL, 2017). However, several critical assumptions may be incorporated in the analysis. The latter assumptions together with additional risk contributors is important to be identified and pointed out during the analysis, and their robustness to be assessed (DNVGL, 2017, Hafver et al., 2016).

Following a forward analysis approach, see Aven (2015b), Quantitative risk assessment identifies risk sources, defines relevant exposure scenarios and their associated consequences and expressing the uncertainty about, establishes the overall risk picture. Following therefore this timeline approach, from the identification of initiating events to the establishment of the risk picture, in the rest of this chapter we will try to identify those sources introducing a form of analysis incompleteness in a QRA. An important aspect to keep in mind while doing this, is the probabilistic approach in traditional QRAs according to which risk is defined as a combination of probabilities and consequences or more narrowly as the product of those probabilities times the consequences.

2.1.1. Ignoring scenarios

A central task when performing a QRA is to identify exposure scenarios with respect to the activities of interest and asses their likelihood to occur (Aven, 2016a).

However not all identified scenarios can be addressed when performing a QRA. It is typical as per IEC (2009) that in QRAs, depending on the scope which is defined initially in the analysis, and the management concerns, to focus either in scenarios associated with risks with potentially large outcomes, since the latter are of the greatest concern to the managers, or in other cases it may be important to analyze both high and low consequences risks (IEC, 2009). However, as per Aven (2016a), we need to be cautious when removing scenarios from the analysis since even erroneous assessments are likely to realize.

Before proceeding to the shortcomings of this practice; excluding scenarios from the analysis, let us first define the type of relevant scenarios, i.e. event chain scenarios, when conducting a risk assessment. We distinguish between scenarios (Aven, 2016a):

i.   identified and further assessed, meaning that they are identified and followed up in the risk assessment and risk reducing measures may be generated
ii.   identified in the risk assessment as a part of the hazard identification step but their probability of occurrence judged negligible, thus they are excluded from further analysis.
iii. Last there are those scenarios that are not identified at all.

 The last two categories are linked to black swan type events and will be defined in more detail in the following chapter.

With respect to the second category, we should be careful when conditional on probability judgements we exclude scenarios from further assessment. Sometimes this type of events can bring about surprising results. To elaborate further on this let us invoke the concepts of common-cause and special-cause variation accessed in the quality management literature. Combining some of the prevailing definitions accessed in literature, common-cause variation reflects a historical experience base and can be predictable under a probabilistic treatment, whereas variation outside the historical experience base or variation arising from phenomena which are either new or emergent within a system, is known as special-cause variation (Wikipedia, 2017b, Aven, 2014). The latter type of variation comes as a surprise to the expected system performance. Linking this to those scenarios removed from the analysis due to low judged probability, this practice entails the risk of excluding processes characterized by this type of variation, and thus we may be faced with surprises. Therefore, we recognize that the list of scenarios included in the analysis can be more or less complete (Aven, 2016a). As accessed in Aven (2016a) and discussed in the probabilistic risk assessment (PRA) community, 'completeness uncertainty' may arise when risk sources are not captured or not followed up in the probabilistic risk assessment model. This may be result of either:

i. events judged of a low probability of occurrence and therefore excluded from further assessment, or

ii. events not identified at all.

The latter include either 'unknown unknowns' i.e. totally unknown events to the scientific society, or 'unknown knowns' meaning that these events do not constitute new or previously unanticipated phenomena, however, the risk analysis team is not aware of them (Aven, 2015a). Paying some more attention to the latter, we recognize that in a well-established industry, take for instance the oil industry, it is hard to think of ways that accidents leading to fatalities and extreme impacts not covered by historical data, may occur. (Aven, 2016a). However, this raises the question whether this practice is also justified in an emerging industry, or in contexts where pioneer technology is applied, or when phenomena emergent in a system are under analysis.

Referring to (i) a counterargument against the exception of scenarios driven by probability justifications is the reliability of those probability numbers. Is this considered adequate for such a decision? How much confidence can we put in the statistical data reported or the probability assignments supporting the exclusion or inclusion of a specific scenario?

Extending now the analysis besides probability considerations, an additional factor potentially introducing some form of incompleteness is the level of the analysis per se (Aven, 2016a). The more detailed a scenario is the less potential to occur. Therefore, we may wonder what is the point of defining extremely detailed scenarios, resource demanding if they don't capture the risk elements of importance. Especially in complex systems, which in engineering world, take for instance a civil engineering context, is quite often the case (Rodriguez-Nikl, 2011), it is of high difficulty to capture the complete set of potential event sequences. The concept of well understood for such systems can be problematic (Aven, 2016a). As per Rodriguez-Nikl (2011), complex systems will inevitably contain surprises and engineers should be concerned and ready to cope with the former.

Common denominator in both two cases; (i) and (ii), is the knowledge supporting the probability numbers and allowing for a specific level of detail in the analysis. This knowledge includes, statistical data, experts' opinions, models and more. It also embodies assumptions. Relative to a QRA performed in offshore installations for instance assumptions may relate to: detection time of abnormal conditions, number of exposed persons per area, impact of energy the structural integrity of a module will withstand (Flage and Aven, 2009) and so on.

 Reflecting on the latter let us refer to the case of the leak occurred at Hammerfest LNG in Norway which summarizes that risk assessments rely on assumptions but deviations are possible in real life. In design basis and therefore in the causal chain approach it was assumed for the leak detection time, that it would approximately take 5minutes, however as the investigation report pointed out it took about 25 minutes for the depressurization to get started. This time was far longer than had been projected in the scenarios, and reminds us that in real life deviations are possible, and

inclusion of exclusion of such scenarios; based on specific assumptions could be more or less valid (Hafver et al., 2016).

Moreover, an additional cause of ignoring scenarios of importance and therefore introducing some level of 'completeness uncertainty' in the analysis may be the scope of the QRA itself (Aven, 2016a), restricting the initiating events considered in a pre-defined set of hazardous situations, typically faced in QRAs' framework as per regulations, see for instance the informative annex C as per NORSOK Z-013 (PSA, 2001) and section 4.3.1. hydrogen safety recommendations as per ISO (2016) where an informative but followed list of the hazards to be included in the probabilistic assessment is defined.

2.1.2. Causal chain approach

Traditional risk assessments as per Haimes (2004) can be seen as a special case of system engineering. The latter provides a structured methodology for studying a system and analyzing this and its interactions to the environment with the use of models; conceptual, mathematical and physical. This methodology is applicable to either structural or non-structural systems, but can also find application in decision making under constraints applying simulation and optimization techniques. Several types of models are facilitated in a system engineering approach; linear, non-linear, deterministic, probabilistic and more (Haimes, 2004). Risk assessments adopt mainly a causal chain approach combined with simulations and events modelling.

- Limitations of cause effects analysis

Cause-effects analysis, an additional term used for causal chain analysis, expresses an ordered sequence of events (Wikipedia, 2017a) and therefore traces pathways from the impact; socioeconomic, environmental or technical one back to its root causes (Belausteguigoitia, 2004).

However causal chain analysis fails in regards of capturing:

   i.   Non-linear dynamic interactions, as well as
  ii.   System's complexity

Thus, it may not be adequate to capture the level of complexity met in today's systems and recent technological innovations (Aven, 2015b, Hollnagel, 2004). Examples of such complex systems, are communication networks, information systems, production and distribution systems as well as pioneer technologies applied in the production of new products and in process development systems (Aven, 2015b)

As stated in Underwood and Waterson (2013) many complex systems accidents, see for instance the space shuttle Columbia accident, were not solely the outcome of a critical equipment failure,

or an unsafe human action, as the main approach adopted in traditional causal chain analyses may point out. De Carvalho (2011) states that accidents take place as complex phenomena within the normal operational variability of a system, and utilizing event tree analysis, or Fault Tree Analysis, typical in a causal chain approach, we fail in capturing the nonlinear complexity of such socio-technical systems on one hand and their dynamic behavior on the other. The latter term according to Underwood and Waterson (2012) means that a goal can be achieved through a variety of initial conditions and under several combinations. Analogously a system can produce a set of different outputs from the same starting point. When an open system, such a sociotechnical one is on focus, then environment can also have an impact in the process (Underwood and Waterson, 2012). Here we see, that from a starting point: a considered root cause many combinations of outputs can be perceived.

Previously a failure of the traditional causal chain approach to capture the dynamic behavior of systems was mentioned. Unlikely to the former, an alternative approach in accident analysis research, accessed as SAA i.e. system accident analysis method, studies the system as a whole entity rather than breaking it into parts and considering them in isolation. As per Hollnagel (2004), it is necessary that we describe the total performance of the system, and this is achieved going beyond causal chains. We should identify steps and stages as part of the total performance rather than events in isolation

Let us not forget that a system as expressed in Agarwal et al, (2011) is a set of interacting process objects arranged in an appropriate way and interacting with each other so that they deliver a process or they fulfil a lower role in a higher-level process, and this makes our point; those system's parts cannot be seen in isolation, as the traditional causal approach implies.

Therefore, SAA provides a better reflection of the system, the interaction between its elements, and basically provides an understanding of how this dynamic behavior contributed to the accident's development. However, this approach is currently applied in a research level rather than in industrial applications (Underwood and Waterson, 2012). For informative reasons, we refer to the systemic accident analysis (SAA) models that are currently in use. These are STAMP, FRAM as well as ACCIMAP but their analysis is outside the scope of this thesis.

ETA or FTA seems to fail in capturing dynamic system's behavior. In specific causal chain approach seems to fail in respect of capturing the total of risk contributors, or in some cases can incorrectly lead to equipment or human being blamed for an accident (Underwood and Waterson, 2013). Moreover, as stated by Leveson and cited in Underwood and Waterson (2013), in most accident reports where a cause effect approach is being adopted, the analysis frequently stops pre-maturely. Therefore, we miss the opportunity of gaining a proper insight of the system on one hand and getting lessons learned such that we further develop efficient safety recommendations (Underwood and Waterson, 2013) on the other.

- Events modelling

Another issue here is the models applied according to this system engineering approach. The real system is represented by a mathematical or a simulation model. Then, the ability of the model to capture the outcome of the real system, given the same input, or according to Haimes (2004); the element capturing the value of the simulation model, is the closeness of the two results. If these are close enough, we consider the model a good representation of the real system (Haimes, 2004). We will return to this factor later in the analysis, while assessing the strength of knowledge facilitated in the quantitative risk assessment.

2.1.3. Expected values

So far, we have presented a set of event chains i.e. a set of exposure scenarios identified while conducting a quantitative risk assessment. However, when it comes to the uncertainty associated with those scenarios, how is this expressed as per the current approach? What is the measure utilized to represent uncertainties?

As Flage and Aven (2009) state, most of the approaches followed in QRAs for treating uncertainty and quantifying risk seem to be based on the use of calculated probabilities and expected values. See for instance; the triplet (s_i, p_i, c_i) suggested by Kaplan and Garrick (1981) applied in nuclear applications. In this notation, s_i represents the i_{th} scenario identified in the analysis, p_i the probability of this scenario occurring and c_i the associated consequences.

Another example derived from a recently developed industry, expresses risk as expected values. In specific, the framework applied in Hydrogen Refueling Stations according to the International Standard Organization (ISO, 2016), describes risk as the product of each scenario's probability and the associated consequences and the total risk is summed over all individual risks. The interpretation adopted for the probabilities is this of frequencies. Therefore, as per ISO total risk is calculated as follows:

$$Risk = \sum_{i=1}^{n}(f_i * C_i),$$

where f_i is the frequency of the i_{th} scenario and C_i the associated consequences.

A similar approach, under which probabilities are interpreted as frequencies and expected values are used to express risk, is adopted by the offshore oil industry. Top events frequencies are used to calculate branch probabilities and expected losses in the consequence analysis (Flage and Aven, 2009). As seen in Vinnem (2007), typical risk metrics and indices applied in offshore QRAs are potential loss of life, abbreviated as PLL; defining the potential loss of life of a randomly selected

person, and fatal accident rate (FAR value) expressing the expected number of fatalities per 100 million hours of exposure.

- Shortcomings of the current approach; probabilities and expected values interpreted as limiting frequencies

Under the current approach prevailing in most QRAs risk is equal to (A, C, P_f) where by A we denote the initiating event, C the associated consequences and P_f is the frequentist probability. Therefore, the uncertainty representation utilized under this approach is probability translated as a relative frequency. This means that the latter probability derives as the fraction of times the considered initiating event, or failure of a protective mechanism, would take place, should the considered situation were repeated infinitively i.e. large number of times under similar conditions. The same rationale holds for the expected number of fatalities, or expected number of occurrences of any event A per unit of time (Aven, 2011).

The frequentist probability is a mind constructed concept though, meaning that we assume we can establish a big population of similar activities, and then the estimation arrives as the fraction of times the event under consideration takes place (Aven and Hiriart, 2011). Here two issues unfold: Firstly, the repetition of the context in the sense of an experiment taking place under similar conditions is problematic, and secondly, this framework implies a correct value for the probability number. However, what is perceived is an estimation of this value and this estimation could be more or less close to the true/underlying value. Therefore, estimation uncertainty arises. This type of uncertainty; representing variation/randomness in the population quantified by measurements and statistical estimations is called stochastic/aleatory uncertainty (Aven and Hiriart, 2011, Bedford and Cooke, 2001). The latter though has to be distinguished by the uncertainty that comes as lack of knowledge, called epistemic uncertainty. How the latter is represented is going to be presented in Chapter 3.

The point where the two challenges meet is the term similar conditions in the definition of the frequentist type of probability (see Aven and Reniers, 2013). Reflecting further on the latter type of probability, we consider the case of a plant, for instance a hydrogen production plant. Estimating a frequentist probability for a fire scenario, means that we can establish a population of similar activities. However, the context of repetition in the sense of an experiment, when leaving the world of gambling or the lab is problematic. Establishing a population of similar activities in the case of the hydrogen plant, means that we consider a (wide) set of identical plants, and we take the probability of a fire as the fraction of times the latter occurs. However, we should acknowledge that every installation/plant is unique with unique characteristics. Moreover, even if our set of data is considered relevant for the estimation of this probability, i.e. the installations are truly similar enough, which is relative and under discussion, then an additional factor is the amount of data

available. In order the estimation uncertainty to become negligible, we need as per Aven (2011) a substantial amount of data.

Last, but quite important issue when adopting this framework and assuming similar conditions is that we specify for instance fixed contribution of the human factor. This is the equivalent to assuming a specific safety culture. Our point here is that under the assumption of similar conditions, important factors in the analysis may be overlooked.

However, in QRAs expected losses are not expressed exclusively with respect to frequentist probabilities. Another probability framework utilized is the knowledge based probabilities, representing the assessor's uncertainty/ degree of belief.

- Expected values based on subjective probability distributions.

This framework may seem intuitively appealing since subjective probability does not imply a frame of repetitions which according to the former analysis is problematic, and at the same time this probability can always be assigned (Aven, 2010a). No true/ underlying value there exists, since this probability does not derive as an estimate aiming to capture the actual value of a quantity, but instead it represents the assessor's uncertainty with respect to the former unknown quantity at the current time he assigns it (Aven and Reniers, 2013). As a result, this number cannot be questioned. What can be questioned though is the knowledge this probability assignment is conditioned on. This background knowledge consists of all the available sources of information, i.e historical system performance data, expert opinions, prior distributions for the estimation of parameters, knowledge about the phenomena involved, models, assumptions, presuppositions and more.

On the light of this thinking we can always challenge the extent to which the assigned probabilities adequately represent the assessor's uncertainty with respect to the unknown quantities and in a subsequent level the degree to which risk assessment describes the quantities is attempting to describe (Aven, 2011). This, according to the same author, is defined as the validity criterion applying in QRAs. Elaborating a little further on this, when such a type of probability is utilized, the probability assignment cannot be seen in isolation to the knowledge it is based on. Additionally to this, the goodness of such a number is a matter of who expresses the former, and thus it is a function of his/her competence, the models and methods he/she calls in in the analysis, all information available together with the quality assurance procedures followed when planning and executing this assessment (Aven, 2003).

▪ Risk is more than expected values.

However, extending beyond the type of probability utilized, let us focus solely on the use of expected values and the implication of the latter in decision making. In safety management and decision making under constraints, expected values can have a misleading effect; the actual outcomes can strongly deviate from those predicted. The expected values fail in respect of capturing events with low probabilities but extreme outcomes (Aven and Hiriart, 2011, Aven, 2010a).

For the illustration of the latter, let us introduce two probability distributions having the same expected values. We denote those by $E\lceil C_1\rceil$ and $E\lceil C_2\rceil$ and then it holds: $E\lceil C_1\rceil= E\lceil C_2\rceil$. See figure 2.1. The first distribution (in blue) may be centered around its expected value, whereas the second (in red) can present high probabilities for extreme outcomes. It is unfortunate if the risk management response is the same in the two cases.
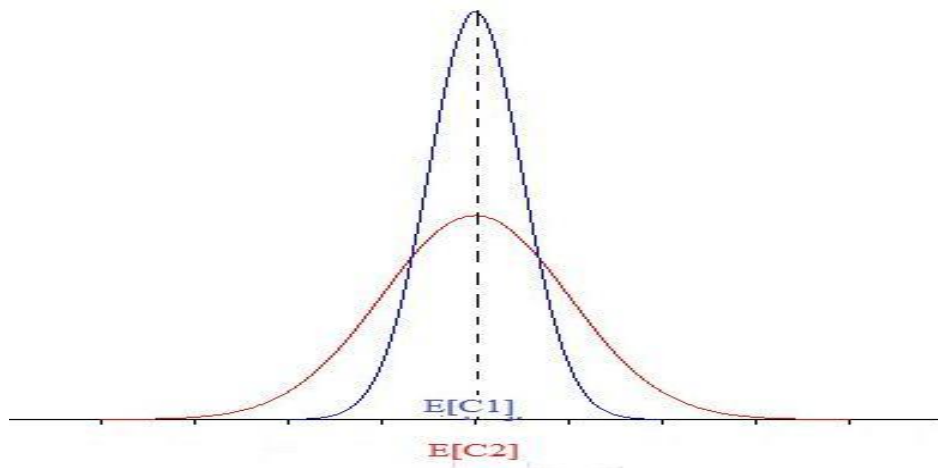
Figure 2.1. Two distributions with same expected values and different probabilities for severe outcomes

This type of considerations summarized as the need to extend beyond expected values, can be seen in an applied-practical level, in the use of the ALARP under the layered approach as suggested by Aven (2011). In this approach if the contribution of factors introducing uncertainties is considered high, then the expected values' suggestions are just informative, and the generated measures are implemented regardless from the expected values recommendations. For further details including also a graphical representation of the 3-layered approach see Abrahamsen and Abrahamsen (2015).

2.2. Codes and regulations limitations

In order to manage risk and safety among others, risk acceptance criteria (RAC) defined as upper limits of acceptable (tolerable) risk have been developed (Aven, 2015b). In specific the risk management process enables that a risk assessment followed up by the risk treatment; usually in

an iterative manner, is contacted. During the risk analysis, the risk picture is established, and subsequently the risk is evaluated, i.e. the calculated risk levels are compared with a set of criteria defined at the initial stages of the analysis. The risk either is found to be within the acceptable limits or measures need to be taken, as well as a decision over the prioritization of the latter (Purdy, 2010). However as per cases these criteria may be predefined and independent to the analysis. The Norwegian offshore petroleum regulations for instance, declares that RAC should be developed before any risk analyses are carried out and any design alternative configurations generated (Aven and Vinnem, 2007).

Moreover, under the concern of enabling flexibility in design on one hand and avoiding conservatism on the other, RAC as per majority have developed to be weak limits. However this implies that risk management's role is restricted to a verification character, and thus no drive for improvement and risk reduction is enabled in the process (Aven, 2015b).

Of course, we cannot overlook at the significance of codes and regulations. As per Rodriguez-Nikl and Brown (2011) regulations have significantly contributed to limiting the complexity of engineering world to a manageable level and it is not surprising the belief that their enforcement will ensure reliable results from a technical perspective. At the same time though, over the last 50 years much confidence has been given to the several codes and regulations prescribing thus the engineers and scientists to be focused mostly on meeting the code, than be concerned with the actual outcomes as per case, and let us not forget that in codes the focus is on statistical uncertainty; stochastic /aleatory, rather than those uncertainties inserted due to imperfect knowledge regarding the relevant phenomena (Rodriguez-Nikl and Brown, 2011) or assumptions that may be more or less valid. In reality, failures occur much more often than described by codes. For instance, in a civil engineering context the failure frequency is two to three orders higher than the levels anticipated by codes (Rodriguez-Nikl and Brown, 2011), justifying therefore our concern whether all type of uncertainties are represented in the analysis. One step further, this should alarm us with respect to the reliability of models and simulations described and prescribed by the codes, and their ability to represent the real world; therefore, the introduced epistemic uncertainties. Our concern should be for those uncertainties not being plumbed in by codes and regulations together with, the uncertainty representations when decisions are to be made. Concluding, what is defined as acceptable risk cannot be the result of a strict numerical conformation to some predefined acceptance criteria, but other concerns, including costs and uncertainties about, should be taken into consideration. Only then risk reduction and safety improvement can be truly perceived (Aven, 2015b).

3. Risk concept

3.1. Traditional and recent perspectives on risk as per literature

There are several perspectives when defining risk, but a widely-agreed definition of the former concept is missing. As a first step to our analysis, let us define and distinguish between two terms; risk concept and risk description. As per Goerlandt and Kujala (2014) risk concept and therefore the adopted risk perspective is a structured way to analyze and make statements about, whereas risk metric/description is the numerical value, estimated or assigned to an aspect of risk, following a specific standard or rule. Yet, not all risk definitions adopt this distinction. In the following we provide an overview of risk perspectives as per literature proceeding finally to the risk definition adopted in this thesis. Starting the analysis though it is important one to have an understanding of what we actually perceive as risk.

- The meaning of risk

We consider a future activity, see the operation of a hydrogen refueling installation. During the fueling process of a fuel cell electric vehicle; FCEV, the hydrogen temperature and pressure is being monitored and controlled by the dispenser. Also, the station is equipped with a mechanical independent pressure release device, so as to prevent the allowable limits of pressure from being exceeded. In this considered activity, one event may be that the dispenser fails to control the hydrogen temperature resulting thus in over pressurization of the vehicle compressed storage system; VCSS. We are concerned about the potential consequences of the considered initiating event, for the occurrence of which, as well as the associated consequences we are uncertain, and that is risk. The quantities of interest here are the event under consideration, the consequences associated with the event, and the uncertainty with respect to both the event and the consequences. The issue here though is how this uncertainty is represented.

- Perspectives on risk

Let us take a better look on how risk has been approached in technical applications until today. Our focus will mainly be on the way this former uncertainty associated with the considered event(s) and its consequences has been described.

Most of the approaches applied in an engineering context and in technical applications describe risk through probabilities and expected values (Aven, 2011, Goerlandt and Kujala, 2014) the latter in the form of expected losses; examples are derived from the offshore industry where the focus is on expected fatalities; PLL, FAR values and so on, or the hydrogen applications where expected

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number of leaks per system-year may be generated. With respect to the former approach we have seen risk being defined through probabilities in many applications including the offshore and nuclear industry. See for instance the triplet (S_i, p_i, c_i) suggested by Kaplan and Garrick (1981), applied in nuclear applications.

For the following analysis we introduce the two prevailing risk perspectives: R= (A,C,P) and R=(A,C,U)

- The $R = (A, C, P)$ perspective

Under this approach, traditionally applied in most technical applications, risk is defined through probabilities. Then, we may denote risk by R and write:

$R = (A, C, P)$, or alternatively $R = C\&P$

Under this notation, A is the initiating event or scenario under consideration, C its consequences and P the associated probabilities to both A and C. However, in order for this definition to be meaningful, the probability needs to be interpreted; as a relative frequency or as a knowledge based one /subjective probability (Aven, 2011). As defined in the previous a frequentist probability is derived as a relative frequency of the event considered taking place in a frame of repetition of the situation/activity restricting the conditions to be similar. The challenges this framework poses, have been covered in the previous chapter. For further details see (Aven and Reniers, 2013). Subjective probability on the other hand, is a measure of uncertainty/ degree of belief as seen through the eyes of the assessor at the current time he/she assigns this probability, and is subjected to his/her state of knowledge.

Some definitions of risk based on probabilities follows (Aven, 2011):

i. 'Risk is a measure of the probability and severity of adverse effects' (Lowrance, 1976)
ii. 'Risk is the combination of probability and the extent of consequences' (Ale, 2002)

Therefore, by now we have for the risk concept:

$R = (A, C, P)$ and $R = (A, C, P_f)$ the latter noted as the frequency based perspective on risk.

