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PROJECT REPORT

QRA of hydrogen facility

ROBINSON

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Document information

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Title

QRA of hydrogen facility

Summary

This report documents a quantitative risk analysis performed for a hydrogen facility planned built on Eigerøy as part of the ROBINSON project. Estimated individual risk for third parties is presented as risk contours, which may be used for establishing consideration zones around the facility.

Project information

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1 Introduction

A hydrogen facility is planned built on Eigerøy as part of the EU project ROBINSON, which aims to facilitate decarbonization of islands. Green hydrogen will be produced through water electrolysis and delivered to an energy management system, which will integrate technologies used in different energy sectors. Produced hydrogen which is not used by the ROBINSON system will be compressed and transferred to storage containers, which will be transported by trucks to external clients.

According to §20 of the Fire and Explosion Prevention Act (*brann- og eksplosjonsvernloven*) facilities that handle dangerous substances are obliged to ensure a satisfactory level of safety for people, environment, and surroundings. The risk should be reduced to a level as low as reasonably practicable. Safety should be established through technical and organizational measures, if necessary combined with restrictions on activities in neighbouring areas.

In order to identify potential hazards related to activities at the facility, a HAZID workshop has been facilitated and documented by Gexcon [1]. The quantitative risk analysis (QRA) summarized in this report is to a large extent based on information gathered through the HAZID. The main object of the QRA is to estimate individual risk for third parties. The results are presented as risk contours, which may be used for establishing consideration zones according to risk acceptance criteria set forth by The Norwegian Directorate for Civil Protection (DSB) [2]. The analysis has been performed according to DSB's guidelines for quantitative risk analysis of facilities handling hazardous substances [3], hereby referred to as *DSB's guideline*.

It should be noted that the current analysis only covers the hydrogen facility, i.e. the electrolysers, buffer tank, compressors, transportable storage containers, and related operations. The ROBINSON project involves several other components handling hazardous substances, such as an AD-BES system for converting liquid waste into biomethane, an LNG/LPG tank, a gas-mixing unit, and a CHP unit for converting mixed gas into heat and power. These components should be included in the QRA when their design has matured. However, since they are planned located at some distance from the hydrogen facility, the effect on risk around the hydrogen facility from the other components is expected to be limited.

1.1 Abbreviations

AD-BES	Anaerobic Digester assisted by Bio-Electrochemical Systems
CHP	Combined Heat and Power
DSB	The Norwegian Directorate for Civil Protection
HAZID	Hazard Identification Study
LEL/LFL	Lower Explosion Limit/Lower Flammability Limit
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSIR	Location Specific Individual Risk
P&ID	Piping and Instrumentation Diagram
QRA	Quantitative Risk Analysis

1.2 Input to analysis

The QRA has been based on the following documentation provided by Dalane Hydrogen:

- 200100703-47-P-XB-001 Electrolyser
- 200100703-47-P-XB-002 Buffer Vessel
- 200100703-47-P-XB-003 H2 Compressor
- 200100703-47-P-XB-005 Flow control, Distribution and Storage
- 200700101-93-R-XE-001 Layyout H2 Container
- Vedlegg A - P&ID 20ft UMOE Container
- 902-0038 - P&ID - 40' Container - rev01.05

- 200100703-47-P-XA-001 PFD - H2 production, Compression and storage
- 900-0032_rev1 HyProvide A-Series Operation Manual
- 200700103 Technical description H2 Container
- Designbasis_Utkast - Forprosjekt Dalane
- Various information exchanged via email and meetings

2 System description

2.1 Location

The hydrogen facility is planned built on gnr. 8 bnr. 481 in Eigersund municipality. The location is indicated by a green star in Figure 2-1.