Within this frequency based perspective of risk falls also the definition of risk through expected values, the latter derived as expected number of occurrences per unit of time (Aven, 2010b), see for instance FAR values.

Both perspectives are based on the use of probabilities to express the associated uncertainties with respect to the quantities of interest. However, probability is not a perfect tool as per se and it is not the only one available. Under this rationale this perspective is too narrow to express risk in a sufficient way. Utilizing an example of Aven (2010b) and considering the probability of an attack given the assessor's degree of belief, i.e. P(A|K), the former assigns a probability of 0.01 to the

considered event. Is this number adequate on its own to capture the uncertainties precisely? As same author expresses, the answer is no.

- The $R = (A, C, U)$ perspective

An alternative approach extends beyond probability considerations and expresses risk in relation to uncertainty i.e. R=(A,C,U) or alternatively R=C&U, see Aven (2011). Under this rationale probability P is replaced by uncertainty U.

Similarly to this thinking, a new definition of Risk was released by the International Organization of Standardization. Under this definition (ISO, 2009):

'Risk is the effect of uncertainty on objectives'.

However as stated by Aven (2012) this definition is not adequately precise, and therefore can be translated in different possible ways. Here we refer to the following two, derived from the SRA glossary (2015):

i. 'Risk is the consequences of the activity and the associated uncertainties'
ii. 'Risk is deviation from a reference value and associated uncertainties'

Both definitions imply some reference value with respect to which the consequences are defined. The focus is normally placed on undesirable consequences, and the activity is associated with at least one (Aven, 2016b).

Under this analysis, we end up in adopting a broader perspective than the R= (A,R,P) allows, yet precise enough compared to the dimension suggested by ISO (2009). We adopt the R=(A,C,U) perspective. A definition of risk aligned to this approach expresses risk as the two-dimensional combination of events and associated uncertainties (Aven, 2015b) and therefore, whenever the term risk is used hereinafter, we recall this approach.

An equivalent definition of risk was also suggested by Aven and Renn (2009). As per se: 'Risk is uncertainty about and severity of the consequences of an activity with respect to something that humans value'.

- Risk description under the R= (A,C,U) perspective.

Once we have defined the concept of risk, a description of the latter under this approach is perceived by specifying a set of events A' and the respective consequences C'. Depending on how the uncertainty in relation to these quantities (A' and C') is expressed, a different risk description derives. In general terms we write R' = (A', C',Q, K) where Q is the defined measure of uncertainty used and K is the knowledge this measure is conditioned on. As expressed previously, probability is the most commonly used tool, however with important limitations and other tools exist too,

including imprecise probabilities as well as representations based on theory evidence and more (Aven, 2012). A summary of the risk perspectives met in literature follows:

Risk perspective	Notation
(1) Risk = Expected consequences or expected utility	(R = EC) (R = EU)
(2) Risk= Probability of an (undesirable) even	(R = P)
(3) Risk = Objective Uncertainty	(R = OU)
(4) Risk = Uncertainty about a loss	(R = U)
(5) Risk = Potential/possibility of a loss	(R = PO)
(6) Risk =Probability and scenarios/ consequences/ severity of consequences	(R = P&C)
(7) Risk = Event or consequence	(R = C)
(8) Risk= Consequences/damage/severity of these + Uncertainty	(R = C&U)
(9) Risk = The effect of uncertainty on objectives	(R = ISO)

Table 1. Risk perspectives as per literature, source: Aven, 2012.

3.2. Emerging risk

3.2.1. Defining emerging risk

For the following we distinguish between present risks, i.e. existing risks, and risks currently evolving i.e. having a dynamic potential. In the second case, we say we are faced with indications of emerging risk (Flage and Aven, 2015). A key factor for such a comparison may be the immediate implication the consequences of the former once the event occurs present, compared to those of the latter. For example, the consequences associated to an industrial accident have an immediate character. Such context though does not apply when we are considering the climate change, and the risk of urban flooding given the climate change, or a pioneer technology and the effects this might bring. Therefore, the time those consequences materialize; might happen in the future, without making it specific; generally calling this time-dimension, combined with our difficulty to fully define those consequences, distinguishes the former from existent risks.

Elaborating further on this, as per Flage and Aven (2015), we are considering the context of emerging risk, when we are faced with indications, expressed as justified beliefs, that a new event, or new within an already established activity, might evolve in the future, giving rise to (intense) consequences to human or something that humans value. An important aspect here is that a weak knowledge base is implied. Therefore, we cannot precisely define when those events will occur and what their consequences will be.

Reflecting on this we invoke in the analysis the context of technological advances and/or introduction of new technologies related to a potential energy shift. Narrowing this down, we consider the introduction of hydrogen as a transportation energy carrier including the production and distribution of the latter. Is this considered relevant to an emerging risk context?

Let us test this in the light of the previous definition. The energy shift is currently on progress. It is based among others in traditional, on the sense of well-established, technologies; steam methane reforming or water electrolysis among others, applied though on evolving environment; happening on site at the integrated refueling stations. On that sense, it is a new context. Is our knowledge considered strong on the field? Since we have limited experience; a database containing hydrogen accident and incident information is in its very start; see Funnemark and Engebø (2005), data from the oil industry may be utilized as per cases, validated models are not always assured, the answer is no. There could be sequences that we cannot fully define, or place in time, consequences applying from production to distribution with respect to assets or humans themselves; see for instance users of the dispensing system and third parties. Also, indications from the scientific community for a risk related to the introduction and adoption of hydrogen as a large-scale energy carrier there seem to exist. Increased interest towards the analysis of hazards arising from hydrogen storage and distribution systems, see for instance Rigas and Sklavounos (2005) and Moonis et al. (2010). Therefore, and in the light of this argumentation we might be faced with emerging risk.

In this section and while trying to approach the concept of emerging risk, definitions as per literature reviewed in the work of Flage and Aven (2015), will be invoked. However as stated by the former authors a definition of common acceptance for emerging risk is missing.

Two types of definitions will follow. In the first set the concept is handled as a compound term and therefore it is approached by analyzing its composing terms, i.e. 'emerging' + 'risk', and in the second, this is handled as one term, i.e. 'emerging risk'.

- First approach: 'emerging'+ 'risk'

Recalling the entry 'emerging' as per Merriam -Webster Dictionary; 'newly created or noticed and growing in strength or popularity: becoming widely known or established' the authors define emerging risk, as a risk (Flage and Aven, 2015):

i. newly created, or
ii. newly identified, or
iii. increasing, or
iv. becoming apparent/established

In the light of the risk perspective adopted in this thesis; R=(A,C,U) where risk is defined through uncertainties, emerging risk is conceived analogously. We recall from chapter 2 that as per R=(A,C,U) perspective, the respective risk description is R' =(A', C',Q|K) where A' is the specified set of events and C' the associated consequences, Q is a measure of uncertainty with respect to those quantities and K the knowledge that C' and Q are based on.

According to definition (i) emerging risk is then understood as, newly created awareness of the possibility that a defined event A' will actually occur with consequences C', i.e. the possibility A=A' and C=C'. Definition (ii) implies that emerging risk is a newly identified possibility that a specific event A' could occur resulting in consequences C'. Under definition (iii) we understand emerging risk as a risk which compared to the past, it is judged to be rising/soaring, and therefore if in our risk metric we choose interval probabilities to represent the uncertainty related to A' and C', then this definition implies; from a wide interval of less severe consequences we are moving towards a narrower interval of probabilities of more intense, in terms of severity, consequences. Definition (iv) declares that the possibility of a specific event A' occurring, becomes established, i.e. widely known (Flage and Aven, 2015).

- Second approach, one term: 'emerging risk'

International Risk Governance council in their report define emerging risk as: 'a risk that is new, or a familiar risk that becomes apparent in new or unfamiliar conditions' (IRGC, 2010), and identifies 3 categories of emerging risk:

a. Risks with uncertain impacts; with uncertainty emanating from *technological innovation* and/or *scientific progress*.
b. Risks presenting systemic impacts, the latter arising from multiple interactions of technological systems; interdependencies between systems or dependencies within.
c. Risks with unexpected impacts. Under this notation new risks emanating from the use of *established technologies* utilized though *within new or evolving contexts,* are considered.

Adopting now the definition of IRGC and in specific as per category (c) and (a) of emerging risk this can be seen in relation to our context introduced in the beginning as illustration.

However, with respect to such an energy shift, other concerns apply too. The energy shift could be seen in relation to the number of hydrogen cars being currently and in (the near) future mobilized, projected against the production enabled. Adding the concern of a robust hydrogen station network

being available, will the production and the related infrastructure reassure a smooth operation along the supply chain, or discrepancies in the system will be noted?

Extending the context some further on, we do not know but indications exist that in the near future, by year 2030, hydrogen powered cars will replace at a certain degree conventional transportation conditional on fossil fuels; see (Congress, 2016, Thomassen, 2016), and therefore increased correlation in the several levels of goods' supply chain is expected to realize, affecting potentially other sectors in dependency to the good's delivery.

Then definition of IRGC, considering emerging risk of category (b), or definition as per Burger and Warner (2012) applied in infrastructures can be meaningful; 'Expanding on the theme of emergent risk requires looking beyond the risks of individual actors. The risk emerges at the level of the ensemble (infrastructure sector) due to a lack of understanding of the interdependencies and the consequences of various supply and information technology (IT) disruptions on the ability of the ensemble to produce the require good or service' (Burger and Warner, 2012).

3.2.2. Discussing the definition and relating this to surprising events

Based on the former review of definitions available we may define the key characteristics of emerging risk. These are:

✓ A Weak knowledge applying

There is not a strict reference to the knowledge dimension in the former definitions besides the Burger and Warner one, where a 'lack of understanding of the interdependencies' is notified. However in the light of the (A,C,U) perspective the risk metric (A',C', Q|K) incorporates this knowledge supporting both C' and Q (Flage and Aven, 2015) and this dimension can be therefore noted in definitions (i)-(iv). Given also the 'uncertain impacts', or the 'risks with unexpected impacts' references in the relevant definitions, a weak knowledge that prevent us from fully defining the consequences and sequences is implied. There are beliefs pointing out to those risks and potentially their sequences, but we do not know whether the actual outcomes will be the specific ones. There is uncertainty related to them. Therefore, in the light of the analysis in Aven (2016b) we cannot call upon the term justified 'true' beliefs. They are simply justified beliefs i.e. beliefs supported by some form of evidence, and this implies a weaker knowledge than the first term would (Flage and Aven, 2015).

Summarizing so far, referring to an emerging risk context, there are indications that risk applies or will apply. However, our knowledge is weak to support with confidence an accurate risk metric. We know; justified beliefs of a risk applying, that we do not know; what the actual outcomes will be, whether they will materialize and when, and therefore, following a similar notation with that followed in the definition of black swan type events as per Aven, we could relate emerging risk

context to 'known-unknowns' type of events, adding this as an additional category in the 3 types of black swan events, contributing to the full taxonomy of surprises and unforeseen events, that will be presented in the following.

    ✓ Relativity in the context

Definitions (i-iv) with an exception placed in (iii), define emerging risk as a new context. However as seen in the IRGC definition (IRGC, 2010) emerging risk may be related either to a new activity, or an already established activity where a new event is emerging/ occurring. There exists some moderation with respect to the term new and what we define as such (Flage and Aven, 2015). However, a relativity in the context may be noticed with respect to the knowledge dimension as well. Those justified beliefs invoked in the definition should be seen in relation to who expresses the belief, and the knowledge reflected on those justified beliefs; with respect to the former we rephrase and point out the importance of being accurate to whose knowledge we are referring, with respect to the latter, knowledge can be dynamic, and therefore it can be updated and enriched, transforming those indications from justified beliefs, to justified 'true' beliefs. We should therefore add in the emerging risk description the time dimension as well, i.e. $(A', C', Q|K_t)$ (Flage and Aven, 2015).

An analogous relativity is noticeable in the definition of the black swan type events as per Aven (2014), as those rare but extreme events that come as a surprise relative to one's current beliefs. So, a black swan is assessed in the light of someone's beliefs, and those beliefs are subjected to the knowledge available at the current time (Aven, 2013a). We will return to this in more detail right in the following section.

3.3.   Black swan type events.

In the previous, we introduced the idea of black swans as 'surprising events relative to one's knowledge/ justified beliefs'. In this section, we will elaborate further on the topic, defining the three types of black swan events according to Aven's definition and approaching black swans from Taleb's perspective as well. Adding the concept of emerging risk, we will define the full taxonomy of events consisting potential surprises and we will identify issues proving critical when trying to meet such events.

▪   Origins of the concept

The black swan is a metaphor originated from Australia, used to illustrate the idea of events and outcomes with a surprising character (Aven, 2014). Following this metaphor; before the discovery of Australia and the establishment of the New World, there existed the unchallenged belief based

on empirical evidence that only white swans existed. However, against the beliefs at that time, the discovery of Australia brought the discovery of black swans as well. That, to the rest of the world came as a surprise. Therefore, utilizing this metaphor with subsequent research implications, 'black swans' developed to be conceived as extremely rare events (judged as) improbable to occur, yet this impossibility subsequently is removed (Aven, 2013b).

- What is a black swan; the 3 taxonomies

First Nassim Nicholas Taleb in 2007, defined the concept of black swans, and thereinafter the latter term gained the scientific society's interest; other researchers followed. According to this definition, black swans are events bearing the following 3 characteristics. First they are outliers, meaning that nothing in the past can persuasively point out to their possibility to occur. Second, such events carry an extreme impact. Last, Taleb states that besides their outlier status, once a black swan occurs human nature tends to come up with explanations for this occurrence (Aven, 2014, Aven, 2015a).

Another definition was expressed by Aven (2014). According to this, a black swan is an extreme rare event relative to one's current beliefs. Under this definition, Aven and Krohn (2014) distinguish between 3 types of surprising/ unforeseen events.

   a. Unknown unknowns,
   b. Unknown knowns,
   c. Knowns but judged of negligible probability

We may also add a category perceived as a 'near black swan'. According to Aven (2015a) under this notation we recognize those events that relative to one's current beliefs arrived as a surprise, yet did not cause any extreme consequences because of the established mitigations acting and preventing such impacts.

But let us define those events in more detail and express key factors when it comes to meeting such unforeseen events.

- **Unknown unknowns**, i.e. events totally new to the scientific community.

In a risk setting, the unknown unknown types of events mean that the actual outcome is not identified in the risk assessment, and therefore cannot be included in the risk picture. Utilizing the risk description applying in the R=(A,C,U) perspective; (A',C',Q|K) we can write A'≠A, implying that in the face of this occurrence, we face a surprise.

In this setting, we can think of diseases with extreme impacts formerly unknown to the scientific community, or substances with unknown properties, think for instance the HIV, or the case of the

thalidomide drug, whose administration proved to give unknown side effects; some type of gross limb malformations previously unanticipated (Aven, 2015a).

In this category of events, scientific uncertainties apply, meaning that we are not able to establish an accurate prediction model for the event (Aven, 2013a). Reversing the point of view, in cases where a solid knowledge base applies including considerable knowledge about the phenomena involved, such occurrences are rarer (Aven, 2015a).

Another issue here, quite critical when it comes to handling this type of unforeseen occurrences is the knowledge supporting the identification process, and therefore an additional interpretation of surprising events of the 'unknown unknowns' type may be; an occurrence not captured by the knowledge that is reflected in the risk description and therefore in the risk assessment (Aven, 2013a). However, this argument remains valid for the remaining types of unforeseen events as well.

- **Unknown knowns,** i.e. established events, known to the scientific community but the risk analysis team is not aware of them, or has not identified those events because the assessment was lacking thorough enough considerations. Utilizing again the risk description, this does not include the actual occurrence A, i.e. A'≠A.

In this context, we can think for instance a terrorist attack such as the one happened in Brussels in 2016; the Brussels Bombing. Terrorist attacks occur, the risk analysis team is aware of this context and if the signals were interpreted, they probably would have included and addressed this scenario as possible to occur. We are therefore in the second case described as per type b. Another issue here is to whom this event comes as a surprise. From a general perspective, such events occur. From the perspective though of the risk analysis team, or the police and the state responsive mechanisms, this occurrence compared to the established risk picture, was surprising. However, once this attack occurs then the risk picture will be updated. Given this attack, the risk analysis team most probably will make different considerations, assessing similar scenarios.

We referred to this illustration example willing to point two important issues. First, as Aven (2013a) states, the concept of a black swan has always to be seen in the light of whose knowledge/beliefs we refer to. Secondly, implied also by the 'current beliefs' reference in the black swan definition, this knowledge is dynamic. What has been a surprise today will not be a surprise tomorrow.

- **Events known but judged of negligible probability**. These are events widely known, including the analysis team, but judged to be of negligible probability of occurrence, and therefore excluded from further assessment.

Maybe the most crucial type of surprises from a risk assessment perspective, since such events constitute well established events, known in the scientific community and the analysis team, and therefore could be predicted and met in advance. However, due to probability considerations they

are not further assessed in the analysis, resulting in surprises. We referred to this in Chapter 2 as one of the key limitations of the traditional approach in QRAs, when scenarios are ignored because of low judged probabilities. However, what if such probability considerations are not representative of the actual outcomes? In such events, of very low rate of occurrences the variation in the phenomena is not known and therefore no frequentist probability can be utilized. We cannot make accurate predictions. In this context, we are faced with knowledge or more precisely lack of knowledge, and therefore the only relevant probability for this setting is the subjective probability (Aven, 2015a). We recall from chapter 2 the epistemic uncertainties related to this lack of knowledge. However, in situations where large uncertainties apply the suitability of subjective probabilities to reflect epistemic uncertainties can be challenged as well (Aven, 2013a). It is not the probability as per se that is uncertain though, but the knowledge reflected on this; all the assumptions embodied and the knowledge supporting this probability assignment (Flage and Aven, 2009).

Returning to the relativity of the context with respect to whose knowledge we are talking about, the same argument applies here as well. An additional issue however to point out, applying in cases of very low occurrences, is that this argument falls apart if for instance we change the scale we look at an occurrence. Given for instance the context of an earthquake and restricting our analysis in Norway, then this occurrence will be considered a surprise of this type. No such occurrences, or critically low occurrences are reflected on the historical data, and therefore the event is ignored when the risk picture is established. However, extending our analysis and considering a macro scale, and this for instance includes Italy, Greece and Turkey; high risk earthquake zones, then the number of such occurrences increases significantly. Figures 3.1.-3.2. illustrate this implication; how the adopted perspective; micro or macro, affects the way we look at the possibilities of occurrences and therefore, whether an actual outcome will constitute a surprise of this type.
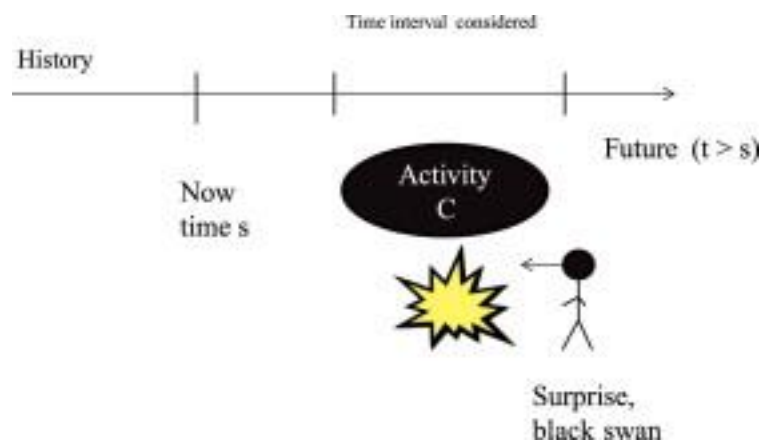
Figure 3.1. Illustration of the relationship between risk and surprise when the perspective is micro, given also the time dimension. Source: Aven 2015a
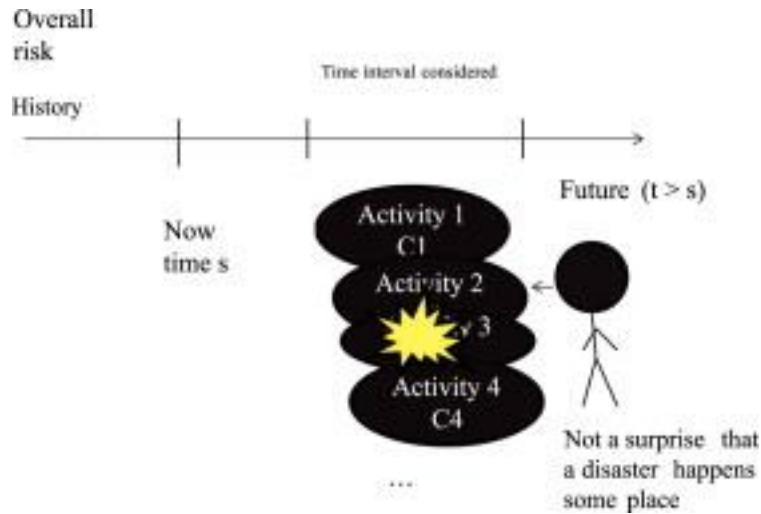
Figure 3.2. Illustration of the relationship between risk and surprise when the perspective is macro, given also the time dimension. Source: Aven, 2015a

- The basis to address such events

Based on the discussion above, common grounds for all levels of unforeseen events is the knowledge supporting the overall risk assessment process. We can identify two dimensions in this respect, the strength of this knowledge, and the time this knowledge is assessed. With respect to the former, this knowledge is relevant to:

a) The identification of scenarios
b) The ability of knowledge based probabilities to reflect epistemic uncertainties. How can this be assured?
c) In the case of the unknown unknowns; we have totally imperfect knowledge about.

The knowledge on the other hand is dynamic. Once a surprising event occurs, our knowledge with respect to that is updated and a new risk picture given this knowledge is produced. We also add the perspective at which we look at the initiating event. Risk cannot be seen in a micro perspective or in an isolated context; broad considerations of initiating events, need to be included in the analysis (Aven, 2013a).

So far, we have approached the surprising events as:

a) Unknown unknowns
b) Unknown knowns
c) Knowns but judged of negligible probability

Taking into consideration emerging risk contexts, defining the latter as cases where we have indications in the form of justified beliefs, and therefore we know, there is something we lack; we do not know. We therefore add the taxonomy of:

d) Known unknowns

Finally, there are those events that constitute (e) 'near black swans', on the sense that those occurrences came as a surprise, yet their consequences were prevented from being extreme only in the presence of protective barriers.

As such we complete the set of events potentially constituting surprises in a risk context.

3.4. The knowledge dimensions

Previous section stressed the contribution of knowledge dimension to surprising/ unforeseen events, having a special meaning for every category; a-e, identified. We are faced with cases where given a lack of knowledge or imprecise knowledge, the actual outcomes are surprising relative to the produced risk picture, and as such we challenge the confidence we place in the overall risk assessment process. Therefore, a question that raises here, is whether we are always allowed to conduct a risk assessment or given a weak knowledge base and insufficient data this type of assessment is not considered fortunate.

3.4.1. Can a risk assessment always be conducted?

Risk assessments aim to provide decision support in decision making under uncertainty. This implies that they systemize the knowledge we have with respect to the processes, systems and activities of interest and our uncertainty regarding those (Aven, 2015b). Therefore they provide the basis to evaluate design alternatives and deviations from prescribed recommendations, and finally decide on their implementation, in the presence of this uncertainty. On this sense, a risk assessment is a valuable tool at our hands which cannot be omitted. The point here though, and the one we will try to make in the following section is that this knowledge or lack of knowledge is critical to be communicated together with the produced results (Hafver et al., 2016), so that we can evaluate the confidence we can put in the provided recommendations. In the following we present two methods assessing the strength of knowledge; a crude assessment of the latter based on a grading rationale, suggested by Flage and Aven (2009), and the recently suggested method by Aven (2013b) identifying potential deviations from assumptions incorporated in the analysis and assessing their impact on deviations in risk description, together with the strength of knowledge this assessment is based on. Other initiatives combining quantitative with qualitative representations also exist. See for instance the NUSAP system (van der Sluijs et al., 2005),

combining quantitative representations of uncertainty; through traditional parameter sensitivity analysis, with a qualitative review of the available knowledge, pointing out also the implication of whose knowledge we are referring to; different experts can assign different qualitative scores to the same part of knowledge, and this is an important aspect. However, here we restrict the analysis in the two methods defined above.

3.4.2.   Strength of knowledge characterizations

- Method 1: Crude scoring of strength of knowledge; SoK

This method identifies 4 dimensions in the background knowledge and with respect to these proceeds to an overall crude assessment of the SoK the probabilistic analysis is founded on adopting qualitative score categories; *strong*, *medium* and *weak* respectively. Those dimensions in background knowledge, are: (a) the extent to which embodied assumptions are reasonable or represent strong simplifications; (b) availability of relevant and reliable data; (c) level of agreement among the experts, and (d) level of understanding of phenomena involved.

Therefore, knowledge is considered *weak* if at least one of the following conditions is valid (Flage and Aven, 2009):

i.   Assumptions embodied are strong simplifications
ii.   The available data are not sufficient or reliable
iii. Agreement among the experts is not assured
iv.   Phenomena relevant to the analysis are not well understood, i.e. validated models are missing, or they are believed to give poor predictions

Analogously, knowledge is considered *strong* if all of the following conditions, if relevant, are valid (Flage and Aven, 2009):

i.   The assumptions made are rationale
ii.   Sufficient reliable data are provided
iii. There exists a broad agreement among the experts
iv.   The relevant phenomena are well understood. i.e. the models are validated and known to provide accurate predictions.

For situations in between, the strength of knowledge is assessed as *medium.*

- Method 2: Assumption deviation risk

According to this method suggested by Aven (2013b) all main assumptions in the analysis are identified and converted into a set of uncertainty factors; the latter, given a deviation from the

stated conditions, are responsible for introducing uncertainty in the analysis. A subsequent step in the method is to asses a magnitude of this deviation, a probability of this magnitude occurring and the impact it brings in the events' occurrences and the associated consequences. Last, an overall qualitative judgment of the strength of knowledge this *assumption deviation risk assessment* is conditioned on is performed.
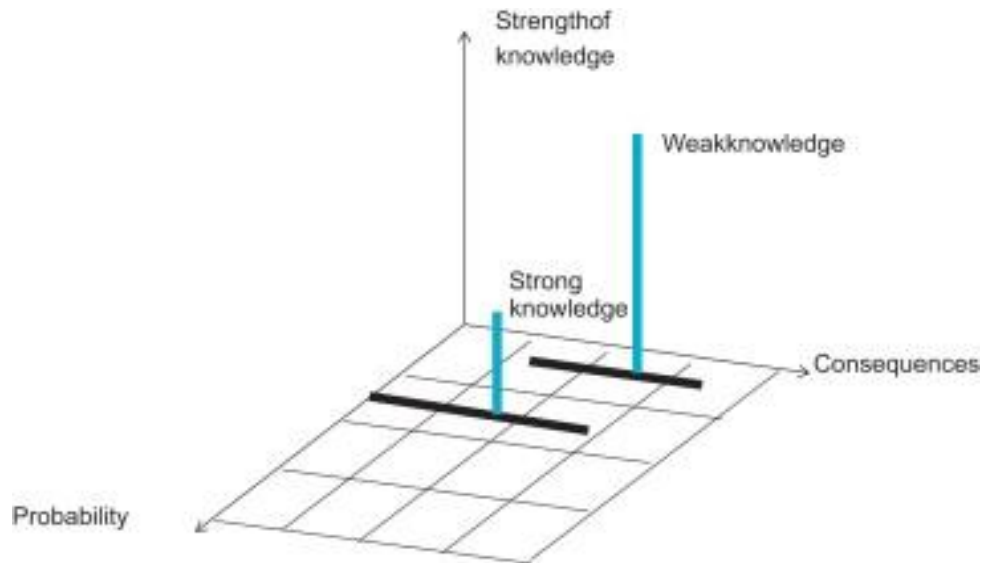
Figure 3.3. A way of presenting the risk related to a risk event when incorporating the knowledge dimension; uncertainty intervals are assessed and the SoK is characterized. Source: Aven, 2013b.

Therefore, as Aven (2013b) states the suggested methodology captures the elements of the risk description according to the new risk perspectives. These are (Aven, 2013b):

(i)   The magnitude of deviation from the assumptions made and associated consequences i.e. effect this deviation brings in the consequences defined in the risk assessment; we denote this magnitude of deviation and the effect in the consequences by D and $\Delta C'$ respectively.

(ii)   a measure of uncertainty referring to this deviation and the associated consequences; we denote this by Q.

(iii)   the knowledge all the above are conditioned on, which is denoted by K_D.

Methodology provides insights in the effect of assumptions' deviations in the overall risk score, and can be also seen as a measure of criticality of each assumption separately (Aven, 2013b).

For the illustration of the method let us present an example. We consider an everyday setting; Mike going to work. Today though it is a special day, as Mike is going to have an important for his career meeting. Based on his empirical evidence, going to work daily takes approximately 20

minutes. Therefore, today he decides to leave 35 minutes earlier. He subconsciously conducts a risk assessment including some important assumptions; his daily access time to work is representative of today as well; incorporating the assumption of a very low accidental rate in this road section, i.e. 2%. Therefore, he concludes that an accident blocking/delaying his way to work is quite unlikely, almost negligible.

A potential deviation event though may be that: his 'daily access time to work is not representative of today', on the sense that the occurrence rate of an accident in this section is increased by a factor 2, 4, or 8 times higher than the one Mike assumed in his initial assessment. This factor represents in our setting the magnitude of deviation.

Then according to the method, we make a crude risk assessment of (Aven, 2014):

- The magnitude of this deviation
- The probability of this magnitude occurring
- The impact this deviation brings to the consequences C, using again a crude risk scoring i.e. high, medium, low; see table2.

It is now time to assess the strength of knowledge this deviation risk assessment is based on, adopting the crude scoring that method1 introduced in the beginning of the section. If a weak or medium score is assigned to the SoK, then the risk score moves up one level; from low to medium, and from medium to high respectively (Aven, 2014).

Deviation magnitude	Probability	Effect on consequences	Risk score; based on probability and consequences given the deviation
2	40%	Time to work increases by 15 min at least	High
4	5%	Time to work increases by 15 min at least	Medium
10	0,001% *i.e. almost negligible*	Time to work increases by 15 min at least	low

Table 2. Assumption deviation risk assessment example; risk scores from the conditions stated. Deviations here are considered with respect to the accident's rate in the specific highway section being 2,4, or 10 times higher than the initially assumed of 2%.

Extending this setting of one assumption, in a setting of multiple ones, the rationale now is that if we have a restricted number of assumptions assigned a high risk-score, then we could assess the strength of knowledge as high. However, if the number of assumptions associated with a high risk-score increases significantly, then the overall Strength of Knowledge is considered weak. For

situations between the two settings defined, we conclude that the strength of knowledge is medium (Aven, 2014).

The assumption deviation risk can be used alternatively to or replacing former approaches of assessing a 'degree of uncertainty', or sensitivity analysis with respect to the impact of specific deviation on the calculated probabilities for the occurrences A and their associated consequences C (Aven, 2013b). Using also the notation as per Aven (2014) deviation risk, aligned to the risk perspective $(C', Q \mid K)$, is defined as $(\Delta C', Q \mid K_D)$, where D stands for the deviation and the remaining are as known.

In chapter 2 we referred to the gas leak incident which occurred in Hammerfest LNG where a critically lower detection time of 5 minutes than the actual one was assumed; we recognize the criticality of identifying assumptions based on weak knowledge. The incident proves that risk assessments are heavily dependent on assumptions but deviations may take place in real life, and therefore assessing the strength of knowledge these assumptions are founded on is of high importance. However, knowledge is not static, evolves and keeps updating, and this dynamic dimension of the latter needs to be acknowledged in the overall risk assessment process.

3.4.3. Dynamic dimension of knowledge

- Time dynamics

In most settings, we are called in present time to take a decision addressing the future. According to the illustration example used in chapter 2 to reflect on the concept of risk, in a risk assessment we are 'concerned about the potential consequences of the considered initiating events, for the occurrence of which, and the associated consequences we are uncertain, and that is risk'. These uncertainties as seen right before are critically conditioned on our knowledge, i.e. the assessor's knowledge. However, if the assessor moves in time ahead of present time, see figure 3.4., his knowledge has been updated. Yet, this has to be acknowledged in the risk assessment process and the assessor needs to update all assumptions based on the newly acquired knowledge, since the latter in not static. As Aven and Krohn (2014) describe, and is also demonstrated in figure 3.4., when moving in the timeline, ahead to the present time v, new warnings and signals with respect to the focused activities may uncover. Therefore, this updated information is critical to be included in the risk assessment so that the latter provides sound and robust results.
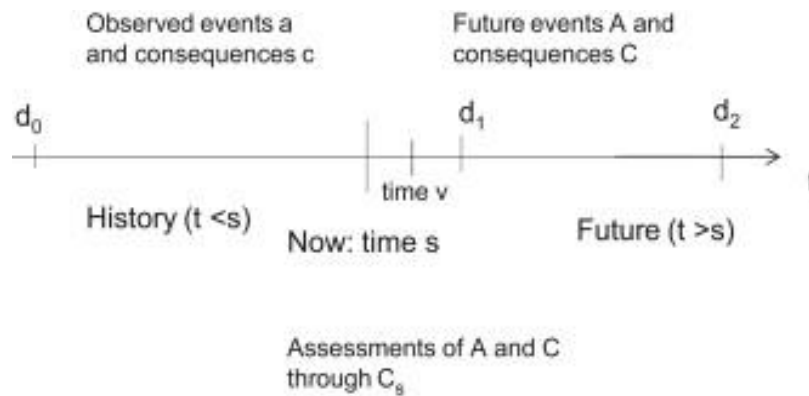
Figure 3.4. A schematic illustration of some of the fundamental components of the risk concept in relation to the time dimension, source: Aven and Krohn, 2014.

- Knowledge transfer and communication

Even if risk assessment is conducted in a way that enables confidence in the produced results, it is important this acquired knowledge with respect to the design alternatives and the uncertainties associated with each, to be communicated to the proper parties. Aligned to Hafver et al. (2016), in order to assure efficient risk management, all the acquired knowledge systemized through the risk assessment needs to transfer properly between risk analysts and decision makers as well as involved stakeholders, with the former people listening to the needs of the latter. Decision makers on the other side should be able to understand how to interpret and use the provided results. In other words, it is essential whatever gap between risk analysts and decision makers referring to acquired knowledge and interpretation of the latter, to be bridged. However how such a result can be achieved extends the scope of the present analysis. Yet, providing clear reflections of the strength of knowledge the risk assessment results are conditioned on, so as the decision makers to have a sufficient understanding of the nature of the risk and the control they possess over the latter, may be a way towards this direction; typical risk matrices used traditionally to present the results to involved stakeholders can be replaced by risk matrices providing indications of the SoK (Hafver et al., 2016), as the one presented in figure 3.5.

Concluding, we remind that risk communication is essential to take place in all phases of a risk assessment, an element that is noticeable in the ISO (2009) framework, through the communication and consultation step; see also chapter 4, figure 4.5.
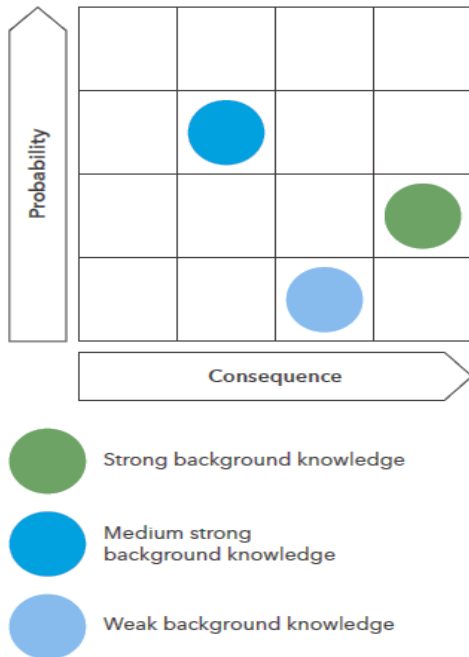
Figure 3.5. Example of risk matrix reflecting on the Strength of the background knowledge supporting the calculated probabilities and consequences, source: Hafver et al., 2016.

3.5. An integrative risk assessment framework

The recent shift in risk assessments calls for probabilities being replaced with expressions of uncertainty. Some of the weaknesses linked to pure probabilistic considerations traditionally adopted, can be summarized in scenarios being excluded from further assessment, and therefore risk elements of importance being ignored, resulting in unforeseen events. Special issues on this behalf is that this knowledge supporting the relevant risk considerations and probability assignments, is not reflected in the probability numbers as per traditional practices. Therefore, a broader perspective is sought. Several attempts have been reported in the scientific world, combining probability with qualitative approaches and presenting an integrative thinking. Klinke and Renn (2002) for instance discuss that in the phase of highly uncertain conditions, or in high complexity contexts, the scientific input represented by traditional probabilistic thinking can serve only as a starting point. There is the need to compile all the information available, including arguments and beliefs representing the 'different science camps'. They also suggest ways to organize and utilize the current knowledge available by reference to the 'Pedigree scheme' introduced by Funtowicz and Raventz. See also Van der Sluijs et al. (2005). In the following we choose to present and analyze one framework aligned to this integrative perspective, introduced by Aven and Krohn (2014) and discussed in a practical level by Aven (2013b).

This new framework focuses on characterizations of knowledge or lack of knowledge instead of aiming to provide accurate risk descriptions. Therefore, keeping traditional probability thinking as its bedrock, it focuses also on the knowledge dimension and the time dynamics in relation to the latter, extending risk picture to capturing also this knowledge and enabling a deliberate thinking. On that sense, the potential of surprises is taken into consideration, and subsequently the basis to meet such events is set. Yet, how this is practically achieved will be discussed in the following.

Figure 3.6. The New Risk perspective with its basic features suggested by Aven and Krohn (2014), source: Aven, 2013b

The risk analysis starts with the step of hazard identification where all initiating events are identified and the cause analysis provides insights in their root causes. Probabilities are assigned to those identified events and the consequence analysis addresses the associated scenarios (Aven, 2015b) quantifying also the associated to them uncertainty. Traditional risk assessment addresses this level of analysis.

At this point let us introduce an alternative way to reflect our uncertainty with respect to the focused quantities; using imprecise probabilities. What we gain by this approach is to reflect more effectively in the full spectrum of consequences (Aven, 2013b). The knowledge based type of probability used typically, reflects to a large extent historical data, but incorporates a set of assumptions as well; a typical assumption for instance is that historical data are representative of the future and the very specific context. Quite often though and given the context of special cause variation introduced in previous chapter, the variation is outside this predicted performance. Extrapolating straight to the future statistics of the past may create some issues on this sense.

Additional assumptions are taken when considering which scenarios to address and choices associated to the sequences considered. As a result, the expected consequences calculated as the product of those probabilities times the associated losses, is conditioned on the former choices and may reflect only a part of the consequences (Aven, 2013b).

According to Aven (2013b), adopting imprecise probabilities or probability distributions seems to address this type of problem. Furthermore, such an interval is less sensitive in the situations considered in the analysis, and therefore the assumptions generating those situations as well. Alternatively, probability distributions may be generated. Yet, on this setting we should be cautious, since establishing a probability distribution poses high demand in available data, and

lacking such, which is usually the case, the probability distribution could be quite arbitrary (Aven, 2013b), thus the expected values founded on such distributions may be misleading.

Therefore, the new framework suggests uncertainty intervals to reflect our uncertainty with respect to initiating events and their consequences. Yet, once those intervals have been assessed; see step 2 as per figure 3.6., the framework calls for strength of knowledge characterizations so as the latter knowledge to be assessed and reflected on the expected values produced.

We refer to the two methods presented in section 3.4.2; either a crude scoring of the SoK, or the 'assumption deviation risk'. It is considered fortunate to apply the more detailed method where insights in the criticality of assumptions may be perceived, yet this is not always feasible. At this point, we are ready to proceed to the consideration of surprises; step 3 as per figure 3.6. 'Black swan assessment' aims to uncover surprises compared to the produced risk picture and the beliefs of the analysts participated in the risk assessment, and therefore the methodology challenges this risk picture including the assumptions it is based on, enabling a deliberate thinking.

For practical reasons, it requires mustering of two teams; team A that has established by now the extended risk picture including the knowledge characterizations, and team B that is aiming to identify weaknesses in the process and challenge the assumptions the latter is based upon.

The approach derives from the red teaming methodology, a valuable tool used widely in cybersecurity and military applications (Aven, 2015a, Abbass, 2015). According to this approach and as Abbass (2015) describes, two teams are defined; the blue team and the red respectively. When the objective set is to challenge a plan, red team tries to identify those assumptions that the plan is founded on and recognize patterns and conditions under which the former assumptions are violated and the plan collapses. Therefore, the main objective is identifying the plan's vulnerabilities, and a prerequisite to the methodology's success is the effective composition of the teams (Abbass, 2015). Analogously in our setting, it is important that the two teams utilized in the process of this 'improved event/scenario identification'(Aven, 2015a), are independent to each other. The goal is to combine all relevant data, beliefs and arguments, representing the different perspectives in an analogous way that Klinke and Renn (2002) express in their discussion about deliberation. Therefore, team B should not include any members of team A or represent any common to the former's team thinking, since the objective is to stimulate a creative thinking, uncovering inherent weaknesses in the risk assessment so far.

Therefore, returning to step 3; see figure 3.6., this includes the following set of actions (Aven, 2013b):

i.   All the identified events given a low risk score with probability, consequences and SoK justifications, derived from the previous step; aligned to the assumption deviation risk method introduced, are listed.

ii.   Team B now challenges the mental model used by team A. This practically is translated as searching for evidence pointing out to the possibility of those risks realizing, i.e. historical

evidence, or justified beliefs not aligned to those called in by the experts participated. The team also searches for unknown knowns (Aven, 2015a).

iii.   At this point a joint list of all risks, i.e. both risks assigned a high risk-score, according to the extended risk picture, and those assigned a low score accompanied with the evidence provided in (ii) is generated.

This methodology handles black swans both the unknown known type and the negligible probability type. Yet, unknown unknowns by definition represent events totally unknown to scientific community and therefore the suggested methodology cannot provide meaningful support when it comes to those (Aven, 2013b).

Reflecting some further in the black swans of the negligible probability type, we have discussed in section 3.3. that in such events given their rare occurrences, the variation in their consequences is not known and therefore we cannot make accurate predictions; frequentist probabilities fail on this behalf and subjective ones given a context of large uncertainties and/or weak/moderate knowledge, are not trustworthy. The main problem with this context is that we cannot, base risk assessment on the assumption of stable processes (Aven and Krohn, 2014). Then, special-cause variation reflecting variation outside the historical experience, demolishes the idea of full predictable performance. There it seems that when handling this type of events, treatment of risk. lies on a cautious thinking. This implies that we should scrutinize both the probability judgments of the event/scenarios identified together with the knowledge supporting them, but also the judgements about what is considered as acceptable risk and this has to be seen in relation to the available knowledge as well (Aven, 2015a).

Aven suggests the following approach based on a cautious thinking (Aven, 2015a):

i.   If risk is found lower than the RAC and the probability margins are wide, risk is considered acceptable, unless the SoK is assessed as weak.
ii.   If risk is lower than the RAC, and the SoK is assessed high, then risk is acceptable.
iii.   If risk is lower than the RAC, with moderate probability margins, and the SoK is assessed moderate or weak as well, the risk is considered unacceptable.
iv.   If finally, risk in terms of probability is above the defined criteria, then risk is unacceptable.

Therefore, despite a low judged probability, the generated scenarios need to be further addressed, when the knowledge the probability numbers and defined sequences are based upon, is considered moderate or weak. We would argue that the same applies for emerging risk contexts, i.e. new technologies or traditional technologies in evolving environment, some newly anticipated viruses and more, as in such cases by definition we are faced with a weak knowledge base. Therefore, cautious thinking is a policy to be persistent on, in such contexts as well.

Before completing this analysis, let us make a few remarks and highlight additional, yet important elements of the presented framework. As part of the overall new integrative perspective combining

probabilistic thinking and qualitative approaches, the enhanced framework suggested and called in in this section, focuses on knowledge characterizations and experience's transfer. Yet, in a practical level, it needs to be coupled with concepts and ideas from other fields (Aven, 2014). In brief, we have referred to the distinction between common and special cause variation and the contribution of the latter to surprises, and therefore the need to look beyond probability considerations due to this reasoning. We also add a concept highlighting performance aspects derived from High Reliability Organizations, aiming in the improvement of the latter performance. That is the concept of collective mindfulness with its five characteristics that in brief represents the following ideas (Aven and Krohn, 2014);

1. *Preoccupation with failure*: Highlighting alertness and the need to focus on early signals and precursors. Also, learning through experience is an important aspect.
2. *Reluctance to simplify:* Summarizes the overall thinking of the new perspective; we cannot be based on rules of thumb, strict probability considerations, statistics and assumptions; more or less valid, and therefore, risk is to be considered in a broader perspective. The assumption deviation risk assessment could be seen as a dimension of this.
3. *Sensitivity to operations:* we should sense the changes in risk and take actions and decisions, whenever needed.
4. *Commitment to resilience:* Implies a form of preparedness for surprising events.
5. *Deference to expertise*: People with the necessary background and qualifications should make judgements with respect to risk and take decisions to act.

We briefly presented the ideas, yet Aven and Krohn (Aven and Krohn, 2014) illustrate those in more detail utilizing also relevant examples and therefore, for further information and reasoning, we refer to the former authors.

4. Risk assessment in hydrogen applications

4.1. Development of the hydrogen refueling station network in Norway

Since 2003 several projects have run aligned to the objective of introducing hydrogen as a potential energy carrier and in a second level facilitating and coordinating the transition from a testing and demonstration setting to commercial use, gaining thus the acceptance of the public. In the following we will introduce three projects that run in this rationale and had been critical to the development of the current (until year 2016) infrastructure of hydrogen service stations in Norway,

4.1.1. Norway HyNor Project

HyNor project (2003-2015) was a project running on national funding (by the Norwegian governmental funding agency Transova) with several participants from the industry as well as regional and central authorities and had been a part of the Scandinavian Hydrogen Highway Partnership (wikipedia, 2017c). Statoil Hydro, among other companies, had been the driving force in the realization of the scheme's main objective which initially was the establishment of a hydrogen transportation infrastructure along the route connecting the cities of Stavanger and Oslo enabling thus the use of hydrogen powered cars in southern Norway. As per Adamson et al. (2013), a central requirement to the commercialization of hydrogen powered vehicles is the access to refueling. Therefore, the existence of a hydrogen production and refueling infrastructure had been crucial to the success of the project. Besides the initial focus placed in the route between Stavanger and Oslo the project's focus towards 2015 was oriented to the expansion of the service station network in the capital region and the establishment of a link between Denmark and Sweden (Scordato and Klitkou, 2014). The project had been a two-dimensional pilot program promoting the use of hydrogen in road transport and testing the technology related to the commercialization of hydrogen powered cars (Scordato and Klitkou, 2014).

The project run in three phases.

- 1st phase 2003-2009. Main objective set was to enable hydrogen vehicles to drive along the route Stavanger- Oslo with the establishment of the first service stations (in Stavanger-Forus and Porsgrunn)
- 2nd phase 2010-2012. In a second tense, the project demonstrated an effort to build a denser network of service stations in the capital region and to acquire a larger fleet of fuel-cell vehicles in cooperation with Toyota, Think and Mazda.

- 3[d] phase. The final stage of the project was aiming to prepare the ground for the commercialization of FCEV in the Norwegian market in co-operation with projects extending the Norwegian borders (Scordato and Klitkou, 2014) and establish a link with Sweden and Denmark

Figure 4.1. HyNor Hydrogen Highway project's initial goal was to fuel the route Stavanger-Oslo. source Scordato and Klitkou, 2014.

A list of the service stations established during this initiative (*demo service stations*) follows. See also table 4.1 for additional information in the technology facilitated to produce hydrogen or bring to site, as well as the facility's operators.

i. In *Stavanger Forus* (2006)- It was shut down in 2011. No onsite production was exhibited. Compressed gaseous hydrogen (CGH2) was trucked in.
ii. In *Porsgrunn* (2007), with a production capacity of 130kg per day
iii. In *Oslo, Økern* (2009), with a production capacity of 20kg per day
iv. In *Drammen* (2009) –2015; moved to Oslo, with a production capacity in its initial location 20kg per day.
v. In *Oslo, Gaustad* (2011), with a production capacity of 20kg per day as well.