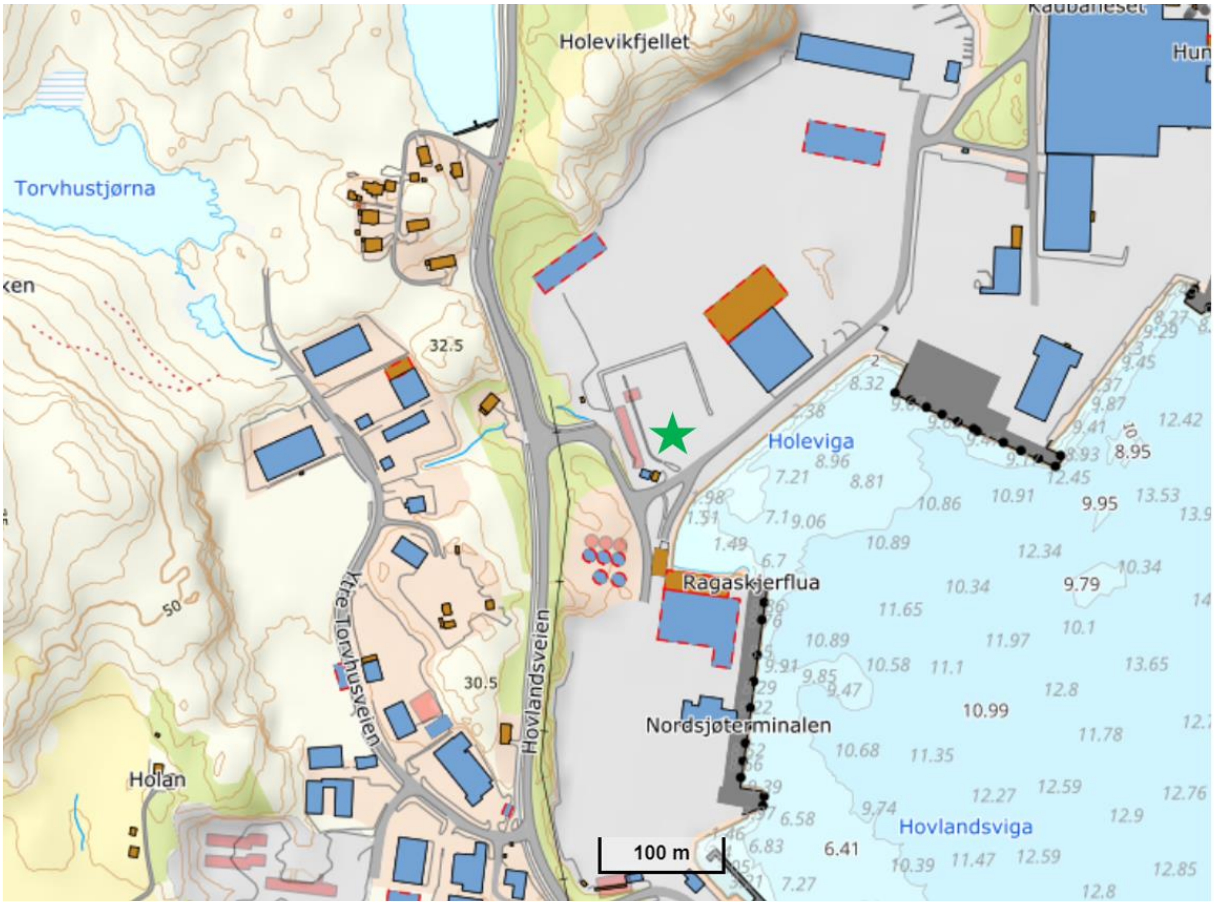

Figure 2-1: Location of planned hydrogen facility indicated by green star. *Source: norgeskart.no*

An updated situation plan for the area is given in Figure 2-2, which also shows objects considered relevant with respect to the risk acceptance criteria set forth by DSB [2]:

1. New public road: 21 m from facility
2. Industrial building: 43 m from facility
3. Industrial building: 57 m from facility
4. Residential house: 113 m from facility
5. Containing public restrooms: 5 m from facility

Based on input from Dalane Hydrogen, the building containing public restrooms may be removed if necessary.

The facility is surrounded by flat and open terrain towards north, east, and south. As indicated by the situation plan, the terrain slopes upwards towards the roads located to the north-west and south-west of the facility.