4.1.2. HyNor Lillestrøm Project

HyNor Lillestrøm was a hydrogen technology testing and demonstration project, running during the years 2009-2013 as a part of the wider HyNor project. It was jointly funded by a set of authorities including the Research council of Norway (NFR), the Akershus County Municipality (Afk), Akershus Energi and Transova; the national organization for state funding of sustainable mobility projects (Ulleberg et al., 2014).

The project, located in the Akershus energy park in Lillestrøm, had a two-dimensional objective of:

i. testing and validating innovative hydrogen production and compression technology (Scordato and Klitkou, 2014) and

ii. building and operating a hydrogen refueling station (HRS) with on-site hydrogeneration based on renewable energy sources. In specific the technologies facilitated for the hydrogeneration comprised on site steam reforming of landfill gas and water electrolysis via solar PV energy. An additional objective was to educate and transfer hydrogen related knowledge facilitated seminars and on-site visits (Ulleberg et al., 2014).

The HyNor Lillestrøm facilities integrated a HRS and a Research and Development building (R&D). The former, provided by the company H2 Logic (Denmark) and build in compliance with *SAE J2601* and *SAE J2719* standards, had a 700bar hydrogen capacity storage and allowed a 3minute refueling of the FCEV (Ulleberg et al., 2014). The station facility comprised of a standardized small-scale hydrogen production, compression and dispenser system; see figure 4.2. The Hydrogen production process utilized is either on site electrolysis based on solar power produced by the PV panels placed in the roof of the facility, or via landfill gas steam reforming. The R&D building provided the facility for testing the landfill gas upgrading and hydrogen purification systems and at the same time was offering the opportunity to researchers and scientists to test out their concepts and new technical ideas (Scordato and Klitkou, 2014, Ulleberg et al., 2014).
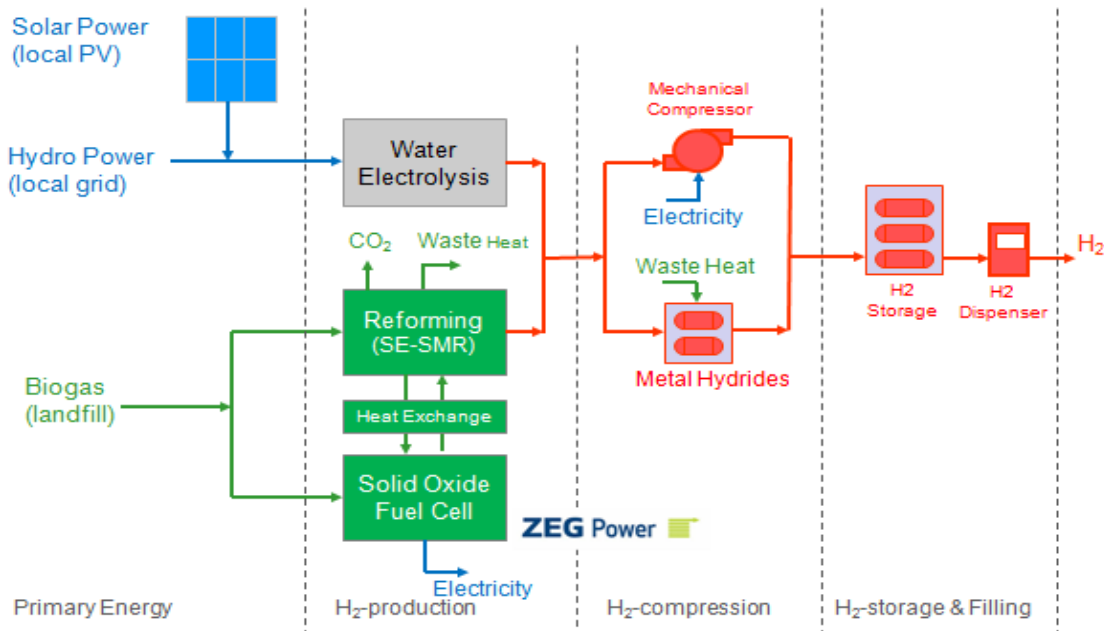
Figure 4.2. HyNor Lillestrøm concept. Source: Ulleberg et al., 2014.

Over the project's development the HRS's utility has changed. Initially the station was designed to supply five small battery electric vehicles, subsequently though as the HRS was utilized by the H2moves- Oslo project, its use was extended to supplying also specific models of FCEVs provided by Hyundai, Daimler and Mercedes-Benz. In 2012 and since then, the HyNor Lillestrøm refueling station has been made available for refueling of all types of FCEVs (Ulleberg et al., 2014). The scheme was extended until 2015 embodying in its activities two additional projects; BioSER, and BioZEG. For further details concerning the latter projects see Ulleberg et al. (2014).

4.1.3. CHIC (Clean Hydrogen in European Cities)

CHIC was a co-financed project by the municipality of Oslo, the Akershus County Council, Transova and the Norwegian Research Council, the general objective of which has been to reduce noise levels and reassure a better air quality lowering the harmful emissions from public transport in the capital area (CHIC, 2016a).

As a part of the project, Air Liquide (Norway) on contract with Ruter Hydrogenics Corporation (Belgium) designed, built and operates up to date an HRS located at the garage of the Rosenholm bus station in Akershus. The service station which launched in May 2012, was designed to provide 100% certified *'green'* hydrogen produced with electrolysis from renewable sources, and fuel a fleet of five fuel cell buses per day (for a period of 5 years). The station integrated a production capacity of 250 kg per day and a storage capacity of 320kg. It was also characterized of relatively short fueling time, of an average of 10min per vehicle (i.e. FC bus). In specific, the five buses were filled within 2 hours during the night (CHIC, 2016b).

Since 2003 many research and demonstration projects, under the rationale to test the pioneer technology and transfer knowledge about, have evolved. In figure 4.3 the hydrogen infrastructure as developed during the former projects is demonstrated. At this point, we recall that the service station in Forus-Stavanger was shut down in 2011. However, to move one step further and facilitate the potential of a massive introduction of hydrogen powered cars in Norway, the need to establish a robust network of hydrogen service stations was manifest. This has been confirmed by the latest; June 2016, national update in the Norwegian parliament according to which, a goal of 50.000 FCEV being mobilized in Norwegian roads, and the first service station being available by year 2017, was set. Towards this direction, a mandate to the Norwegian government enterprise ENOVA secures support for a refueling network in and between the main cities of Norway (Thomassen, 2016).
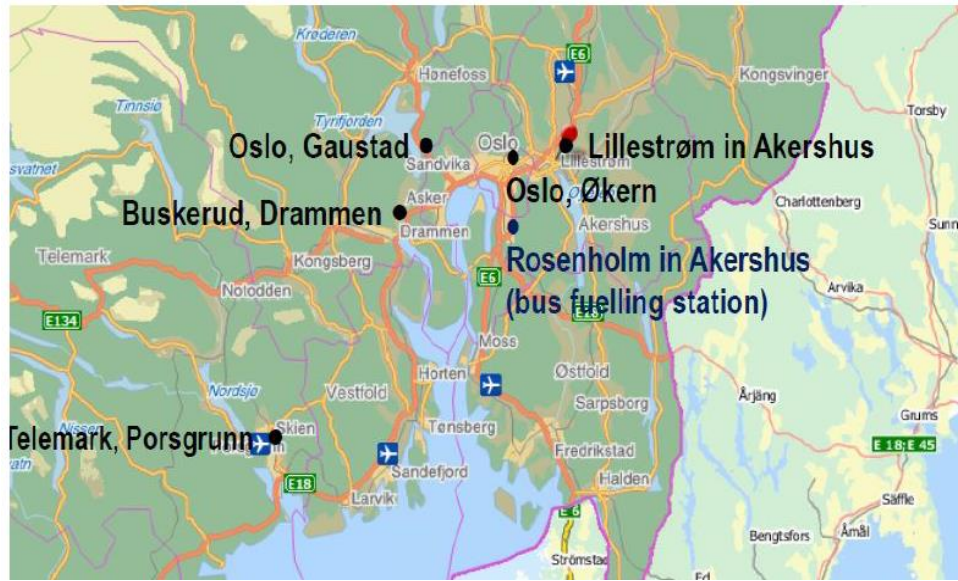
Figure 4.3. Hydrogen refueling stations in service by year 2014 in Norway. Source: Scordato and Klitkou, 2014.

In the following, two recent efforts towards the commercialization of hydrogen are presented; the hydrogen service station launched in Gardemoen Oslo airport in 2015 and the latest one in Oslo just in last December (2016).

4.1.4. Commercialization of hydrogen- Extending the network

- Oslo airport (Gardemoen)

As a part of the regional strategy adopted in Akershus and Oslo counties for the early introduction of hydrogen, the two partners; private sector and state, through funding from both the former and the state-owned organization Enova are cooperating to develop an HRS network comprising of 6 stations located in the wider Akershus and Oslo region, by year 2018 and extending this to 12 HRS by 2025. The goal is that, besides the current number of filling stations in service being sufficient for the number of FCEVs mobilized in region, the HRS network capacity should be at least two years ahead of vehicle deployment (Hvoslef and Salvesen, 2015). Furthermore, commercialized hydrogen should be produced locally based on on-site electrolysis instead of industrially produced and trucked in (the station).

Already the service station in Drammen, based on shipped-in hydrogen, has been transferred to

- Owner and operator of four hydrogen stations in Eastern Norway
- Operating agent for the HyNor Lillestrøm station

Porsgrunn
In operation since 2007
Capacity 130 kg/day
350 bar car/bus
700 bar

Oslo - Økern
In operation since 2009
Capacity 20 kg/day
700 bar

Oslo - Gaustad
In operation since 2011
Capacity 20 kg/day
700 bar

Figure 4.4. Current HYOP service network in Eastern Norway, source: HYOP, 2014

the Oslo airport Gardemoen (September 2015), serving thus both the airport needs and the transport connected to the airport as well as the highway E6 (Hvoslef and Salvesen, 2015). The latter relocation project has been a collaboration between Akershus County Council, Avinor and Lillestrøm Centre of Expertise.

- Kjørbo hydrogen service station

The source of information of the following section is the webpage of NEL company which is a hydrogen technology manufacturer company (NEL, 2016). Kjørbo service station is located in the homonymous region in the entrance to Oslo from the South, where an inclusive public transport / FCEV lane starts.

Technology provided and source of hydrogen

The H2Station® technology provided by Nel-Hydrogen makes it feasible to achieve an integrated solution applicable also in existing gas station infrastructure. Compared to a conventional fuel dispenser, the hydrogen dispenser produces only 1/3 of the footprint, allowing thus the latter to be placed next to the conventional gasoline and up to 50m distance, as it is integrated in the specific station.

During spring 2017, it is awaited a pressurized electrolyzer supplied by NEL Hydrogen to be installed supplying the station with green hydrogen from PV solar power produced in the

neighboring powerplant of Kjørbo. In specific the latter powerhouse uses solar panels with efficiency up to 200 000 kWh each year, twice the amount of the building's annual energy consumption, and the surplus of energy is planned to be utilized by the integrated HRS.

The station integrates fast fueling of long range FCEVs and high storage capacity, competing gas in that context. It must be stated that it exhibits the highest currently capacity achieved in Hydrogen service station in the country.

Operators and funding

The station is operated by Uno-X hydrogen, a joint venture between (i) Uno-X; (ii) the gas company Praxair and (iii) NEL Hydrogen, as the technology developer. The hydrogen station is financially supported by the County of Akershus and the state funding program Enova.

The service station network that has been established since 2003, have been summarized in table 3. Two of them are no longer in service, either because they were shut down or relocated. Yet we are concerned about the coming development. In the following we present some incentives, still in a rough level, for future development of the existing network.

4.1.3. Future expansion of the HRS network

- H2 Locic

Two (more) new-generation hydrogen service stations are planned according to the company; H2Logic, to be delivered in service in Bergen, the first one in the second quarter of 2017. 20 hydrogen fueling stations in total are planned to be delivered in public use by year 2020 in Norway. This venture is going to be based on the relevant experience from a similar network deployed in Denmark. The network is planned to comprise both green field stations and integrated hydrogen stations into conventional gas filling stations (Fuel Cells Works, 2015).

- HYOP

The company was planning on a 5th HRS in Skedsmo region, by the E6 at Hvam, near Olavsgård during the start of 2017. Among the company's goals is to transfer their service stations in new locations and increase their capacity introducing high pressure tanks and compressors (Innovasjon, 2016) In specific there had been the established goal to relocate the Økern service station to Høvik by the E18 motorway in Bærum and the Gaustad service station to Ryen during 2016. However, these service stations are not yet developed/relocated.

Hydrogen Infrastructure; Refueling stations in Norway					
Location	**Project under which it was developed**	**HRS developed/ build by**	**Operated by**	**In operation since**	**Source of H2: technology facilitated**
Kjørbo	-	joint venture between • NEL and • UNO-X-Hydrogen AS	UNO-X-Hydrogen AS	November 2016	*On site* electrolysis production based on local solar energy (from the surplus of the neighboring powerplant)
Oslo Airport (Gardemoem)	-		HYOP	May 2015	n/a
Rosenholm Bus station in Akershus *bus-only fueling**	**CHIC**	Air-Liquide Norway	Air-Liquide Norway	May 2012	Electrolysis *on site* from renewable energy; 2 electrolyzers in containers, each 60 Nm3/h
Lillestrøm, *Kjeller1213* (Akershus Energy Park)	**HyNor Lillestrøm**	H2-logic A/S	• HyNOr Lillestrøm AS, • HYOP as operating agent	June 2012	• *On site* electrolysis from PV solar energy and • landfill gas reforming
Gaustad567	**H2moves Oslo** (part of the project **H2moves Scandinavia**)		H2 Logic *(initially)* HYOP *(current status)*	November 2011	• Electrolysis *on site* • Capability of *trucked-in* hydrogen
Drammen, Oslo *Kjellstad1011*	**HyNor**		HYOP	May 2009-2015; moved to ***Oslo airport Gardemoen***)	*Trucked-in* Hydrogen produced from bio-waste reforming
Oslo HyNor, *Økern34*	**HyNor**		HYOP	May 2009	*Trucked-in* hydrogen from electrolysis
Porsgrunn	**HyNor**		HYOP	June 2007	H_2 *byproduct from chlorine production*

Hydrogen Infrastructure; Refueling stations in Norway					
Location	**Project under which it was developed**	**HRS developed/ build by**	**Operated by**	**In operation since**	**Source of H2: technology facilitated**
Stavanger, *Forus*	**HyNor**		STATOIL-HYDRO	October 2006-December 2011; shut down	*trucked in* CGH2

Table 3. Hydrogen service stations in Norway, based on Scordato and Klitkou, 2014

We note that in red indication are labelled those refuelling stations that are no longer in service.

4.2. Initiatives in planning and permitting procedures

As derives from the previous section, the HRS network has been showing signs of expansion. Yet, in order to facilitate the transition from a research scale to the commercialization of hydrogen and adoption of the latter as a transport energy carrier, besides the presence of available robust network, it is critical that HRS exhibit safety levels, at least as high as those anticipated in conventional petrol stations. Therefore, planning and permitting procedures for the establishment of HRS assuring safety, should be developed. The first initiatives were developed under two European projects, and are presented in the following.

4.2.1. HyApproval project

HyApproval was a project financed under Framework Program 6 by the European Commission, running between years 2005 and 2007. The main objective has been to develop a 'handbook for the approval of hydrogen refueling stations' to be used for the certification of such stations in Europe.

The project identified and placed special focus on three levels of safety assurance. These were: (i) to prevent accidents, by applying BAT, following technical specification standards currently available and formatting handling procedures for operators and customers/users; (ii) to develop mitigation strategies such as the enforcement of safety distances; and (iii) also develop some form of emergency response planning. A start for the harmonization of the currently available planning procedures for HRS's had been set. Yet, hydrogen related statistics were lacking, and education and training related to handling hydrogen was still in premature level (Backhaus and Bunzeck, 2010).

4.2.2. HySafe project

A joint venture sponsored by the European Commission consisting of 24 partners; representing research institutes including universities, and industry. The project established a set of goals, among which was to develop and validate methodologies with respect to risk assessment in hydrogen applications and develop RAC and methodologies for risk informed safety distance determination procedures. Among the project's objectives has also been to acquire and build a better understanding of the relevant phenomena governing hydrogen's behavior, developing and validating models approaching those phenomena; dispersion simulations, combustion and explosion modelling, given a poor understanding on those. Other goals are summarized in training and assisting authorities and private parties on hydrogen safety aspects, from production to large scale adoption and use. The project run between March 20004 and February 2009. At the end of the project still the produced risk assessment methodologies needed refinement. Additional criteria in designing garages, including ventilation requirements, needed to be formed, as well as criteria for parking hydrogen powered cars in confined areas (Backhaus and Bunzeck, 2010).

4.3.   ISO TS 19880-1: 2016. Gaseous hydrogen refueling stations

This section reviews ISO TS 19880-1 which constitutes a guidance tool in planning and permitting procedures for gaseous hydrogen refueling stations, and replaces the previous version: ISO/TS 20100: 2008.

4.3.1. Scope and limitations

ISO/TS 19880-1:2016 provides guidance related to safety and performance aspects of gaseous refueling stations and recommends minimum design characteristics applying in the former. The document describes requirements with respect to the fueling procedure of light duty (land) vehicles; for instance, FCEV and can be used as a guidance tool, for vehicles bearing hydrogen storage capacities beyond the capacity of current fueling protocols such as SAEJ2601 integrated in ISO (2016); see for instance fueling of buses and trams (ISO, 2016).

The recommendations provided apply to both inclusive hydrogen refueling stations and integrated ones; facilities dispensing hydrogen, integrated into conventional gas fueling stations, existing or new ones (ISO, 2016), under public or private ownership.

As per ISO/TS 19880-1 (2016) 'risk assessment is the overall process of risk identification, risk analysis, risk evaluation and *risk mitigation.* Risks can be assessed at an organizational level, a departmental level, for projects, individual activities or specific risks'. The former according to

the specifications has to be performed in line with ISO 31000; Risk Management-Principles and guidelines or IEC 31010; Risk Management-Risk assessment techniques (2009) and/or ISO 12100 (2016).

Figure 4.5. presents the risk management process and the contribution of risk assessment in the latter, culled from ISO 31000 (2009).
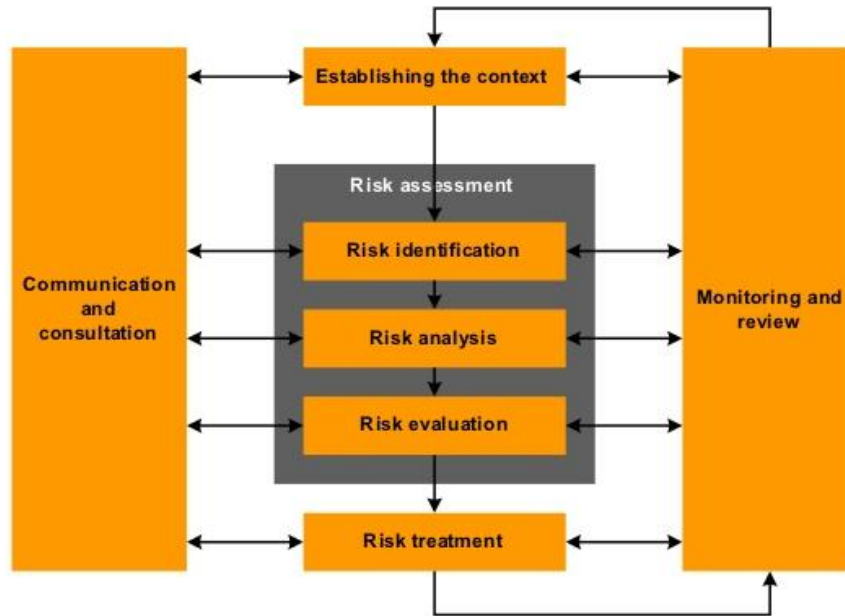
Figure 4.5. Contribution of risk assessment to the risk management process, source: ISO 31000; Risk management- Principles and guidelines, 2009.

According to Purdy (2010) ISO 31000: Risk Management-Principles and Guidelines, defines the following three steps of the risk assessment process:

- **Risk identification** i.e. the structured process of understanding the system under consideration, identifying what could happen, and under what conditions, meaning 'why' 'how' and 'when' with respect to internal or external to the system hazards.
- **Risk analysis:** Each identified risk in the previous step is handled such that a thorough understanding of it and a full development of its sequences and the associated consequences is performed and likelihood of the scenarios and their consequences is estimated/assessed. An important aspect in risk analysis is enabling confidence in the estimated risk levels, and therefore, assessing the *sensitivity* of the results to altered conditions and assumptions cannot be seen in isolation to this part.
- **Risk evaluation** involves the establishment of the risk picture and a comparison of the calculated risk levels with a set of criteria, i.e. criteria prescribed by regulations and/or defined when the context is established. The risk is either found within the acceptable limits, or given their exceedance a decision over the prioritization for attention has to be reached.

According to ISO 31000 *risk treatment* extends beyond the risk assessment process. According to this step, if the risk levels were found unacceptable, risk treatment calls for the establishment of new measures or the improvement of existing ones, assessing their impact on risk levels. Therefore, involves decision making with respect to the implementation of risk reducing measures, and prioritization over the latter. Typical forms of risk treatment, depending on the application context may be:

i. Risk avoidance i.e. stopping the activity giving rise to the risk, or deciding not to proceed to the activity
ii. Risk source removal
iii. Retaining risk by applying risk informed decisions, and more.

The latter; (iii), is the main line followed as per ISO T/S: 19880 (2016).

At this point we need to highlight an inconsistency of ISO/TS:19880-1(2016). According to this documentation, risk assessment is to be conducted as per IEC/ 31000 (2009), and whereas the latter distinguishes between risk assessment and risk treatment, the former incorporates risk treatment, under the clause risk mitigations, in the overall risk assessment process. We recall the definition of risk assessment as per ISO/TS:19880-1(2016) quoted in the beginning of this section. However, given the high level of iteration between the steps of risk analysis, and more specific those of risk evaluation and risk treatment (Purdy, 2010), this note is not of critical importance. In specific, risk treatment step defines a set of risk treatment options, additional to the base case established in the risk analysis, and a new loop is generated; the risk levels given the set of measures under consideration are re-established and they are projected against the risk acceptance criteria. The process is repeated until the preferred set, in terms of benefits against costs, is found (Purdy, 2010). As Haimes (2004) also expresses, whereas risk assessment differentiates to risk management, significant overlaps between exist.

The rest of the chapter is based on ISO/TS 19880-1:(2016) and therefore this document is primarily the source of the information presented.

4.3.2. Integrated processes and HRS representative units

Several streams of hydrogen production there currently exist; Appendix A demonstrates the dominant forms of hydrogeneration to date. ISO/TS 19880-1: applies in hydrogen refueling stations that may either produce hydrogen on-site, or supply on it. The main objective of on-site hydrogen production is reducing storage required on-site and restricting the bulk truck delivery of hydrogen, as well as the hazards stemming from the later (HyApproval WP2, 2008). Two technologies are currently in use for on-site production: water electrolysis and steam-reforming.

As per Godola-Jopek et al., (2012) main keys to the operation of a filling station is the technology facilitated for *the hydrogen storage on* one hand and the options for *producing hydrogen on site* on the other; where this is applicable. According to same authors, filling stations are designed such that integrate the storage of hydrogen in the liquid and gaseous state; at a cryogenic liquid state and deep temperatures, i.e. -253C, and compressed gaseous hydrogen respectively (Godula-Jopek et al., 2012, HyApproval WP2, 2008). Then under a relatively easy processing, hydrogen can be converted from liquid to gaseous state enabling thus high-pressure storage and dispensing hydrogen to cars and vehicles.
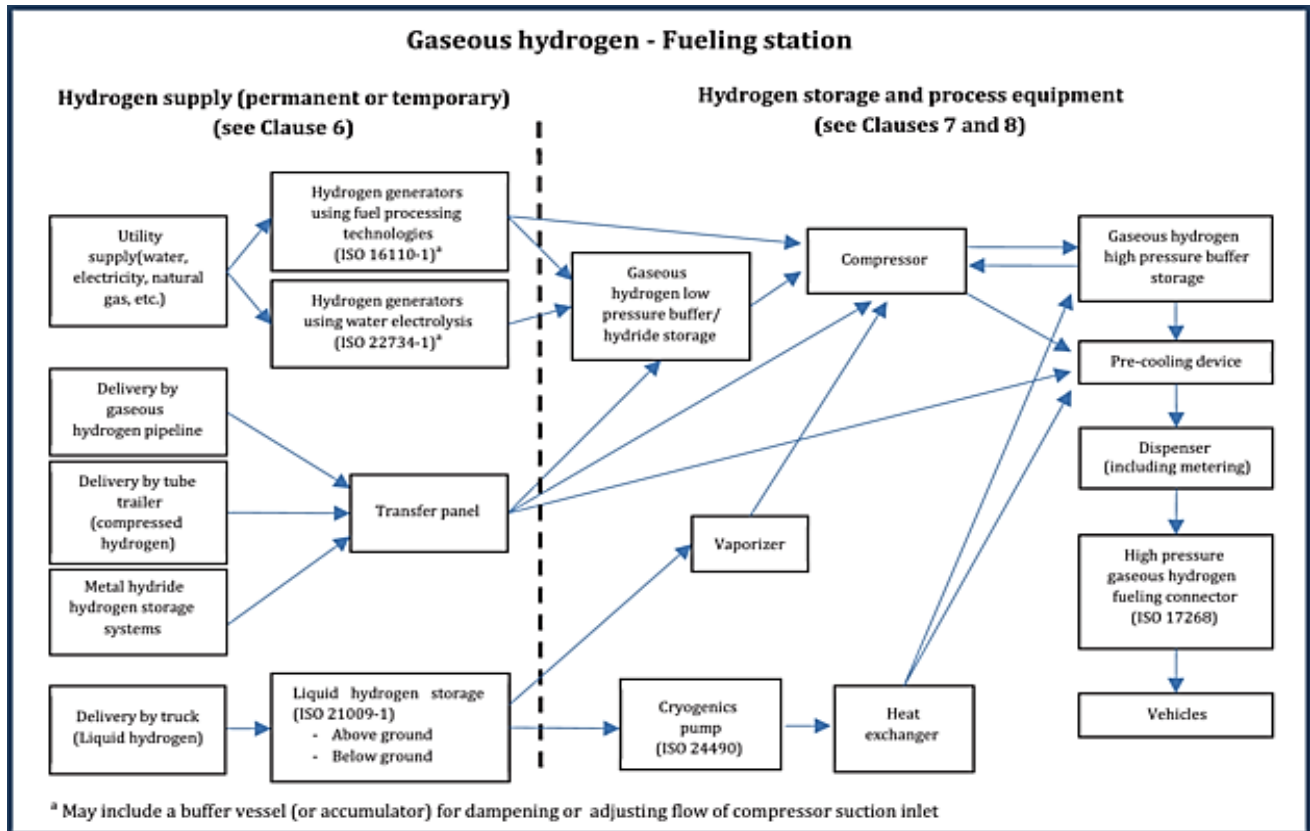
Figure 4.6. Flowchart presenting typical elements of a hydrogen refueling station, including the hydrogen supply, source: ISO/TS 19880-1:2016

Analogously, ISO/TS 19880-1:2016 provides guidance to gaseous hydrogen refueling stations, dispensing compressed gaseous hydrogen and bearing one of the following streams of production and/or supplies, as well as compression and storage technology options; see also figure 4.6.

1. **Supply on hydrogen**
   - Liquefied hydrogen LH2 by truck/ road tanker. The LH2 is then stored either above or below ground.
   - Gaseous hydrogen GH2 by pipelines

- Gaseous hydrogen GH2 by tube trailers (compressed hydrogen) ok
- Metal hydride storage systems

2. On site production
- *Utility supplies* for onsite production based on either
    - fuel processing technologies or
    - water electrolysis

With respect to **process and storage of hydrogen** the HRS comprises the following elements:

3. Hydrogen purification systems, where applicable
4. Storage technologies:
- compressed hydrogen (CHH2) storage
- liquid hydrogen (LH2) storage

Depending on the type of storage technology applied, typical representative components are compressors, storage vessels and dispensers equipped with filling nozzles; applying in compressed hydrogen storage options, and cryogenic vessels, cryogenic pumps pressurizing the liquid, vaporizers and dispensers; when liquid storage options are enabled respectively (Moonis et al., 2010).

Figure 4.6 summarizes the full set of interacting processes relevant to a hydrogen refueling station, including dispensing hydrogen in the vehicles.

5. Dispensing

A connector between the fuel dispensing system and the vehicle, i.e. a nozzle, permits a quick filling process. The latter is done automatically, while the two components are connected, and the only manual operation done is the connection and disconnection of the nozzle. With respect to the gaseous hydrogen fueling of the vehicle, 3 technology options are available (HyAppproval WP2, 2008);

   i. Pressure difference from a gaseous pressure vessel, i.e. tube trailer or cylinder pack.
  ii. Compressing hydrogen from a low-pressure source i.e. hydrogen delivered in tube trailers, or produced on site, and leveling between the high-pressure buffer storage and the vehicle
 iii. Compressing hydrogen directly from a low-pressure source without gaseous buffer storage
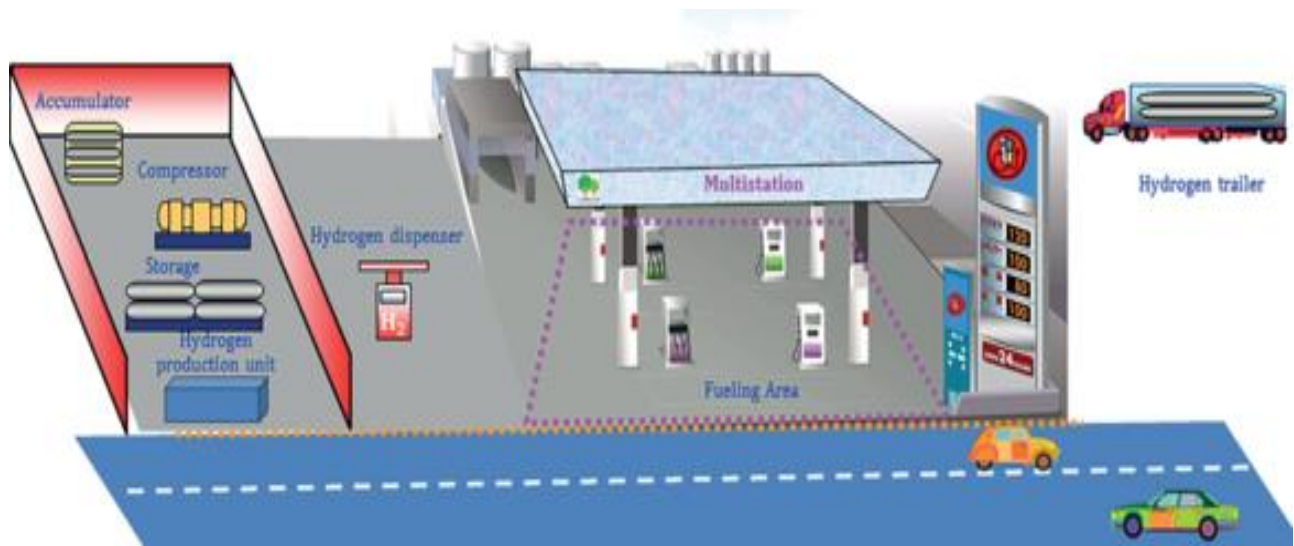
Figure 4.7. Typical layout of a hydrogen refueling station, source: ISO/TS 19880-1:2016

At this point we need to differentiate between the regulations for the entire system and the regulations providing guidance for each system's part. Figure 4.6. indicates the related cross references.

4.3.3. Terms and definitions in ISO/TS 19880-1:2016

Before proceeding to the (semi) quantitative risk assessment methodology, it is of importance to introduce the readers to the definition of basic terms invoked in the analysis. According to the list of terms and definitions as per ISO/TS 19880-1 (2016):

   i.   **Risk** is defined as the combination of probability of occurrence of a harm and the severity of the latter; incorporating in the definition also the uncertainty what those consequences and their severity will be. We note that as per ISO/TS 19880-1:2016, this uncertainty is principally expressed by probability.
   ii.   **Risk level**: the magnitude of risk as assessed.
  iii.   **Risk acceptance criteria**: terms with respect to which the significance of risk is assessed, i.e. acceptable or non-acceptable.
   iv.   **Probability**: an expression of the likelihood /chance that a specified (initiating) event will take place to an asset, human; users and operating personnel, or the environment.
   v.   **Frequency**: rate of occurrence of an event; defined as a fraction of times the considered event takes place in a set of repetitions or in a specified period.
   vi.   **Mitigations**: the combination of measures established during design and measures implemented during operation and/or maintenance by the station operator, the dispenser

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operator as well as whoever is involved in the operation and maintenance of the filling station and its components.

As per the specification the term encompasses any action taken to increase the overall system safety making special reference to the effect of mitigations in safety distances determination. The latter implies that mitigations may be implemented under a risk informed approach to decrease safety distances.

vii.   **Safety distance**: the minimum risk informed distance between a hazard source and a target, mitigating thus the effect of a likely foreseeable incident, or preventing this (minor) incident from escalating into a greater one incident or accident. The term target may refer to human, equipment, constructions or the environment.

The document discerns between; restriction distances, installation layout distances, protection and clearance distances, and external risk zones.

viii.   **Safety function:** function performed by a control or safety system aiming to achieve and maintain a specific safety state (during process/operation). A safety function is realized with respect to a specific hazardous situation (also hazards).

Hazardous situations		
Hydrogen releases		
Fires, deflagrations, denotations, blast waves		
Hazards of asphyxiation conditional on hydrogen and inert gases' releases in confined spaces		
Pressure impact and /or debris		
Cryogenic burns		
Additional hazards also included are:	i)	Electrocution hazards
	ii)	Hazards derived from working at heights
	iii)	Hazards of injuries while moving equipment

Table 4. Hazards applying in gaseous hydrogen refueling stations, based on ISO/TS 19880-1:2016.

Such situations applying in gaseous hydrogen refueling stations are, hydrogen releases and conditional ignition, thermal effects such as straight conduct to flames or radiation from the latter, or gases sourcing of the latter, as well as deflagrations and denotations with their blast effects, i.e. overpressure and impulse (ISO, 2016), but may also include mechanical impact, such as collisions or falling objects. Table 4. presents hazardous situations relevant for a gaseous HRS as per the discussed documentation.

Before we proceed to the methodology as per ISO/TS 19880, let us first define and distinguish between the following two terms: semi-quantitative risk assessment and quantitative risk assessment. Depending on how consequences and the associated likelihoods are assessed when conducting a risk assessment, the form may be, qualitative, semi-quantitative, or quantitative. For the needs of the subsequent analysis, we define only the latter two terms (ISO, 2016):

ix. **Semi quantitative risk assessment**: according to which either consequences are expressed numerically using models and simulations and their likelihood is expressed qualitatively (e.g. consequences only modelling) or the opposite.

x. **Quantitative risk assessment**: according to which both consequences and likelihood are expressed in a quantitative way, meaning that detailed data and models are used to express them; calculated risk levels are expressed in terms of quantified consequences and probabilities of occurrence.

4.3.4. Methodology of quantitative risk assessment

It may be possible to conduct a quantitative risk assessment in order to permit the HRS to use alternative design solutions to the prescribed given that they provide at least same safety levels as the prescribed configurations do, or to allow for shorter safety distances and/or a simplified station layout by applying relevant mitigations (ISO, 2016).

Methodology is based on a combination of deterministic and probabilistic models evaluating potential consequences of hazardous situations and exposure scenarios with respect to the targets identified when the context is established (ISO, 2016).

The analysis steps are the following (ISO, 2016):

1. The **context is established**, meaning that:
    i. *The system is defined:* The system and the HRS layout with specified design/ size details including the mitigations introduced during design, as well as the events they mitigate, are documented. In specific the system is broken down in its operational environments, if more than one exists, and for each one all components and their functions are identified.
    ii. *Target determination:* The targets being protected are defined; the hazards with respect to which they are protected against are defined too.
    iii. *Analysis scoping:* Tolerability criteria, either defined as per analysis, specified as per protected target, or they are prescribed by regulatory requirements (with respect to target and hazard category also) and defined in relation to the country of interest too.

A (best) practice when establishing tolerability limits is that given their reinforcement they assure at least the same or lower risk levels than achieved in similar applications; see for instance fueling petrol/ gas stations (ISO, 2016).

Acceptance criteria should be specified. They may vary in their form and thus single values, probability distributions, intervals or cost benefit analysis with respect to the different alternatives, may be used.

For personnel risk or risk applying to human; users and external public, FAR, AIR, PLL values or F-N curves may be used. Other risk acceptance criteria may cover average number of hydrogen releases or number of fire scenarios per system/year, or harm criteria such as specified gas concentration, heat flux levels, peak overpressure values and more.

2. **Hazard Identification** as per ISO (2009) seems to be covered under this document by the systems definition and target determination step.

As presented in the previous section there is a list of defined situations of hazard and accident applying in gaseous HRS; covering *primary hazards* such as H2 releases and subsequent ignitions and *secondary hazards* such as thermal and blast effects outcoming of the previous. At this stage, every target is defined and the relevant hazards to the former targets are identified.

3. **Risk assessment**: integrates the cause and consequences models and assesses the total risk, projecting this against the tolerability limits defined when the context is established

4. **Risk informed mitigations** are implemented or new ones are developed such that the assessed risk level falls within the tolerability limits. The step should account for the introduced uncertainties as well.

Mitigations are applied to reduce prescribed safety distances; following a risk informed safety distance process, or to relax predefined mitigation measures, by conducting a (semi) quantitative risk assessment. Yet, as perceived from the documentation, although it is not directly quoted, safety distances are on their own a form of mitigation; imposed to prevent the initiating event i.e. a hazard from occurring or escalation of the former, i.e. it is the minimum distance to prevent or minimize the exposure of the specified target. In ISO/TS 19880-1: 2016, five types of safety distances are defined; restriction distances, installation layout distances, protection and clearance distances, and external risk zones. Other documents may refer to restriction distances as hazardous areas, or hazardous zones. Appendix B2 provides information on the defined hazards and targets applying to each type of distance. For further definitions on the former and safety distances prescriptions as per countries, see also ISO/TS 19880-1:2016, Annex A.

IEC 31010 (2009) that ISO/TS is based upon with respect to Risk Assessment, makes special reference to the effect of uncertainties in the risk analysis results. An understanding of the uncertainties introduced through data, methods and models is critical to the interpretation of risk levels and communication of the latter to involved stakeholders. According to same documentation (IEC, 2009);

uncertainty analysis determines the imprecision in the results due to variation in the parameters and the assumptions incorporated in the risk analysis, and therefore sources introducing uncertainty should be recognized and stated; data and models among them.

sensitivity analysis assesses the impact of altered input parameters in the magnitude of risk. It is used to identify those input parameters to which the analysis is more sensitive, and thus those parameters having more effect in the overall accuracy.

In the following we focus purely in the risk assessment process as per ISO/TS 19880-1:(2016), once the context has been established and the acceptance criteria have been defined. For sake of completeness though, risk treatment is briefly described as per ISO/TS 19880-1: 2016.

3. **Risk Assessment**:

Cause analysis providing insights in the root causes of hazardous situations and their likelihood, the latter assessed mainly qualitatively. Relevant exposure scenarios are defined, and in a subsequent level quantified in terms of probabilities of occurrence, without neglecting the uncertainty about this probability.

Two critical concerns apply; exposure scenarios to be fully defined on one hand and data resources demand for their quantification, on the other.

i. *Exposure scenarios*: With respect to the generation of those, simulation models are utilized and ETA, Event Sequences Diagrams or fault expressions are used for the graphical documentation of the former.
   With respect to the root causes they are either listed or approached and documented through fault expressions or fault trees applying a top down approach.

ii. *Sufficient and reliable data* should be available for the exposure scenarios quantification.

Note: with respect to the criterion for reliable data; it may be possible as per ISO/TS 19880 that non-published or non-hydrogen specific data are used in quantification of the exposure scenarios. It then should be made available to any scrutiny requests, and communicated properly, analogously to the suggestion of IEC 31010 with respect to handling and communicating uncertainties.

Consequences analysis*: determining the physical effects; thermal and pressure effects of the exposure scenarios and translating those effects into harm to targets, i.e. harm modelling.

i. **Physical effects**. This step requires modelling of the relevant physical effects. Input at this step are hydrogen release characteristics, causal relations, ignition sources; the latter are listed and their location is specified, and thermodynamic parameters. The models used should be validated for use in specified applications on hydrogen and within the expected ranges.

In specific this step requires:

- *Modelling of hydrogen releases and the extent of flammable envelope* i.e. dispersion calculations and establishment of ignition probabilities. Ignition should be divided at a minimum to immediate and delayed ignition.
Dispersion calculations/ numerical simulations are typically used to link the different release frequencies to the stoichiometric clouds, conditional on the ignition potential probabilities. The latter probabilities of the different stoichiometric clouds, combined with explosion simulations, are used to estimate the explosion risk (Hansen and Middha, 2007).

Note: nozzle models as per se are used for calculation of the releases' thermodynamic parameters

- *Jet flame behavior*, i.e. fire modelling. The event under consideration is an instantaneous ignition giving rise to jet fires. Parameters to be specified are: flame length, width or heat flux, ignition source location.

Note: the location where each of the former characteristics is calculated should be defined in the analysis.

- *Deflagration and denotation behavior*, i.e. explosion modelling; non-ignited releases may be accumulated leading to a delayed ignition producing flash fires, blast or vapor cloud explosions. This type of ignition is coupled with thermal and pressure effects. Factors affecting the overpressure originating from these types of sequences is the turbulence generated and contributing factors to the latter may be high congestion due to presence of obstacles

Note: CFD models, empirical or phenomenological models may be utilized, under the constraint that these models are validated as well.

A number of assumptions, regarding the ignition potential; i.e. spontaneous ignition, internment and continuous ignitions sources, and how these probabilities are influenced by the imposed detection/shut down systems are part of this modelling process (Hansen and Middha, 2007).

ii. **Harm models** or **harm criteria**. translating the physical phenomena's effects calculated in the previous step into harm to humans, assets or the environment, i.e. assessing the impact on the targets defined. Probabilistic or deterministic models may be facilitated, as well as probit functions or criteria. All the above should be named in the analysis.

Establishing the risk picture. Risk is described as a combination of the frequency f_i of a specified scenario and the consequences of the latter. Then, the total risk arrives as the sum over individual risks R_i computed respectively as the product of *potential loss* and the *associated probabilities,* i.e. as expected values:

$$Risk = \sum_{i=1}^{n}(f_i * C_i)$$

Where: f_i is the probability associated with the i_{th} scenario, derived as a frequency and *Ci* the associated consequences.

Figure 4.8. provides an example of a risk informed approach with respect to safety distances determination according to the methodology.

4. Risk treatment

We just refer to the possible mitigations described as per ISO/TS 19880-1:2016 as risk informed mitigations. They contribute to the risk treatment step extending beyond risk assessment. These are:

- Mitigation measures to improve safety
- Mitigation measures reducing the potential for the formation of a flammable or explosive mixture.
- Mitigations reducing the ignition potential
- Mitigations preventing escalations, e.g.:
    - mitigations of escalations and their impacts; fire and/or explosion originating from the fueling station, or
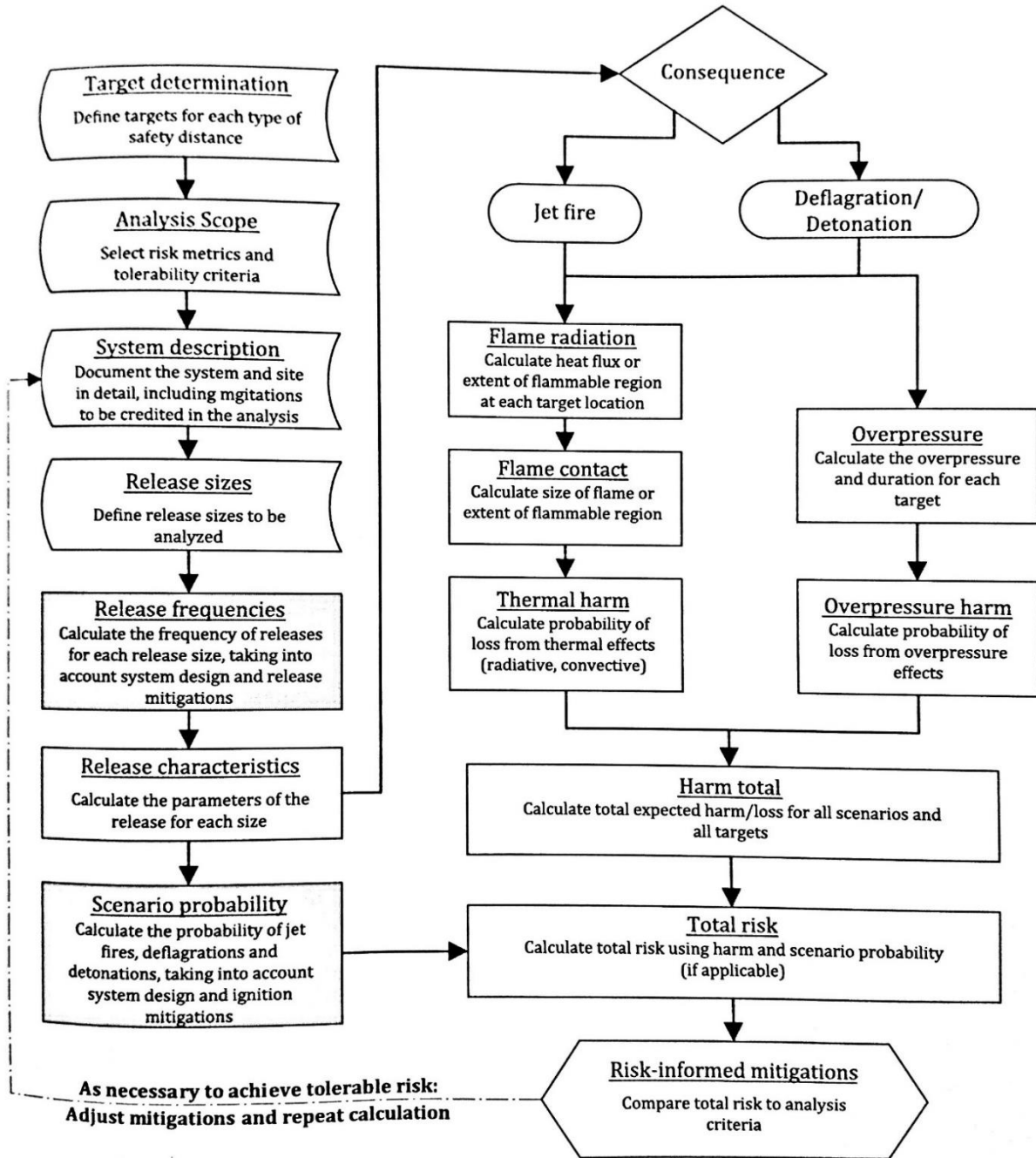   - Mitigations reducing the effect of an external to the fueling station fire/explosion event

Figure 4.8. Example of risk informed approach to safety distances, source: ISO/TS 19880-1:2016

4.4. Limitations applying in ISO/TS 19880-1: 2016

ISO/TS 19880-1:2016 represents an example of traditional risk assessment thinking, aligned to the perspective adopted for years in most engineering contexts. Yet, in the light of the analysis so far, when performing a QRA the analysis team is in need of data, models and sufficient statistics. Conditioned in the presence of the former, the ISO framework manages or fails to capture accurately the risk elements, and produce robust risk recommendations, when it comes to the design and operation of an HRS. This section aims to reflect on the presence of this input, and conditioned on the latter to evaluate the confidence that we can place in the produced recommendations following the ISO - QRA methodology.

4.4.1. Input to analysis- availability of data

During the consequences modeling according to methodology the following input data are required at a minimum:
  (i)   release characteristics
  (ii)   ignition probabilities
  (iii)   explosion probabilities
For harm calculations, we also need population data. such as private cars currently using hydrogen, number of refueling station/years, pipeline kilometer/years and more.

Adjusted or generic data, may be utilized when hydrogen specific data are missing, see Haugom and Friis-Hansen, 2011; Ham et al.,2011. ISO (2016) defines that such non-hydrogen specific data may be utilized, as long as this is reported and the data are made available to any scrutiny requests. Leak frequencies may for instance derive from hydrocarbon systems, as has been attempted in several QRAs conducted within European projects launched for the introduction and safety demonstration of hydrogen. However, the failure rates in hydrocarbon systems, are considerably different than those anticipated in hydrogen (Moonis et al., 2010). As Zhiyong et al. (2011) mention, in hydrogen refueling stations new components, such as hydrogen dispensers are introduced, or well-established ones; pipework for instance, applied though in a new setting, and therefore those generic data may introduce significant uncertainties. However, in the absence of specific data we need to rely on generic statistics. In such cases modification factors or a Bayesian approach to estimate weighted factors may be used, requiring though several modification factors to be estimated for the different pressure and state conditions of hydrogen (Moonis et al., 2010).