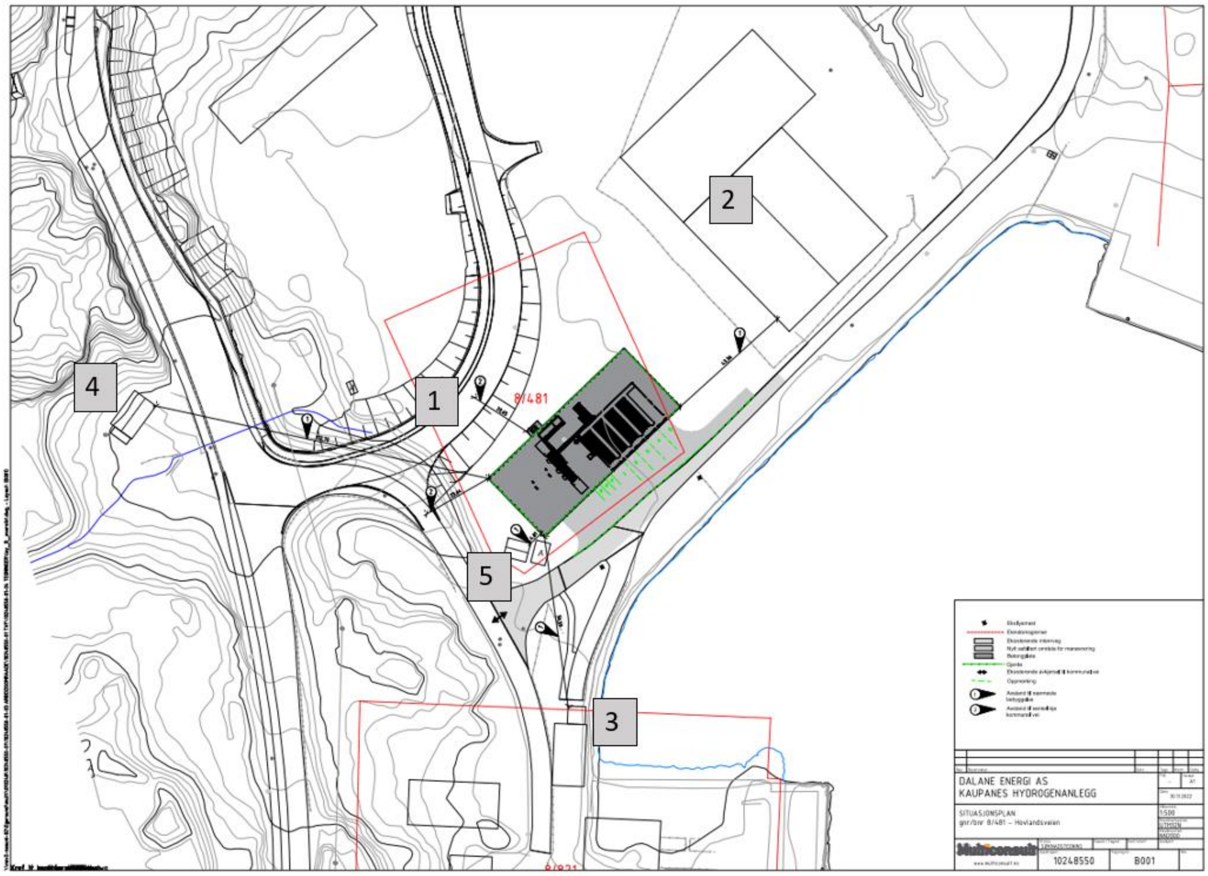

Figure 2-2: Layout of hydrogen facility and nearby objects according to situation plan. *Source: Multiconsult*

2.2 Facility

A preliminary 3D model of the hydrogen facility is shown in Figure 2-3. Hydrogen is produced from water and electricity in two electrolysers placed in a dedicated container (1). The hydrogen is scrubbed, deoxidised and dried, and then transferred to a buffer tank (3). From the buffer tank, the hydrogen is routed either towards Prima Protein for use by the ROBINSON energy management system, or towards a compressor container (4). Cooling of the compressors is provided by a dedicated cooling system installed in a separate utility container (2). Compressed hydrogen is transferred to storage containers (5), which are transported by trucks to external clients.