According to the framework (ISO, 2016), *sufficient* and *reliable data* should be utilized. Yet, an official database where all incident and accident statistics are held is in its early stages, we refer to the Hydrogen Incident and Accident Database; HIAD established during the HySafe European project (Funnemark and Engebø, 2005). Databases keeping hydrogen related data may already

exist but they are not exclusively hydrogen related, and therefore modification factors or the Bayesian approach as described above need to be applied. Some hydrogen supplier companies have also started collecting hydrogen statistics; we refer to the European Industrial Gases Association for instance, known under the acronym EIGA, but neither EIGA or the participant companies have been part of the hydrogen related European programs and therefore we are concerned whether such data should be made available or restricted to commercial use instead. It has been suggested that leak frequencies may derive from other industries using or processing hydrogen, nuclear industry for instance. With respect to the latter industry though, leak frequencies are available at limited extent as well (Moonis et al., 2010).

4.4.2. Consequences analysis

An important issue at this step, is the presence of models producing reliable results. With respect to this, we discern two dimensions, the level of understanding of those phenomena governing hydrogen dispersion and reactive behavior but also the ability of models to capture that behavior. An additional dimension in this respect though *is the validation of models* in the specific applications and expected ranges*, as ISO/TS 19880-1:2016 also highlights.

- Hydrogen safety aspects

Although hydrogen risk assessment handles established hazards, i.e. gaseous releases and conditional ignition, fire or explosion scenarios, i.e. phenomena analogously anticipated in other industries, yet hydrogen is quite new to our experience exhibiting a different reactive behavior than this of well defined by now hazardous materials. Compared to other fuels, including the natural gas and LPG, hydrogen exhibits a highly reactive behavior, that can be summarized in a wide range of flammability limits, extreme burning velocities and high combustion energy releases (HyApproval WP2, 2008; Hansen and Middha,2007). Figures 4.9-4.11 provide an illustration of these extreme characteristics. Yet, hydrogen being the lighter element, lighter than air disperses very quickly, and therefore in unconfined areas, no accumulation takes place, and the related risk is low. However, when considering the ignition energy, lower ignition energy is required for hydrogen to ignite, and given the latter event, the energy release is considerably high. Therefore, the risk comes through combustion i.e. in fire and explosion scenarios (HyApproval WP2, 2008). This quite different behavior creates concerns about the applicability of models and methodologies used in other hazardous industries; typically the petroleum industry, in hydrogen applications as well.
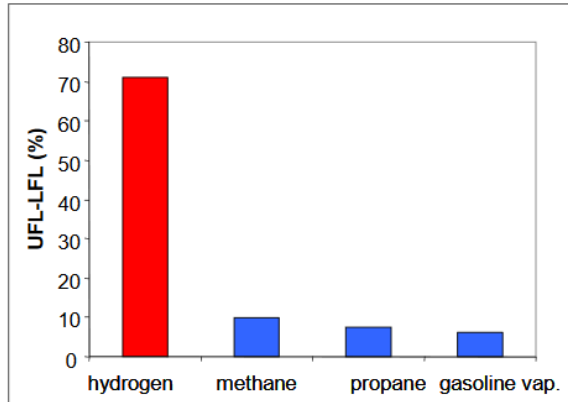
Figure 4.9. Flammability range of hydrogen Vs other fuels, source: HyApproval WP2, 2008
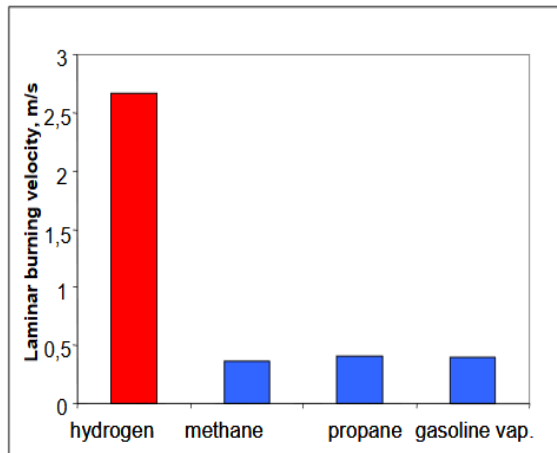

Figure 4.10. Laminar burning velocity at stoichiometric ratio of hydrogen Vs. other fuels, source: HyApproval WP2, 2008
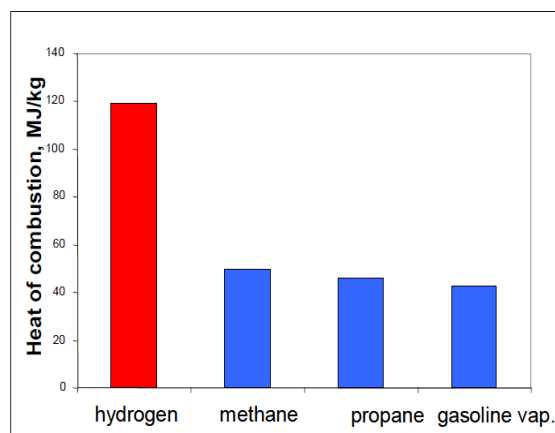

Figure 4.11. Combustion heat release of hydrogen Vs. other common fuels, source: HyApproval WP2, 2008

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- Models and methods used

Due to increased burning velocities; up to one order of magnitude higher than the respective of natural gas (Ham et al., 2011), hydrogen tends to denotate rather than deflagrate. The simplistic models developed for hydrocarbon uses though, fail in considering transition to denotation whereas even more comprehensive ones, see SCOPE for instance, considering also congestion parameters, have weaknesses in modeling flame acceleration, and fairly describe denotation or transition of deflagrations to denotations. CFD software packages can handle this transitional behavior from denotations to deflagrations quite satisfactorily (Moonis et al., 2010). Yet when it comes to predicting hydrogen's buoyancy and the relevant dispersion calculations, the latter models do not seem to provide satisfactory results or any better than the analytical ones do (Ham et al., 2011). A wide variety of models is available, yet, their precision is dependent on certain conditions; short/long distance from the leak source, confined/unconfined areas and so on. As a benchmarking exercise on QRA methodologies for HRS has also proven; see Ham et al., (2011), dependent on the models utilized and the assumptions incorporated, the results of the consequences modelling can be considerable different. The concern therefore remains. The models and methods available are not known to provide reliable results, and they are highly dependent on the assumptions taken.

In many cases such models may also facilitate hydrocarbons or mixtures of hydrogen-hydrocarbons ignoring the different reactive behavior that hydrogen exhibits, or they may not be validated yet for the specific applications (Moonis et al., 2010). Considerable work should be done to develop and validate those models against experimental data (Moonis et al., 2010, Ham et al., 2011). Moreover, little guidance on the use of methods applied in natural gas risk assessment, is provided when it comes to hydrogen. We refer for instance to the TNO Multi Energy Method, where suggested blast values are provided only for hydrocarbons (Moonis et al., 2010), yet this methodology at the current state of development may be used.

4.4.3. Overall evaluation

Summarizing, given the wide presence of models, their considerably different predicting abilities, and the dependency of the latter abilities in the assumptions and the background of the analysts, we are prevented from placing the necessary confidence in the produced risk metrics. Also, this wide presence of models and methodologies with different accuracies each, restricts the atmosphere of consensus among the experts. Keeping in mind the 4 dimensions identified in the background knowledge, according to the analysis in chapter 3 i.e. (a) assumptions embodied; (b) availability of reliable data; (c) agreement among the experts; and (d) understanding of phenomena involved, we challenge whether the knowledge available, at least at the current development level of hydrogen applications, is sufficiently strong to permit a credible risk assessment in HRS when the methodology adopted for the quantitative risk assessment silences the SoK it is based on.

The ISO framework, aligned to the traditional perspective, does not seem to reflect at this SoK in a profound and accessible way. Of course, there is the requirement that uncertainty and sensitivity analyses are conducted. Reporting the use of non-specific data, which is typically the case as argued formerly, and the type of models and evaluating the results in the light of this, can be seen as a form of sensitivity analysis. Yet, not straightforward characterization of knowledge as a part of the methodology applies, and mainly this SoK is not projected at the produced risk picture. Typically, traditional risk matrices are utilized to present the risk levels or risk contours to express risk applying to refueling stations.

An additional issue to highlight, relates to the use of frequentist probabilities as per the ISO framework. Low hydrogen related failure rates should not be confused with high safety levels. the former may be the outcome of underreporting hydrogen leaks or our restricted access to data. or the small number of hydrogen refueling stations currently in use. At this point our concern arises. Given the low occurrences, predicting variation in the consequences considered under a statistical approach, is not highly recommended. Yet the framework highlights the use of traditional frequentist probabilities, quite often derived from other industries as explained, or knowledge based ones, without however sufficient justification of the knowledge supporting the latter, including the assumptions as part of this. One additional issue here, referring to the wide extent of assumptions inserted either due to the limitations of the available models or due to our weak phenomenological knowledge with respect to hydrogen's reacting behavior, is that this potential deviation of the assumptions and the implication of such deviations in the produced results is not being highlighted.

Therefore, given the discussion on the surprise dimension, and the surprising events' occurrences in chapter 3, we remain reserved whether in an industry such as hydrogen industry, presenting an emerging character; at least when we are focusing in the specified applications, such surprising events' occurrences are captured following the ISO methodology as it is.

5. Introduction and analysis of a case study

In the following we are reviewing a case study, based on a QRA for a reference HRS conducted by DNV GL during the HyApproval project. The scope of this QRA, hereafter called the reference QRA or simply the QRA, has been to *calculate and evaluate safety distances* applying on a typical HRS. Yet, since the QRA was not available in public domain, and the corresponding DNV report was under confidential status, we restrict the analysis to a certain extent. At this point we wish to highlight that important input has been the work of Haugom and Friis-Hansen (2011), as well as HyApproval WP2 (2008) reviewing parts of the reference QRA and being our main reference study.

The goal we set is to examine the QRA methodology, based on traditional probabilistic assessment framework. Our approach though will be following the ISO/TS 19880/1:2016 recommendations, and the objective served is to identify weaknesses and limitations applying in the specific case study.

5.1. System definition and context establishment

We introduce a gaseous hydrogen refueling station (HRS) bearing on site production. According to the QRA methodology introduced previously in this chapter, components are listed and their functions, including expected operating ranges and design characteristics, are defined. Mitigations introduced in the design are defined as well. We do not call upon an existent HRS; details on design characteristics are usually not publicly available, but we assume it comprises of typical representative units, i.e. (HyApproval WP2, 2008):

 i. Hydrogen production unit
 ii. Gas purification
 iii. Hydrogen compression
 iv. High pressure storage
 v. **Dispenser**, and
 vi. Utilities supply for hydrogen production; cooling water, power supply and more.

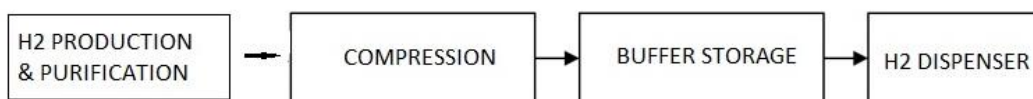Figure 5.1. presents the general flowchart applying to a gaseous HRS with on-site production.

Figure 5.1. Flowchart of a gaseous HRS bearing on-site production, source: HyApproval WP2, 2008

To keep the analysis short, we need to focus only on a single part of the system, that is the dispenser unit, since the dispenser area and the interface between vehicle and user is expected to contribute significantly to the overall risk stemming from the operation of a hydrogen refueling station (Haugom and Friis-Hansen, 2011, Zhiyong et al., 2011). Therefore, the objective is to evaluate the safety distances applicable to the CGH2 dispenser. In this respect, we need to identify hazards applying to the operation of the dispenser and define relevant exposure scenarios.

Typical components and safety devices applicable to a dispenser unit, are the fueling hose, a nozzle, ambient temperature and pressure sensors, a pressure relief device and more, illustrated in figure 5.2.

The fueling process should comply with the fueling protocols currently available, such as SAE J2601. Therefore, regarding the function of the dispenser and the operating conditions:

- The ambient temperature during fueling should be maintained within the interval $[-40°C, 50°C]$
- The dispenser (applicable in this case study) bears the appropriate nozzle to fuel vehicles at 70 MPa.
- Given this nominal working pressure the maximum operating pressure (MOP) should be less than 125% of the former, i.e. in our case study, the MOP of the dispenser is defined in 87,5 MPa
- Minimum gas temperature should not fall below $-40°C$, and the maximum fuel rate should not exceed 60 g/s for light duty vehicles.

If one of the former conditions is violated, the fueling should terminate within 5 seconds. For this operating information on the dispenser unit and the expected and permitted ranges we are based on ISO (2016).

The dispenser control system is provided to detect any of the above deviations and either stop the fueling or apply safety mitigations. These mitigations are (ISO, 2016):

i.   Leakage detection
ii.   Dispensing emergency shut down (ESD); emergency shut down can initiate either automatically or on demand.
iii. Overpressure protection
iv.   Dispenser temperature control faults
v.   Hydrogen release limitation; in case of fueling line break
vi.   Process control failure
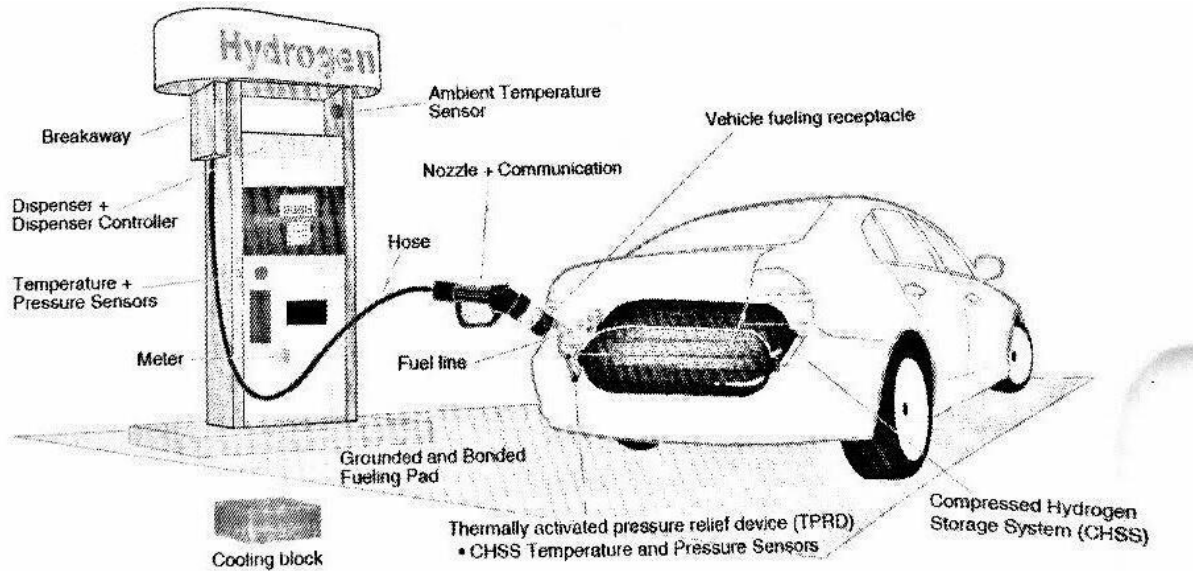
Figure 5.2. Dispenser's key components and safety devices. Source: ISO/TS 19880-1:2016.

▪ Target determination

The hazard identification in the reference QRA provided a list of hazards, yet those relevant to this case-study are the following leak scenarios apropos of the operation of the dispenser unit (HyApproval WP2, 2008):

  i.   Hydrogen gas leak in the H2 dispenser area.
  ii. Hydrogen gas leak from piping/valves/connection between the storage and the dispenser.

Hereinafter we refer to the hazards identified as a hydrogen gas leak in the dispenser area, or simply hydrogen leak. Sources giving rise to the leak, may be the very nature of hydrogen; its proclivity to ignition, denotation, and deflagration, also technical faults; for instance, a hose rupture, fueling line break or introduction of hydrogen to the metal making the latter to lose support. Human errors can also contribute significantly to leaks (HyApproval WP2, 2008). The risk in hydrogen though, comes through combustion given an ignition (HyApproval WP2, 2008) and therefore it is critical that no ignition sources are present; such ignition sources may be lightened cigarettes and mobile phones.

Vulnerable targets to this respect may be the operating stuff, customers but also public, i.e. people living and working in the surrounding area, as well as cars fueling and passing by, constructions including the shop and surrounding buildings. Yet the objective of the case study is to define safety distances with respect to harm applying to *human targets on* and *offsite,* and the harm considered is lethal exposure. Therefore, non-living targets are excluded from the assessment. Then the (remaining) recognized targets are: (a) the operator of the dispenser, constituting a 1st party target; (b) customers on site considered as 2nd party targets; and (c) people in the surrounding area as 3^d party targets.

- Data documentation:

We do not have access to the specific data utilized, but according to Haugom and Friis-Hansen (2011), when hydrogen specific data were unavailable, hydrocarbon statistics under modification factors were utilized. For instance; failure frequencies and ignitions probabilities. As it is also stated in HyApproval WP2 (2008) and the reference QRA, a very limited amount of pressure data, as well as jet and cloud characteristics were available for the consequences modeling and harm calculations.

- Tolerability limits selection

ISO/ TS 19880-1:2016 does not prescribe specific RAC. These are usually defined in close interaction between stakeholders and the authorities. Typically, expected values; for instance, FAR values or PLL, or consequence based harm criteria are utilized.

This case study, as defined in the context establishment, aims to evaluate and establish safety distances with respect to the operation of the CGH2 dispenser unit and the hazards stemming from the latter, for the protection of living targets on and offsite. Therefore, produces an *effect distance* where a certain impact applies. The impact considered is *fatality or severe injury.* In this respect two harm criteria are established; a *'harm criterion'* where a 1% chance of exposure of the target to fatality or lethal injury applies, and a *'no harm criterion'* for lower chance of this type of exposure.

Yet, in order to translate the phenomena's physical effects into harm to targets, harm models or criteria as per ISO (2016) are called upon. Table 5. demonstrates the harm criteria relevant for this study. *Certain assumptions* are taken*;* for instance, impact on targets is assessed for an approximate 20 seconds' exposure to the hazard. Another assumption holding is that no heat radiation is considered when assessing the impact of a fire scenario, i.e. it is assumed that only in contact to the flames the targets are affected. An additional, yet critical assumption taken refers to the determination of the level of effect that is capable of causing a certain severity of injury.

Hazard/exposure scenario	target	'No harm' i.e. =< 0.1% fatality risk	'Harm' i.e. 1% fatality risk
Fire/ Jet Fire	People	*1,6 KW/m2*	*9.5 KW/m2*
Flash Fire	People	*½ LEL*	*LEL*
Explosion	People	*2kPa*	*7kPa*

Table 5. 'Harm' and 'No harm' criteria applying in the relevant physical processes; fire and explosion scenarios, source: HyApproval WP2, 2008.

Then the acceptable risk is defined in terms of frequency where such impact, i.e. the 'harm' criterion, applies. A threshold individual harm exposure frequency is introduced, that is $F_t = 3.5 \cdot 10^{-5}$/year, representing the individual fatal risk potential for the evaluation of safety distances, taking into account the effect of mitigations introduced in such industrial applications suggested in EIGA document: IGC Doc 75/07/E (2007). The rationale behind this limit as per EIGA, is that risk stemming from such activities should not be significant compared to the risk linked to everyday life. Thus, the natural minimum individual fatality risk, assessed in this study, broken down in its 3 segments and considering 1/3 of this value, reflects the occupational risk in every day context. Given now the effect of mitigations in such applications, EIGA considers ½ of this remaining value, and as such the suggested value Ft derives.

i. For events with an annual frequency; f less than the threshold frequency; F_t , i.e. $f < F_t$, the probability of harm occurrence is considered negligible. Such events are excluded from further assessment and *no safety distance requirements apply.*

ii. Exceeding though the threshold frequency F_t, we need to apply additional mitigations or determine safety distances assuring 'no harm effect'. The latter is translated as follows:

 ▪ For events with a chance less than 1% of exposing targets to fatality or severe injury, and an annual frequency up to 100Ft, then the reference QRA suggests that safety distances are calculated to meet the 'harm criteria' introduced in table 5.

 ▪ Yet, for events with annual frequencies exceeding the value 100Ft and given that the 'harm criterion' is set as 1% chance of fatality or severe injury, extending the threshold of 100Ft may contribute to unacceptable risk levels. Therefore, safety distances are calculated to meet the 'no-harm' criteria introduced in table 5. and/or additional mitigations should be considered. Figure 5.3. illustrates this criterion.
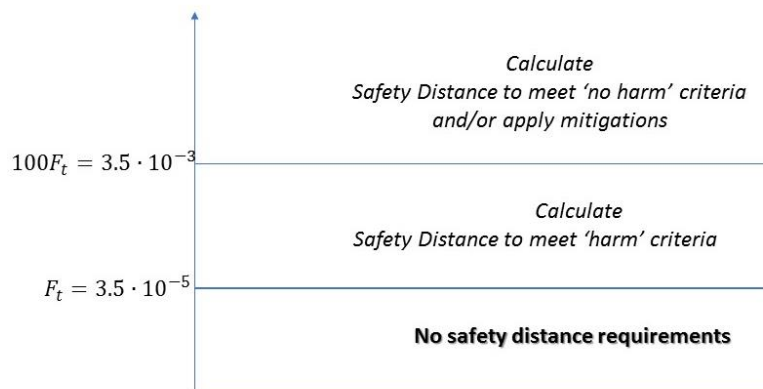

Figure 5.3. Safety distance criteria under an expected event frequency justification, based on HyApproval WP2, 2008

Before proceeding to exposure scenarios and the quantification of the latter, we present the rationale under which the event frequencies derive in this case study. It holds that:

$$f = F_{event} \cdot P_g \cdot P_f \tag{1}$$

where f: is the event frequency, for instance the leak frequency in our setting, P_g is a risk reduction factor related to the geometry, in a leak scenario resulting in jet fire for example, it may represent the probability that the jet will be pointing to the target, and P_f is the failure probability of the mitigations considered.

5.2.   Performing a QRA based on ISO TS 19880-1:2016

The hazard identification step identified a leak hazard applying in the dispensing area with vulnerable targets, people on and offsite. Before defining the relevant exposure scenarios in detail let us mention the assumptions and conditions under which these are formulated.

- Assumptions and conditions

The leaks are classified in small and large leaks, with flow rates $[0.1 - 5mm]$ and $[5 - 12\ mm]$ respectively and event frequencies $3.3 \cdot 10^{-2}$ and $4.7 \cdot 10^{-3}$, whilst full bore ruptures are dismissed from further evaluation due to low probability justifications, based on the threshold frequency criterion introduced. Yet, this *assumes* that a (reliable) crash barrier is implemented conditional on its performance the event frequency remains lower than the threshold of $F_t = 3.5 \cdot 10^{-5}/year$ (HyApproval WP2, 2008). It is also *assumed* that if the leak detection is successful and the shutdown system operational there is no risk stemming of the high-pressure storage upstream, i.e. the dispenser is successfully isolated. Detection and shut down can initiate either automatically or on demand. Moreover, failure of the leakage detection and shutdown system, is interpreted as failure to detect gas and isolate the valves on demand (Haugom and Friis-Hansen, 2011).