The electrolysers have a total effect of 0.86 MW, which corresponds to a hydrogen production of 16.2 kg/h. While only two storage containers are indicated in Figure 2-3, the QRA assumes that four full containers are present at the facility. This implies a total amount of stored hydrogen of approx. 3000 kg.

Access control to the facility is provided by fences and gates. The facility will usually be unmanned during normal operation, except for the personnel involved in the filling operations and loading/unloading of storage containers.

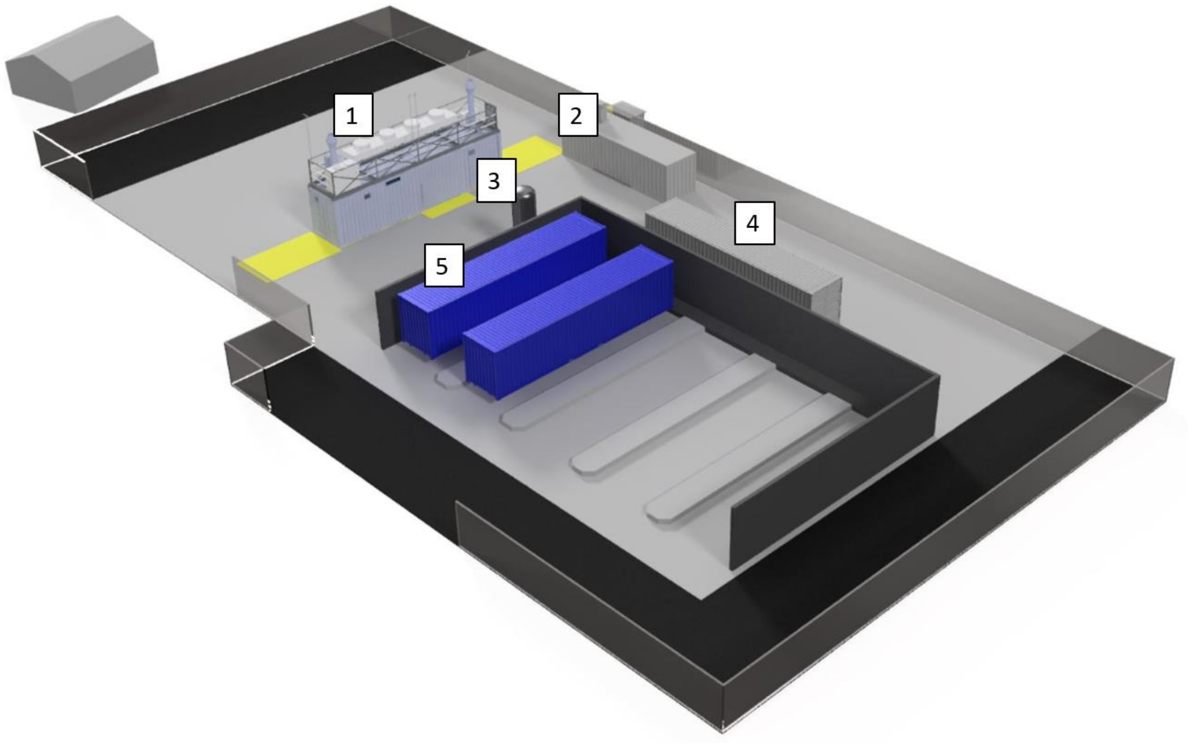

Figure 2-3: Preliminary 3D model of hydrogen facility (not updated to match the most recent situation plan). *Source: Dalane Hydrogen*

2.3 Weather data

Wind data for the facility has been based on meteorological statistics from a weather station at Eigerøya, downloaded from Norsk Klimaservicesenter at seklima.met.no. The resulting wind rose is shown in Figure 2-4, and indicates dominating wind directions from north-west and south-east.