- Exposure scenarios

The QRA utilizes ETA to define in full the exposure scenarios including the quantification of the latter. The approach is the following; any event is conditioned on the outcome of the precursor event as well as the effect of mitigations applied and the failure probabilities of the latter. Before any CFD simulations or consequence modelling though, no risk reduction because of geometry considerations can be assessed. Thus, the frequency of each scenario based on (1) derives as:

$$f = F_{event} \cdot P_f \tag{2}$$

All events' outcomes including the mitigations are considered under a binary approach, i.e. occurring /not occurring, and functioning/ not functioning respectively (Haugom and Friis-Hansen, 2011). Figure 5.4. presents the ETA relevant to this case study and in table 6 information on branch-event frequencies, as well as the end-event frequencies and the safety distance determination based on the latter are provided.
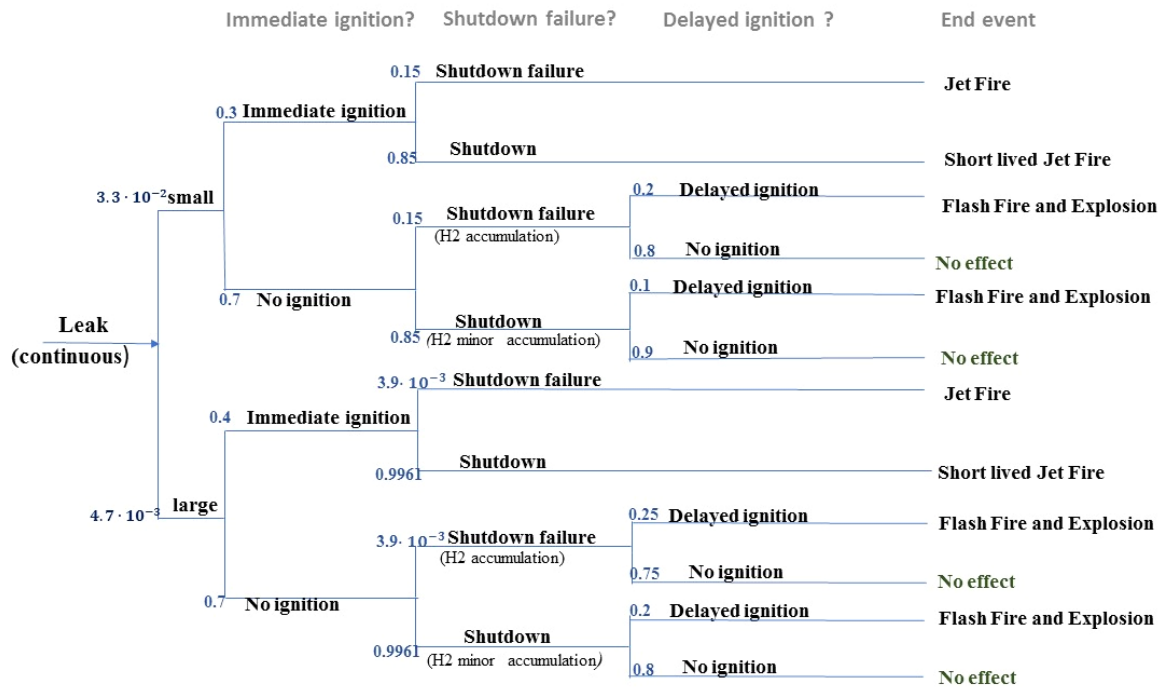
Figure 5.4. Illustration of the CGH2 dispenser Event Tree.

Hydrogen leaks may be instantaneous or continuous. The latter conditioned on the time of ignition can give different outcomes. An immediate ignition will result in a jet fire scenario, whereas a delayed ignition will result in flash fire and in the presence of congestion also an explosion scenario (Zhiyong et al., 2011). Immediate ignition can occur because of an ignition source, such as sparks, being present or because of the energy release during the initial leak. If though the leak is not immediately ignited hydrogen can accumulate forming an air cloud mixture which in presence of (additional) ignition sources can ignite (Haugom and Friis-Hansen, 2011) and give rise to the scenarios described. In this case study two set of leak scenarios are considered, a set of 6 small continuous leaks, denoted by S1-S6, and a set of 6 large continuous leaks, denoted by L1-L6 respectively, illustrated in figure 5.4. in the dispenser event tree. The mitigation considered in the analysis, is the Emergency Shut Down system.

Scenario / Leak type	Leak type frequency	Immediate ignition/ Branch prob.		Shutdown failure/ Failure prob.		Delayed ignition/ Branch prob.		End-event frequency	Calculate Safety Distance *based on fig 4.10* to meet:
S-1	$3.3 \cdot 10^{-2}$ (Small leak)	Yes	0.3	Yes	0.15	-		$1.49 \cdot 10^{-3}$	'Harm' criterion
S-2				No	0.85	-		$8.42 \cdot 10^{-3}$	**'No harm' criterion**
S-3		No	0.7	Yes	0.15	Yes	0.2	$6.93 \cdot 10^{-4}$	'Harm' criterion
S-4						No	0.8	$2.77 \cdot 10^{-3}$	**No effect**
S-5				No	0.85	Yes	0.1	$1.96 \cdot 10^{-3}$	'Harm' criterion
S-6						No	0.9	$1.77 \cdot 10^{-2}$	**No effect**
L-1	$4.7 \cdot 10^{-3}$ (Small leak)	Yes	0.4	Yes	$3.9 \cdot 10^{-3}$	-		$6.35 \cdot 10^{-6}$	*No saf. distance required*
L-2				No	0.9961	-		$1.62 \cdot 10^{-3}$	*'Harm' criterion*
L-3		No	0.6	Yes	$3.9 \cdot 10^{-3}$	Yes	0.2	$2.38 \cdot 10^{-6}$	*No saf. distance required*
L-4						No	0.8	$7.14 \cdot 10^{-6}$	**No effect**
L-5				No	0.9961	Yes	0.1	$4.86 \cdot 10^{-4}$	'Harm' criterion
L-6						No	0.9	*no effect*	**No effect**

Table 6. Branch and end-event probabilities for the leak scenarios relevant to the CGH2 dispenser, based on the reference QRA, source: HyApproval WP2, 2008.

For scenarios L-1, L-3, since the end-event frequencies are below the threshold exposure frequency F_t , no safety distance establishment is required. For scenarios S-4, S-6, L-4, L-6, no ignition takes place, and therefore no effect is considered. For the remaining scenarios and based on the criteria introduced and illustrated in figure 5.3 safety distances to meet the 'Harm' and 'No-harm' criteria are calculated. Table 5 provides the relevant values, on physical processes that are linked to each criterion. For instance for S-5, it was assessed to calculate safety distances to meet the 'harm criterion'; relevant values to this criterion for living targets are:

Fire/ Jet fire	*9.5 KW/m2*
Flash Fire	*LEL*
Explosion	*7kPa*

This implies that CFD calculations, and consequences modelling using specialized methods are required to evaluate effect distances where such impacts apply. Yet the reference study (HyApproval WP2, 2008) mentions that *limited pressure data, jet and cloud characteristics* were available. Moreover, for short lived jet fires i.e. S-2, L-2, it is more appropriate to use *load criteria applying in flash fires and not (prolonged) fires*, as was used in the reference QRA and therefore

the discussed case study. As such only for a limited number of scenarios the study could establish safety distances applying on a 350 bar CGH2 dispenser. The rationale though is that from the set of suggested safety distances, deriving from each scenario assessment, the longest one to implement.

5.3. Weaknesses identified in the case study following the ISO methodology

While presenting this case study, we referred to a number of assumptions and conditions under which the former was defined, including the lack of relevant data as per cases. In this part, we will summarize this information and assess the implications of such weaknesses with respect to the confidence we can place to the recommendations on safety distances, deriving from the analysis.

- Scenarios initially excluded from the analysis

Certain events were initially excluded from assessment due to low probability justifications. For instance, full bore ruptures were not considered at all in the analysis. However, the frequencies for full-bore ruptures derived from (1) had assumed that a sufficiently reliable barrier keeping the event frequency lower than the threshold F_t had been implemented. Yet this assumption related to the barrier's effectiveness needs to be assessed. Conditioned on the latter, the frequency may be more or less close to the actual occurrence rate. Moreover, for the leak scenarios defined, it is not specified weather the leak frequencies reported are hydrogen specific or derive from relevant hydrocarbon systems. In the second case modification factors are introduced.

- Causal chain approach

The case study utilized ETA for the event propagation illustrating an ordered sequence of events, where each one of them was considered under a binary logic i.e. failure/success. Yet, given the nature of the application; a refueling station is realized as a system of interacting processes, where high level of complexity applies, focusing only in one part of the system at a time and neglecting the interactions with the rest as ETA implies, may have unfortunate implications. For instance, the analysis considers the dispenser isolated from the high-pressure storage upstream, and no critical interactions between the remaining units of the system are established.

One maybe argues that this has been an implication given the present analysis's level, since it was chosen during the context establishment to focus only in the dispenser unit, yet as argued in the beginning of this thesis, ETA traditionally handles each part of a system in isolation and therefore the concern remains valid in a wider context than this framed in the case study.

- Risk Acceptance

However, our greatest concern here is how we assess acceptable risk. Risk acceptance is defined through a straightforward projection of the end-event frequencies f against the threshold frequency F_t introduced, reflecting thus the harm criterion of a 1% exposure chance to fatality risk. Yet, what is our confidence with respect to the estimation of these frequencies?

✓ Event frequencies f

According to (1) event frequencies are calculated as: $f = F_{event} \cdot P_g \cdot P_f$. We referred to our reservation with respect to whether the leak frequencies F_{event} used are relevant to hydrogen systems and the hydrogen dispenser in specific. Potentially they derive from hydrocarbon systems and are adjusted to reflect the former. As argued in chapter 4, this is quite often the case in hydrogen risk assessments, given the restricted statistics currently available. Also, with respect to the risk reduction factor P_g reflecting the specific geometry, a set of available data, such as pressure data, cloud characteristics and more are required for the CFD calculations; assessing the hydrogen dispersion, and the gas cloud characteristics accounting for those geometric considerations. However, the reference study reports that such data, were mainly lacking. With respect to the failure probability of the mitigations a certain number of assumptions were introduced; assumptions on the barriers' reliability or how a certain failure is translated.

✓ Threshold harm exposure frequency F_t and harm criteria

With respect to the harm exposure threshold frequency F_t on the other hand, one may question the criteria called upon for the determination of this reference value. The rationale behind this limit as per EIGA, was given previously: risk stemming from such activities should not be significant compared to the risk linked to everyday life. Thus, the natural minimum individual fatality risk, assessed in this study, broken down in its 3 segments and considering 1/3 of this value, reflects the occupational risk in every day context. Given now the effect of mitigations in such applications, we consider ½ of this remaining value, and as such the suggested value F_t derives. But someone could argue that this determination is quite arbitrary. On top of that we add that natural minimum individual fatality risk is a value that differs from country to country. As defined in the beginning of this thesis, the selection of those upper limits of acceptable risk, remains a valid concern, yet is not further addressed in this study.

With respect to the harm criteria, a certain assumption has to be made for the minimum level of effect that can cause a certain severity of failure or injury; see for instance the fire and explosion

loads applying in the 'harm effect' and this assumption can be more or less valid. Safety distances are calculated up to those criteria and therefore they are conditioned on the relevant assumptions.

Concluding, the overall point we wish to make, is how confident one should be when deciding on implementation of safety distances by this straightforward projection of f against Ft, or when calculating the safety distances up to the harm criteria introduced.

Focusing on the first, by conducting this type of straightforward comparison between the calculated and determined frequencies f and Ft respectively, we may miss important information hidden on the assumptions, and the overall approach under which event frequencies derive. There is no indication related to how much confidence one should place in the recommendation to implement safety distances, especially if we consider cases where the probability margin prescribing no safety distance implementation is relative small. Remember the discussion in 3.5 related to the RAC and the inherent necessity to implement a cautious thinking in a setting like this. Extending the discussion to cover also safety distance calculations, the latter are calculated based on the harm criteria, which on their turn are based on certain assumptions, more or less valid. No indication of the degree of assumptions introduced or whether they are reasonable enough, is made available, when the decision maker is called to decide on certain design/layout of the HRS. One may therefore question the degree at which this decision is actually a risk informed one.

6. Discussion and recommendations

6.1. Extending beyond probabilistic risk assessments in hydrogen refueling stations

Taking as our point of departure the evaluation of ISO /TS 19880-1:2016 in Section 4.4. which stressed the potential of surprising events compared to the produced risk picture, meaning that the former is not sufficiently reflected in the discussed ISO methodology, in this part we proceed to our recommendations for a robust framework when assessing risk in the relevant applications; that is the integrative perspective suggested by Aven and Krohn (2014) presented in chapter 3. Yet, in order to proceed to recommendations on a practical level rather than a theoretical representation of the discussion in 3.5, we recall and utilize the results of the case study presented in the previous section, as well as the limitations as per ISO; summarized in a weak phenomenological knowledge applying in hydrogen, including the scarcity in validated models and relevant statistics as input to the overall risk assessment.

6.1.1. The integrative risk assessment framework in hydrogen refueling stations

The integrative approach suggested does not render the probabilistic risk analysis the ISO/TS 19880-1:2016 is based on invalid. It integrates the latter with more qualitative approaches, and therefore exceeds mere probabilistic considerations of risk. In specific, it is suggested that the ISO probability based thinking is coupled with strength of knowledge characterizations the latter thinking is founded on, including the assumption deviation risk assessment, and the consideration of surprises.

Yet, the question that someone justifiably will pose is how this can be achieved in a practical level. The focus is placed on two broad dimensions. That is the development of RAC assuring the required safety in hydrogen refueling stations, when establishing for instance safety distances, as seen in the introduced case study. The proposed approach is founded on cautious thinking during risk evaluation and treatment extending thus the current rationale under which calculated probabilities are simply projected against defined criteria.

 The second refers to the strength of knowledge characterizations and the surprise assessment during the risk assessment process, i.e. the qualitative features of the new perspective. Recalling the analysis in 4.4. and focusing in the lack of sufficient knowledge; expressed as a combination of weak phenomenological knowledge with respect to hydrogen reactive behavior and lack of relevant evidence, the operation of a unified hydrogen database enabling experience transfer and providing reliable statistics, is awaited to contribute towards this direction. Figure 6.1. summarizes the overall thinking.
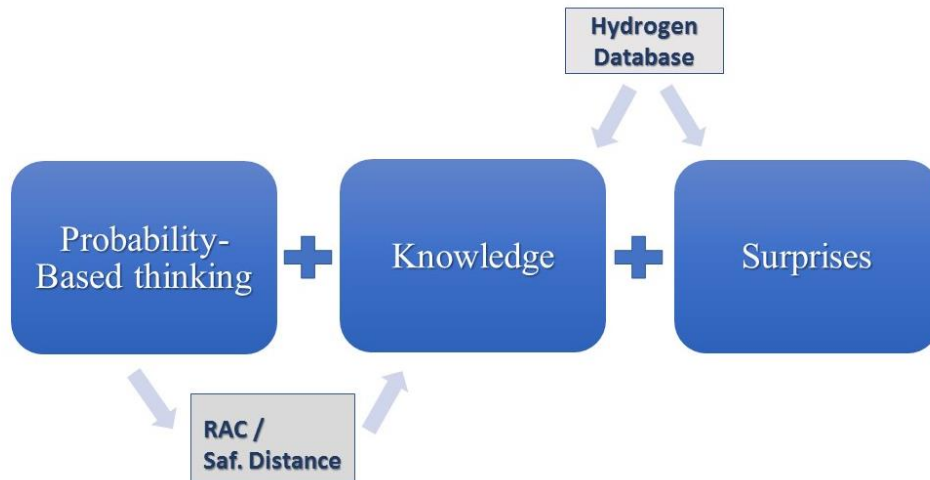
Figure 6.1. Practical features of the new integrative perspective in risk assessment, in relation to hydrogen refueling stations. based on Aven and Krohn, 2014 and Aven, 2014.

Risk acceptance criteria, are typically formulated based on exclusive probabilistic considerations. Yet in the light of the analysis so far, the strength of the knowledge supporting those probability numbers is not always assured. Therefore, the new framework suggests that we expand the current thinking governing risk evaluation and further reflect on the SoK the overall analysis is based upon. With respect to characterization of this knowledge, and the consideration of surprises i.e. the new features of the integrative framework, consulting a database where hydrogen statistics and relevant experience is acquired, provides the risk analysts with valuable evidence during the surprise assessment and a wide knowledge base contributing to both statistical calculations and the consideration of surprises.

Right in the following we reflect on the benefits gained by consulting statistical databases in hazardous industries, and in a subsequent level, narrowing down in hydrogen related applications, we discuss how this database facilitates the knowledge assessment and surprise consideration of the new framework.

- Establishing and operating statistical databases in hazardous industries.

Quite early the offshore oil and gas industry, especially in Norway and UK, launched a reporting system under which incident and accident statistics for almost all hazards applying to offshore operations were acquired. In parallel efforts were established to collect where possible population data, for the frequency calculations. Such population data may be the number of wells drilled, number of well-years and more (Funnemark, 2005). With respect to the benefits the establishment and operation of such database offers, we discern two levels:

i.   the first refers to the *requirements for statistical input to the consequences models*, as already discussed, and the second refers to

ii.   the *overall experience that can be gained by reporting incidents and accidents* and the *lessons that can be learned* while attending the future.

With respect to the latter we can recognize trends and develop a proactive behavior, since similar accidents may occur, developing also improved controls and mitigations over risk (Funnemark, 2005). By making the statistics and the investigation reports' results available to public, we facilitate the transfer of knowledge, a critical factor in the overall risk management process. We referred to this also in section 3.4.3; risk analysts, decision makers and involved stakeholders need to develop communication channels and bridge any knowledge gap, uprooting also unjustified beliefs with respect to risk (Hafver et al., 2016). This can be facilitated by providing all of them with access to the same information which is being continually updated. According to Funnemark and Engebø (2005), in the long run this may also contribute to developing an overall improved state of safety in the relevant applications since it is awaited to affect and improve the safety culture among the people operating and using those. But let us reflect on this in relation to hydrogen related applications in specific.

▪ A unified central database for hydrogen related applications

In order to develop credible risk assessment methodology in hydrogen refueling stations and extending this in hydrogen related applications, we need to have access to sufficient and relevant statistics, for the consequences calculations as discussed. Therefore, we need to operate and maintain a central database, collecting exclusively hydrogen related statistics; accidents, incidents, near misses and hazardous situations, applying from production to commercial use.

Yet the contribution of a hydrogen database is not restricted to statistical calculations, it has a critical meaning for the qualitative elements of the new framework. Informing and continually updating a hydrogen incident and accident database can prove a valuable tool for risk analysts and involved stakeholders in checking performance aspects and enabling a learning through mistakes process (Funnemark and Engebø, 2005). Those performance aspects can provide a better understanding of how risk develops over time, which is critical if seen in relation to the surprise element. Recalling the discussion in chapter3; knowledge is updated as we move in time and the assessor needs to acknowledge that. With respect to the 'learning through experience' process, similar or less similar accidents may occur. Databases in a broad level highlight this potential and in this sense, enable a deliberate thinking when considering hazardous situations. This is a critical factor when for instance identifying initiating events or causal relations during the accident scenarios' development. A trustworthy hydrogen database, could prove a valuable source of evidence to the risk analysts, when they are challenging the extended risk picture and the mental model the latter is based upon, as discussed extensively in section 3.5 as well as the probability judgments, or while they are searching for unknown knowns, during the surprise assessment.

Under the trustworthy entry, we refer to a common reporting format and a quality assurance requirement before any statistics are made available.

Registration and investigation of hydrogen related incidents and accidents, and publication of the results, can help us develop a proactive rather than reactive behavior. A dynamic, continually updated database could alarm risk analysts for hazards applying, in the same sense that preoccupation with failure, of collective mindfulness does. Last, we add that reporting of all incidents irrespective of the leak size and the magnitude of outcome, should be made a regulatory requirement. We suggest this is included in the ISO update, and a change in the ISO policy allowing non-hydrogen specific data for the consequence calculation is reconsidered.

Concluding, the overall contribution of consulting this dynamic hydrogen database is of course the wide access to statistics and the assurance of knowledge transfer which is critical to risk management in the sense described previously, but also if seen in relation to the new framework specifically, it provides a tool to perform the strength of knowledge characterizations and the surprise assessment.

- Safety distances determination and RAC

In this section, we focus on risk acceptance stressing the need to change our focus when evaluating risk. Probabilistic risk acceptance criteria reflect one of the basic weaknesses of existing methodologies in risk assessments; that is meeting those criteria instead of looking for the best arrangements, as discussed in section 2.2.

Recalling the case study in chapter 5, the decision on the implementation of safety distances is based on probabilistic RAC alone, the latter expressed as a projection of the end events frequencies f in the ETA against a threshold frequency F_t reflecting a specified severity of harm. Yet, as argued formerly, such a decision may be based on assumptions more or less valid, statistics not relevant to the specified applications and more, with unfortunate implications for the risk assessment; that is the potential of surprises in the sense of harm occurrences not predicted and met in advance given those low probability justifications.

Aligned to Aven (2014), risk acceptance founded exclusively on probability judgements is too narrow as a perspective to adopt, and therefore the former author suggests adjusting this approach in a way it reflects other aspects than the probability figures, that is the evaluation of the SoK the former figures are based on. As argued in section 3.5., we should scrutinize both the probability judgments with respect to the scenarios identified together with the knowledge supporting those. In the setting of new technologies and application areas characterized by restricted experience and weak knowledge this concern remains critical, and hydrogen refueling stations in the light of the analysis so far, fall within this category.

Therefore, we suggest the following approach for the safety distance determination, illustrated also in figure 6.2.:

- For events with annual event frequencies f exceeding the threshold $F_t = 3.5 \cdot 10^{-5}$, safety distances are to be assessed.
- Below this limit we need to assess the SoK the analysis under which those frequencies have derived is founded on.

If the SoK is evaluated as *'High'*, no safety distance requirement applies. Yet, if this SoK is assessed as '*Medium'* or '*Low'*, then the approach suggests the implementation of safety distances. We refer to the two methods introduced in the previous for the evaluation of the strength of knowledge; either the crude risk scoring or the assumption deviation risk assessment, the latter providing insights in the criticality of the embodied assumptions as well.

Figure 6.2. Safety distance determination in relation to the SoK the harm frequencies are based on, aligned to the approach on RAC suggested by Aven, 2014.

However, we can further expand this thinking by evaluating the probability margins with respect to which risk is considered acceptable together with the SoK under which the assessment produced those probability numbers. This is aligned to Aven (2014) and was discussed in section 3.5. The reader may also see table 7.

Therefore, the approach suggested introduces a lower limit that is a new threshold frequency denoted by F'_t, let us define this as $F'_t = 1 \cdot 10^{-7}$, below which no safety distance requirements apply, unless the SoK supporting the analysis is assessed poor. Then, the approach claims further considerations. That is to gather additional data, and/or acquire more knowledge such that the approach enables a confident decision not to establish safety distance. However, if this knowledge cannot be obtained, or is not available, then the criterion founded on cautious thinking argues that safety distance has to be established.

At this point we would like to clarify that the choice of the lower limit is just indicative, and takes as its point of departure the case study discussed in the previous chapter. What is considered as a

large probability margin cannot be predefined, or seen in isolation to the specific case under consideration.

		Poor	Moderate	Strong
Probability based justifications	Above Ft	Safety distance requirement	Safety distance requirement	Safety distance requirement
	Small margin below Ft	Safety distance requirement	Safety distance requirement	**Risk acceptable**-No safety distance required
	Large margin below Ft: e.g. $f < F'_t = 3.5 \cdot 10^{-7}$	*Further considerations are required.*	**Risk acceptable**-No safety distance required	**Risk acceptable**-No safety distance required
		Poor	Moderate	Strong
		Strength of Knowledge		

Table 7. Risk acceptance in relation to the SoK the analysis is based on, considering also the probability margins. Based on Aven, 2014.

Concluding, our recommendation with respect to safety distance determination, relies on a cautious thinking. Adopting a cautious thinking implies that in the face of (highly) uncertain conditions, the activity giving rise to the risk should either terminate, or risk reducing measures should be implemented (Aven and Vinnem, 2007), including the establishment of safety distances in the setting discussed.

7. Conclusions

The present thesis stressed that the approach on risk assessments traditionally adopted in engineering applications viewing risk as the combination of likelihood of hazards and associated consequences; also reflected in the ISO/TS 19880 methodology, may require certain modifications in order to enable confident decision making with respect to the design and operation of an HRS.

Traditional quantitative risk assessments have some major uncertainties issues inserted at different steps of the analysis. Uncertainties may be introduced initially, when the context is established and scenarios based on deliberate choices and assumptions more or less valid are selected for further assessment. This is a general concern applying in most applications areas, yet remains critical in hydrogen given the restricted evidence currently available. Following the context establishment and the selection of scenarios, uncertainties may be introduced along the events' propagation and the consequences modelling. Source of incompleteness to this respect may be the scarcity in hydrogen specific statistics, and validated models for the relevant applications including the lack of guidance for methods adopted in hydrocarbon systems, when it comes to hydrogen. Finally, at the point when one is called to decide on the significance of risk and the implementation of mitigations, uncertainties are also present. RAC based on probabilities alone, conditioned on certain assumptions are typically utilized, silencing that the focus in such criteria is in stochastic uncertainties, rather than uncertainties inserted due to imperfect knowledge. Given this argument, and the weak knowledge applying in the specific applications, such an approach is too narrow to adopt. Therefore, it questions the risk informed character of a decision founded exclusively on such criteria.