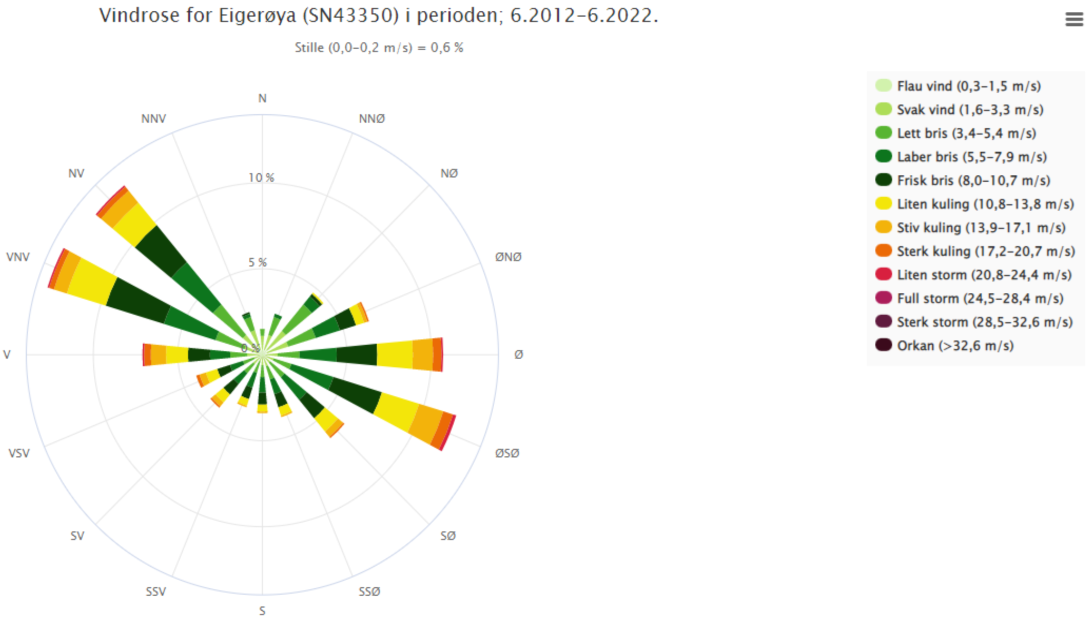

Figure 2-4: Wind rose applied in QRA.

3 Risk modelling

3.1 Scope

This analysis evaluates risk related to activities at the hydrogen facility. Risk associated with transport of storage containers between the facility and external clients has not been considered. For the hydrogen transfer pipe towards Prima Protein, which will be buried between the facility and Prima Protein, risk is calculated for the part of the pipe located above ground at the facility.

Only individual risk for third parties has been considered. Risk for first and second parties has not been evaluated[1].

3.2 Initiating events

Initiating events with major accident potential which were identified in the HAZID are all related to release of hydrogen gas from the different components. (Other hazardous substances, such as nitrogen, oxygen, propylene glycol and lye are also handled at the facility, but are not considered to imply significant third-party risk.)

The hydrogen system is equipped with a pressure relief system, which ensures that overpressure in the process is vented out before reaching critical levels. The QRA assumes that the pressure relief system is designed in a safe manner, such that associated hydrogen releases do not pose significant risk. Such releases are thus not considered further in this analysis.

A qualitative assessment of hydrogen leakages from different parts of the facility, that are assumed to have major accident potential, is given below.

3.2.1 Electrolysers

The 40 ft container housing the electrolysers is divided into three separate rooms: two process rooms and one power/utility room. Each process room contains an electrolyser module producing hydrogen gas through alkaline water electrolysis. The hydrogen is scrubbed, deoxidised and dried before being routed towards the buffer tank at a pressure of up to 35 barg.

The process rooms are mechanically ventilated and equipped with hydrogen and fire detection. Upon detection of 10% of LEL the system will be shut down, and non-ATEX equipment will be de-energized.

A hydrogen leakage from pressurized equipment in the process rooms will hit equipment and walls, lose momentum and get mixed with air before being vented out through the ventilation outlet. The leakage may have a high initial release rate, which will drop rapidly due to reduced pressure, as there is only approx. 0.7 kg hydrogen present in the system. (There is a check valve on the outlet of the electrolyser container, in addition to an ESD valve, so backflow from equipment downstream the leakage is expected to be limited.)