What is suggested in a broad level, is to adopt a more cautious thinking while assessing and evaluating risks in the specific applications. A change in regulations requiring the quantitative risk assessment framework to extent the current thinking and reflect other aspects than probabilities and expected values is highly recommended. In specific, we recommended the implementation of the new integrative framework as per Aven and Krohn (2014), comprising the traditional probability based rationale the ISO is founded on with a strength of knowledge assessment and the consideration of surprises.

The operation of a database, where hydrogen statistics are acquired under common format is awaited to contribute to the implementation of the new framework. The benefits that can be gained when consulting an accident database are both qualitative and quantitative. The former refers to the qualitative approaches enabled by the new framework regarding the strength of knowledge characterizations and the surprises assessment, and the latter is wider and applies to both the traditional and the new integrative perspective since enables statistical calculations and improvement of the available models, for the consequences and harm calculations. Central to the

success of such an effort, is that reporting of all incidents irrespective of leak size and magnitude of outcome, is made a regulatory requirement. Therefore, our suggestion has been the latter to be considered in the next ISO update, and the on-going policy allowing the use of non-hydrogen specific data is also re-examined. Additionally, the present approach of RAC based on probability judgements alone, is suggested to be supplemented with SoK characterizations of the analysis under which those judgements derive, aligned to Aven's (2014) recommendations reflecting thus the overall cautious thinking of the new framework.

Yet, the use of predefined RAC, realized as upper limits of acceptable risk, as was stressed in the beginning of this thesis, is considered problematic among several researchers. Further research on the future could contribute to a new rationale supporting the selection of the former criteria, whereas considerable work should be done with respect to building strong phenomenological understanding in hydrogen applications. The validation of numerical models against experimental data is expected to contribute towards this direction and therefore is placed among the priorities while we are attending the future.

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APPENDICES

A. Hydrogen production technologies up-to-date

Hydrogen production as state-of-the-art is based on natural gas as which is a direct derivative of crude oil (Godula-Jopek et al., 2012). However, with the substantial advances in fuel cells there is increased attention to other hydrocarbon fuels including methanol, propane, gasoline, logistic fuels (Holladay et al., 2009) and so on.

Moreover, recent calls for a green energy shift contributing to low or towards zero emissions in transportation sector, introduces electrolyzers systems for the hydrogeneration, powered by solar energy, wind energy; the latter derived from either offshore windfarms or inland based wind-energy parks, as well as hydropower (Godula-Jopek et al., 2012).

As per Scordato and Klitkou (2014), in Norway in specific, there is a clear shift in the dominant solutions for the hydrogen production for transportation needs towards technologies based on electrolysis due to the wide presence of relative cheap hydropower. According to the same authors, biogas reforming is not as usual, but its potential is expected to increase in the near future (Scordato and Klitkou, 2014).

The worldwide vehicle production nowadays is in the scale of 65 to 70 million cars per year. Only in Europe it is registered that more than 16 million cars per year are in mobility. To ensure an average kilometer range between 400 and 500 km per vehicle in hybrid mode, it is estimated that a minimum of 3 kg of fuel (hydrogen) needs to be carried in the storage system (Godula-Jopek et al., 2012). Embracing therefore the former 'green' forms of hydrogeneration would have a double effect; achieving hydrogen production levels meeting current and near future demand in transportation sector, and providing a real zero emission down line of future transportation on the other (Godula-Jopek et al., 2012). Numbers give a picture of a potential *new trend in energy;* In specific according to the same authors (Godula-Jopek et al., 2012) when it comes to wind energy, in the next10 years, more than 5000 windmill stations, mainly offshore in North and East sea, are planned to launch. Moreover, facilitating nuclear power could possibly result in a major sharing in the overall hydrogen production in future.

A tremendous amount of research is placed *on technologies with potential to produce hydrogen.* In the following we will briefly review the most dominant of them.

A1. Fossil fuel processing technologies

As per Holladay et.al (2009), fuel processing technologies, with methane steam reforming (SMR) being the most mature and widely applied process in commercial use at the current time (2009), are based on the reforming of a hydrocarbon fuel such as gasoline, methane, ammonia or methanol into a hydrogen rich stream. One thing to point out here is that most hydrocarbon fuels contain some amount of sulfur which has to be removed since this is responsible for poisoning the fuel processing catalyst, and the latter case poses a big challenge to the overall (hydro-generation) process (Holladay et al., 2009).

a) **Natural Gas steam reforming**

As per Godula-Jopek et al., (2012) Natural Gas (methane) steam reforming is currently the cheapest and commercially most well-established hydrogeneration technology applied though primarily in petrochemical and chemical industry. Regarding the production costs, these are dependent on the availability and therefore, the cost of natural gas feedstock.

According to this technology, natural gas reacts at the presence of steam over a catalyst table made of nickel at elevated pressures and temperatures; close to 800 C. The process product which is a mixture of CO and H2, once is cooled down it further reacts with additional steam over a water-gas catalyst. More hydrogen is produced and the released CO is converted to CO2. The latter together with other remaining impurities is being removed through a PSA (Pressure Swing Absorption) process (Moore and Raman, 1998).

b) **Other types of Hydrocarbons reforming**. This may be based on:

i.   Partial oxidation

It is an exothermic reaction and considerably faster than steam reforming. The fuel reacts with oxygen at a mediocre to high pressure (moderately high) with or without the presence of a catalyst, depending on the feedstock used as well as the process (Godula-Jopek et al., 2012) An important advantage of the process is that only air and fuel are strictly required for the reaction (Godula-Jopek et al., 2012).

ii.   Auto thermal Hydrocarbon reforming

It is a combination of an endothermic steam reforming process with an exothermic partial oxidation reaction. In specific it is the partial oxidation reaction that provides the necessary energy for the steam reforming process to take place. (Godula-Jopek et al., 2012) It is an overall advanced process with strong elements the faster start up, the improved heat integration and the lower operating temperatures among them. Depending on both the later and the fuel, the catalyst's choice

is differentiated. The whole process is of high efficiency/productivity and has been demonstrated with a variety of hydrocarbon fuels; methanol, gasoline, natural gas (Godula-Jopek et al., 2012).

iii. Gasification

It is an attractive option to hydrogeneration using any carbon source (Wikipedia, 2017d). Systems operating on gasification for the hydrogen production utilize a variety of feedstock including coal, petroleum coke, biomass, hazardous wastes and more (Godula-Jopek et al., 2012). Here ee will briefly refer to coal and petroleum coke gasification.

✓ Coal gasification

The process utilizes steam and a suitable concentration of gases to break the coal's molecular bonds into its basic elements and form a gaseous mixture of hydrogen and carbon monoxide. The gas product of this process can be utilized for higher efficiency electricity production allowing at the same time better capture of greenhouse gases (Wikipedia, 2017d). The process comprises three steps: (i) reaction of the feedstock to oxidant and conversion of the former to synthesis gas (syngas). This takes place in a gasification reactor at high pressures; varying between 1000-1500 ℃, (ii) followed up by a catalytic shift reaction and (iii) the produced hydrogen is finally purified by removal of the residual carbon and ash (Godula-Jopek et al., 2012).

✓ Petroleum coke gasification

Gasification can also utilize petroleum coke and convert this into synthesis gas (syngas). The latter consists mainly of hydrogen, carbon monoxide and H2S (Wikipedia, 2017d).

Other potential feedstock utilized for the gasification process are (Godula-Jopek et al., 2012):

✓ Biomass
✓ Municipal waste
✓ Hazardous wastes and more.

We complete the analysis by simply citing the remaining hydrocarbon reforming processes for sake of completeness, as per Godola-Jopek et al (2012):

iv. Hydrogen production by reaction-integrated novel gasification (HyPr-RING)
v. Plasma assisted production from hydrocarbons.

A2. Non-hydrocarbon reforming production

We distinguish between two major technologies:

(a) hydrogen production from water, and

(b) Hydrogen production from biomass

It is of some interest to include the option of (c) hydrogen production from aluminum for a complete presentation. The following analysis is based mainly in Godola-Jopek et al. (2012).

a) Hydrogen from water: water splitting processes

Electricity from either renewable or non-renewable energy sources can be utilized to produce hydrogen through a water electrolysis process, according to the equation;

$$2\,H2O_{liquid} + electricity \rightarrow 2\,H2 + O2 \tag{eq-1}$$

In the following, we present as per Godola-Jopek et al, (2012) the main water splitting processes currently available; water electrolysis and water splitting combined with high temperature nuclear energy and solar energy.

i. Water electrolysis

Water electrolysis is a technology applicable in large and small scale allowing thus for central and localized production of hydrogen (Godula-Jopek et al., 2012). The latter may find application also in hydrogen Refueling stations for onsite production. This type of technology has for instance been facilitated in the Lilestrøm HRS being on service in Akershus energy park. The central idea is the use of an electrical current passing through two electrodes so as the water to break into its elements; hydrogen and oxygen (Holladay et al., 2009). The hydrogen production capacity depends on the surface area of the electrodes, and thus the process cannot achieve the same high capacities as conventional fuel processing. However this technology can be competitive for regions where electricity is available at low costs (Moore and Raman, 1998), as holds in case of Norway for instance where hydropower is a relative cheap source of electricity (Godula-Jopek et al., 2012).

With respect to the types of electrolyzers used for the process, three types are currently available for industrial use: (1) Alkaline electrolyzers; suitable for stationary applications, they operate at pressures up to 25 bars, (2) Proton Exchange Membrane (PEM); applied on on-board systems, used for production of gases for FC, producing hydrogen up to 99.9% purity and finally (3) solid oxide electrolysis cells (SOEC) (Godula-Jopek et al., 2012).

Depending on the energy source for the electricity, the following water electrolysis systems are available:

ii.   Photovoltaic Electrolysis Systems

Hydrogen can be produced based via water electrolysis based on solar energy. First the solar energy is collected and then it is converted to either heat or electricity that can power the electrolyzer. Different Methods to produce electricity from solar radiation are utilized with photovoltaics and parabolic troughs among them. The PV (Photovoltaic) cells facilitated produce direct currents, and thus the electric power provided can directly electrolyze water and produce hydrogen (Godula-Jopek et al., 2012) see also figure 1.
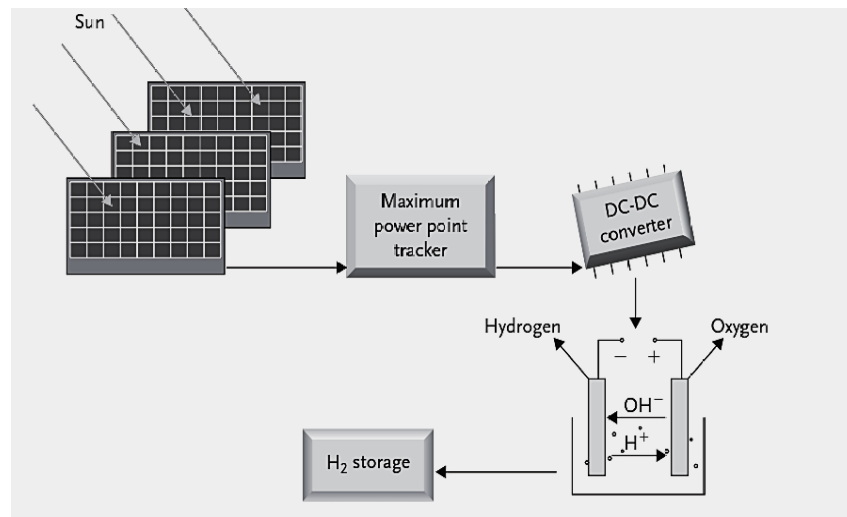

Figure1. Photovoltaic electrolysis hydrogen production, source Godola-Jopek et al., (2012)

Figure 1 demonstrates a hydrogeneration process based on photovoltaic electrolysis. A similar integrated solution of PV cells, providing the electricity for the water electrolysis process and hydrogeneration was utilized in Lillestrøm HRS in the Akershus energy park.

iii.   Wind electrolysis System

The electricity produced through wind is used for the electrolysis of water into hydrogen and oxygen according to (eq-1). In specific the kinetic energy of wind is converted into mechanical by the turbine rotors and subsequently to electricity. Types of electrolyzers used for such applications are the alkaline electrolyzers and the PEM electrolyzers.

There is the option of standalone applications, where an integrated wind power-hydrogen unit produces and stores the hydrogen. The latter, can be used for supplying hydrogen *refueling stations* (transportation sector) or used in fuel cells to regenerate energy. Figure 2 illustrates such a standalone application.
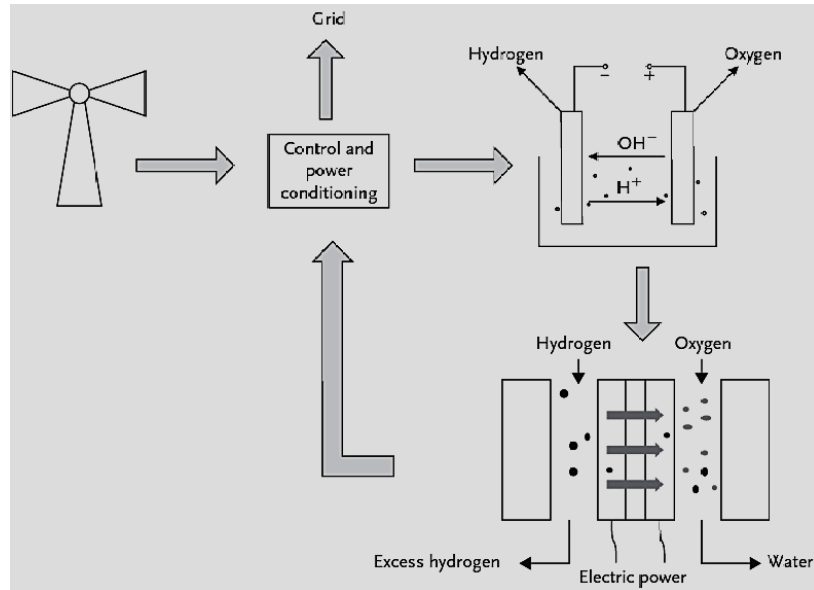

Figure 2. Integrated solution of a wind power-hydrogen system.

At this point we refer to two cases of innovative integrated hydrogen -wind power solutions one in Greece, near Athens and one in western Norway. The former is an innovative 3MW wind hydrogen system located at the Centre for Renewable Sources (CRES) wind park, and the latter is a demonstration project which combines wind power with a hydrogen facility, initiated in 2004 on the island UTSIRA (Utility Systems In Remote Areas) in Western Norway (Godula-Jopek et al., 2012).

iv.   High temperature electrolysis of steam

This is a special case of water electrolysis. Whereas the conventional water electrolysis is performed at moderate temperatures, steam electrolysis takes place at higher temperatures and as such offers significant greater energy efficiency and kinetic and thermodynamic advantages compared to conventional electrolysis.   In specific, if the temperature is increased to reach 1050 K, the thermal and electrical demands of the process is reduced by 35%. Since the steam electrolysis process requires that class of elevated temperatures, it can be combined with advanced nuclear reactors; operating at high temperatures (Godula-Jopek et al., 2012).

    v.   Direct water splitting processes at high temperatures; combined with high temperature nuclear and solar energy

Hydrogen from nuclear reactor as a green form of energy has great potential for the hydrogen production in future. To produce hydrogen from a nuclear reactor mainly two processes apply (Godula-Jopek et al., 2012)**:**

    (i) *High temperature water electrolysis*, i.e. a water splitting endothermic process utilizing nuclear process heat, or
    (ii) *Thermochemical processes* utilizing either nuclear heat, or alternative energy stocks such as wind, water or sun.

b) Hydrogen from biomass

A non-hydrocarbon related process of hydrogeneration, with however lower efficiency compared to the former processes; based on hydrocarbons. A wide variety of biomass feedstock can be utilized in the process. Four broad categories are defined; (i) energy crops, (ii) agricultural residues and waste (iii) forest residues and waste and finally (iv) industrial and urban (municipal) wastes (Godula-Jopek et al., 2012).

With respect to the process applied, two types are defined:

    i.   Pyrolysis/ thermochemical processes and
    ii.   Hydrogen derived from modified microorganisms, accessed also as (Holladay et al., 2009) Biological hydrogen.

A hydrogen production method that is still in immature level, i.e. *limited at laboratory scale,* presenting though great potential for the future and bearing the advantage of a relatively low environmental impact.

c) Hydrogen from aluminum

Aluminum is a rather promising and cheap material available for on board pure hydrogen production.

A summary of the energy sources and the potential pathways for the production of hydrogen as discussed, is briefly presented in figure 3.
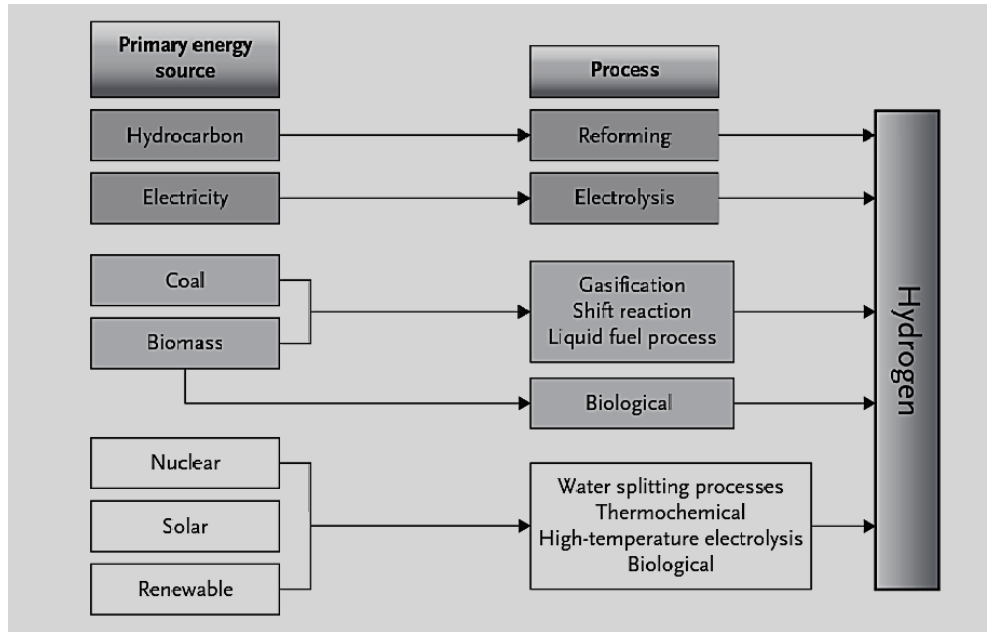
Figure3. General pathways of hydrogen production, Source: Godola-Jopek et. al, (2012)

A.3. Summary of hydrogen production technologies- associated efficiencies

Comparison of dominant fuel processing technologies; HC fuel reforming technologies

Technology	Advantages	Disadvantages
Steam reforming	Most extensive industrial experience Highest air emissions Oxygen not required Lowest process temperature Best H2/CO ratio for H2 production	Highest emissions
Auto-thermal reforming	Lower process temperature than POX Low methane slip	Limited commercial experience
Partial oxidation; POX	Decreased desulfurization requirement No catalyst required low methane sip	Decreased desulfurization requirement Low H2/CO ratio

Table A3.1: Comparison of most dominant HC fuel reforming technologies, source: Holladay et al., 2009.

Summary of available hydrogen production technologies, including the associated efficiencies

Technology	Feed stock	Efficiency	Maturity Reference
Steam reforming	Hydrocarbons	70–85%a	Commercial
Partial oxidation	Hydrocarbons	60–75%a	Commercial
Autothermal reforming	Hydrocarbons	60–75%a	Near term
Plasma reforming	Hydrocarbons	9–85%	Long term
Aqueous phase reforming	Carbohydrates	35–55%a	Med. term
Ammonia reforming	Ammonia	NA	Near term
Biomass gasification	Biomass	35–50%a	Commercial
Photolysis	Sunlight + water	0.5%c	Long term
Dark fermentation	Biomass	60–80%d	Long term
Photo fermentation	Biomass + sunlight	0.1%e	Long term
Microbial electrolysis cells	Biomass + electricity	78%f	Long term

Table A3.2: Available hydrogen production technologies and associated efficiencies, source: Holladay et al., 2009.

NA = not available.

a Thermal efficiency, based on the higher heating values.

c Solar to hydrogen via water splitting and does not include hydrogen purification.

d Percent of 4 mol H2 per mole glucose theoretical maximum.

e Solar to hydrogen via organic materials and does not include hydrogen purification.

f Overall energy efficiency including the applied voltage and energy in the substrate. It does not include hydrogen purification.

B: Risk assessment of hydrogen refueling stations
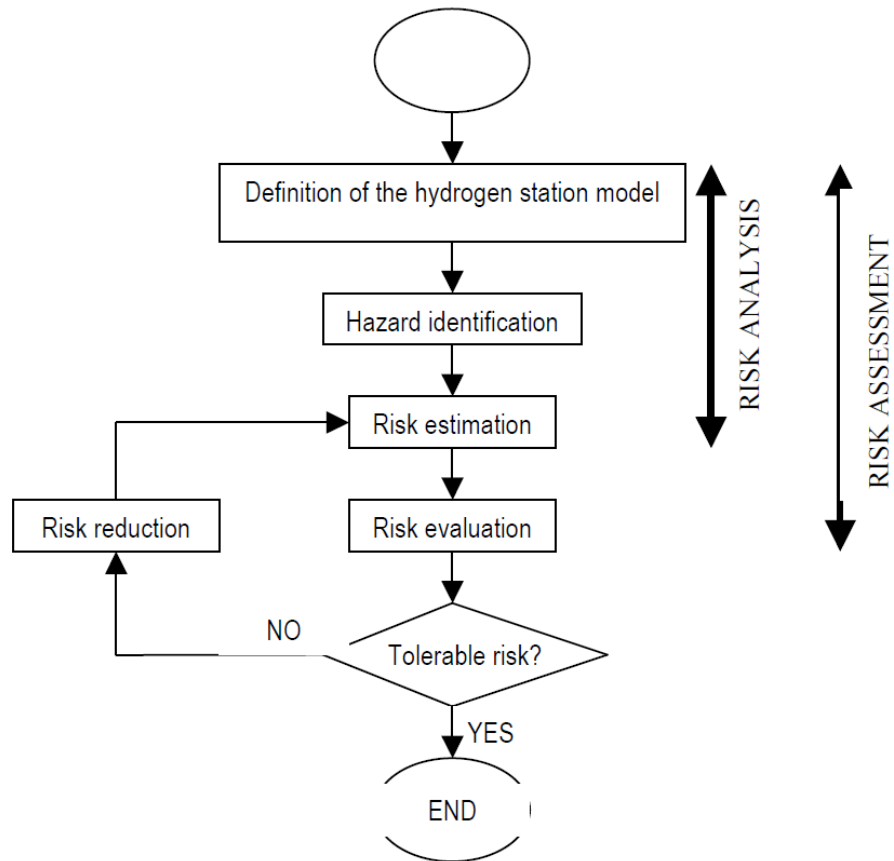
B.1. Flow chart of an HRS risk assessment

Figure4. Risk assessment of an HRS representing an iterative process, source: HyApproval WP2, 2008.

B2. Safety distances definitions

Type of safety distance	Source of hazard	Target	comment
Restriction distance	HRS installation under operation	*not meaningful to define a target.*	<u>Safety distance definition</u> does not apply. Area around the HRS where certain activities are not permitted. i.e. areas where explosive or flammable clouds may apply
Installation layout distance	Units of equipment	Units of equipment	Mitigates escalation within the HRS installation
Protection distance	External hazard, e.g. a fire	Installation/ units of equipment	Prevents/mitigates secondary effects
Clearance distance	HRS installation	Vulnerable targets within layout 1st party targets: personnel 2nd party targets: customers 3d party targets: public	Mitigates escalation of a hydrogen incident
External risk zone	HRS installation	Objects outside the HRS installation i.e. people and constructions	Concept difficult to align with <u>safety distance definition</u>

Table B2.1: Presenting safety distances in relation to targets and source of hazards aligned to the definition of safety distance as per ISO/TS 19880-1:2016. Based on ISO (2016) and HyApproval WP2 (2008).