3.2.2 Buffer tank

The purpose of the buffer tank is to reduce pressure variations in case of changes in hydrogen consumption at Prima Protein, and to provide a buffer volume for the compressors. The buffer tank has a volume of 5 m^3 and is protected by a pressure safety valve with a set pressure of 35 barg, corresponding to the tank's design pressure.

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[1] A first party is someone who is directly involved in the operation of the facility. A second party is someone who is not directly involved in the operation, but has an interest in the facility. A third party is someone who is indirectly affected by the facility, such as neighbours or random passersby.

A leakage from the buffer tank may give rise to a gas jet with high momentum and long duration, as the available volume is relatively large and effective shutdown is not possible.

3.2.3 Compressors

From the buffer tank the hydrogen is routed either towards Prima Protein or the compressor container. The compressor container contains two three-stage hydraulic piston compressors, which are operated in parallel and increase the hydrogen pressure to 350 barg.

The container has a single room, which is equipped with hydrogen detection and designed for natural ventilation. The entire room is defined as an ATEX zone. (Non-ATEX control equipment related to the compressor system is installed in the utility container.) Pressure relief panels are installed in the roof, to allow for safe pressure venting in the event of an explosion inside the container.

A leakage from pressurized equipment inside the container may have a high initial speed, but will hit equipment and walls and lose momentum before being vented out through the ventilation openings.

3.2.4 Transfer to storage containers

From the compressor container, the hydrogen is routed towards the storage area, where it is transferred to a storage container through a flexible filling hose. The hose is protected by a breakaway coupling, which will be released at a certain load and automatically close the internal valves on both sides. This will limit potential releases caused by stretching of the hose.

Should a release still occur during the transfer operation, the resulting jet may have a high initial speed. However, the jet is very likely to hit a wall or container and lose momentum before escaping the storage area.

3.2.5 Storage containers

The transportable 40 ft storage containers consist of 18 horizontal cylindrical fiberglass bottles, with a total capacity of approx. 734 kg hydrogen gas at 350 barg (assuming an ambient temperature of 15 deg C).

The bottles are interconnected in six batteries, and each battery has instrumentation for surveillance of pressure and temperature, and a dedicated actuated valve for controlling the filling sequence. Each battery also has a thermal pressure relief device (TPRD), which ensures pressure relief to a safe location if the temperature reaches a certain level, e.g. due to a fire. The containers are naturally ventilated by vent openings in the floor, roof, and walls. The floor is elevated from the ground by a chassis, enabling air flow through the floor vents.

A leakage from a storage container is assumed to hit bottles and walls and lose momentum, before escaping through the ventilation openings. The release duration is likely to be long, as the available volume is relatively large (even if the leakage is limited to a single battery).

3.2.6 Pipelines

Transfer of hydrogen between the different modules at the facility is provided by piping supported by a piperack mounted above the ground.

A leakage from a pipe above the ground may give a gas jet with high momentum. Measures for detecting outdoor leakages are not implemented in the design, so the release duration is likely to be long.

3.3 Segmentation

The hydrogen system is logically split into isolatable segments by the emergency shutdown (ESD) system. After successful shutdown, any leak from a given segment will be limited to the inventory of that segment. The segments comprising the hydrogen system are listed in Table 3-1. A process flow diagram for the hydrogen system, indicating the segmentation by coloring, is shown in Figure 3-1.

Table 3-1: Segments included in the hydrogen system.

Segment no.	Description	Pressure (bara)	Temperature (deg C)	Inventory (kg)
1	Electrolysers	31	15	0.72
2	Buffer tank	31	15	15
3	Compressors	191	15	0.237
4	Compressor discharge	351	15	0.025
5	Transfer to container	351	15	0.005
6	Storage container no. 1	351	15	734
7	Storage container no. 2	351	15	734
8	Towards Prima Protein	11	15	0.39
9	Storage container no. 3 and 4	351	15	1474

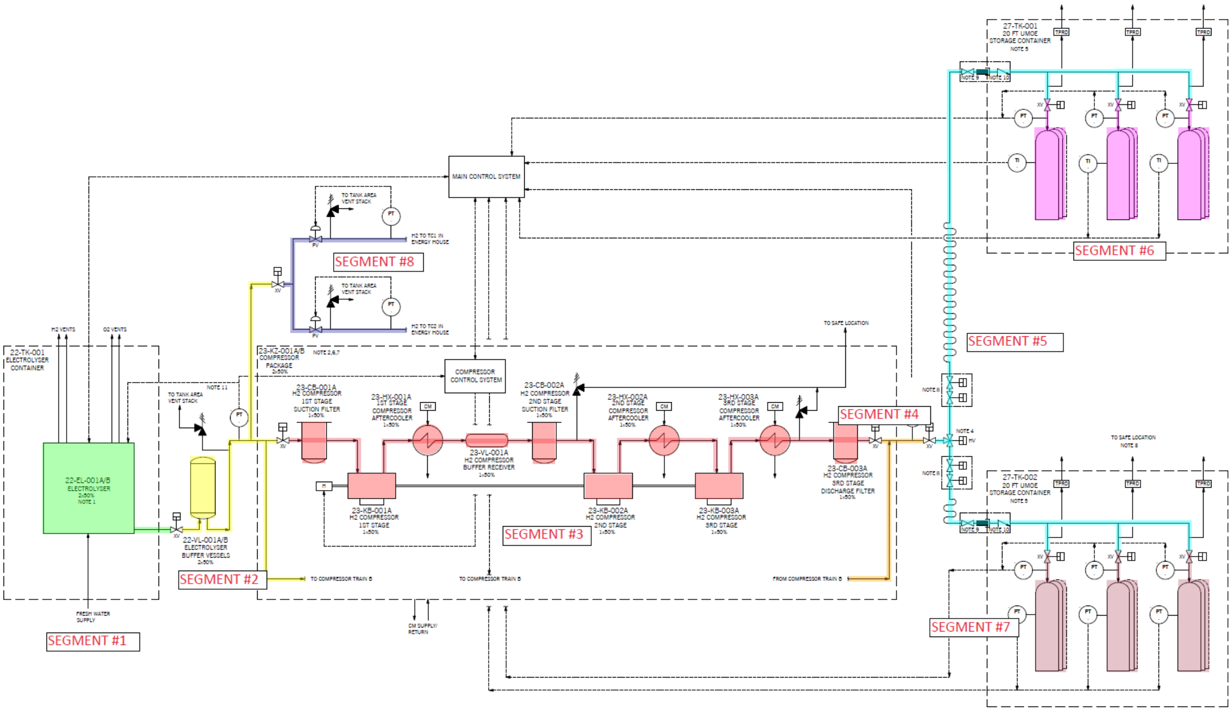

Figure 3-1: Process flow diagram for hydrogen system. *Source: Dalane Hydrogen*

3.4 Leak frequencies

Leak frequencies for the hydrogen system have been estimated based on the HyRAM model [4], with equipment counts from P&IDs as input. HyRAM is based upon analyses performed at Sandia National Laboratories [5], and is the leak frequency model recommended by DSB's guideline for facilities handling hydrogen. For each of the covered equipment types, the HyRAM model suggests a leak frequency per component for leak areas of 0.01 %, 0.1 %, 1 %, 10 %, and 100 % of the assumed flow area through the component. For pipes, the frequencies are given per meter piping. Leak frequencies for filters have been reduced by a factor of 10, also in line with DSB's guideline.

Calculated yearly leak frequencies distributed on segments and hole diameters are shown in Table 3-2. Only leaks with hole diameters of at least 0.5 mm have been included, as smaller leaks are assumed not to have major accident potential. The results suggest a total yearly leak frequency of approx. 1.93E-01. The segments giving the largest contributions to the leak frequencies are the compressors (4.68E-02), the buffer tank (2.66E-02), and the storage containers (2.62E-02 per container).

Table 3-2: Leak frequencies distributed on segments and hole diameter categories.

Segment no.	**Description**	**Very small (0.5-2 mm)**	**Small (2-6 mm)**	**Medium (6-10 mm)**	**Large (10-20 mm)**	**Very large (20-80 mm)**	**Rupture (>80 mm)**	**Sum**
1	Electrolysers	2.76E-03	8.13E-04	0.00E+00	4.52E-04	0.00E+00	0.00E+00	**4.02E-03**
2	Buffer tank	2.42E-02	1.66E-03	0.00E+00	7.24E-04	4.13E-06	1.47E-06	**2.66E-02**
3	Compressors	3.50E-02	7.30E-03	0.00E+00	4.51E-03	0.00E+00	0.00E+00	**4.68E-02**
4	Compressor discharge	8.69E-04	6.79E-04	1.38E-04	1.72E-04	0.00E+00	0.00E+00	**1.86E-03**
5	Transfer to container	2.30E-03	1.28E-03	5.85E-04	0.00E+00	0.00E+00	0.00E+00	**4.16E-03**
6	Storage container no. 1	1.79E-02	5.62E-03	2.33E-03	3.17E-04	0.00E+00	0.00E+00	**2.62E-02**
7	Storage container no. 2	1.79E-02	5.62E-03	2.33E-03	3.17E-04	0.00E+00	0.00E+00	**2.62E-02**
8	Towards Prima Protein	3.49E-03	7.06E-04	0.00E+00	2.48E-04	4.40E-06	0.00E+00	**4.45E-03**
9	Storage container no. 3 and 4	3.58E-02	1.12E-02	4.65E-03	6.34E-04	0.00E+00	0.00E+00	**5.24E-02**
Sum		**1.40E-01**	**3.49E-02**	**1.00E-02**	**7.37E-03**	**8.53E-06**	**1.47E-06**	**1.93E-01**

In reality, the third-party risk will depend on the activity level at the facility, e.g. on the number of filling operations of storage containers, the number of containers present, and their filling level. In this analysis, it is assumed that four full storage containers are present all year. Regarding the filling operations, it is assumed in the QRA that both flexible transfer hoses are pressurized all year. It may be argued that leak frequencies for transfer hoses should rather be based on the number of transfer operations per year, as this may have a larger impact on wear and tear on the hose, frequencies for operator errors, etc. Shell has conducted a study of leak frequencies for standard LNG fuelling hoses, which are assumed to be subject to a similar safety regime as the hydrogen transfer hoses (breakaway couplings, process detection, frequent inspections and testing). Based on this study, Shell proposes a frequency of 2.9E-07 per operation for larger hose leaks. The HyRAM model used in the current analysis assumes a yearly frequency of 2.1E-04 per hose for the two largest hole categories. This is on a level with the Shell frequency if one assumes two filling operations per day per hose, that is, a total of four filling operations per day at the facility.

It is assumed in the analysis that procedures are in place for avoiding hydrogen leakages caused by loading and unloading of the storage containers, e.g. as a consequence of collision between the truck and pressurized equipment. Furthermore, it is assumed that the containers are approved for transport of dangerous goods according to the ADR directive, and that the transport itself does not affect the leak frequencies of the containers while present at the facility.

3.5 Ignition probabilities

HyRAM implements a time-independent ignition model based on leak rate, where 1/3 of ignitions are delayed ignitions (explosion/flash fire potentially followed by fire) and 2/3 are immediate ignitions (fire). DSB's guideline recommends using HYEX, which is a refined version of the HyRAM model. The ignition probabilities proposed by the two models are shown in Figure 3-2. In the current analysis, for releases causing flammable gas exposure only within the fenced area controlled by the facility, ignition probabilities corresponding to the maximum of the probabilities given by these models are applied.

For releases causing flammable gas exposure outside the fenced area, a total ignition probability of 1 is assumed. This is also in line with DSB's guideline, and reflects that no restriction of public access nor ignition source control can be expected outside of this area.

Notably, the risk calculations documented in this report assume that the fenced area is extended by 3 m towards north-west, as this has been observed to give a significant reduction of the estimated risk (in particular by reducing the ignition probabilities for the flammable releases from the compressor container).

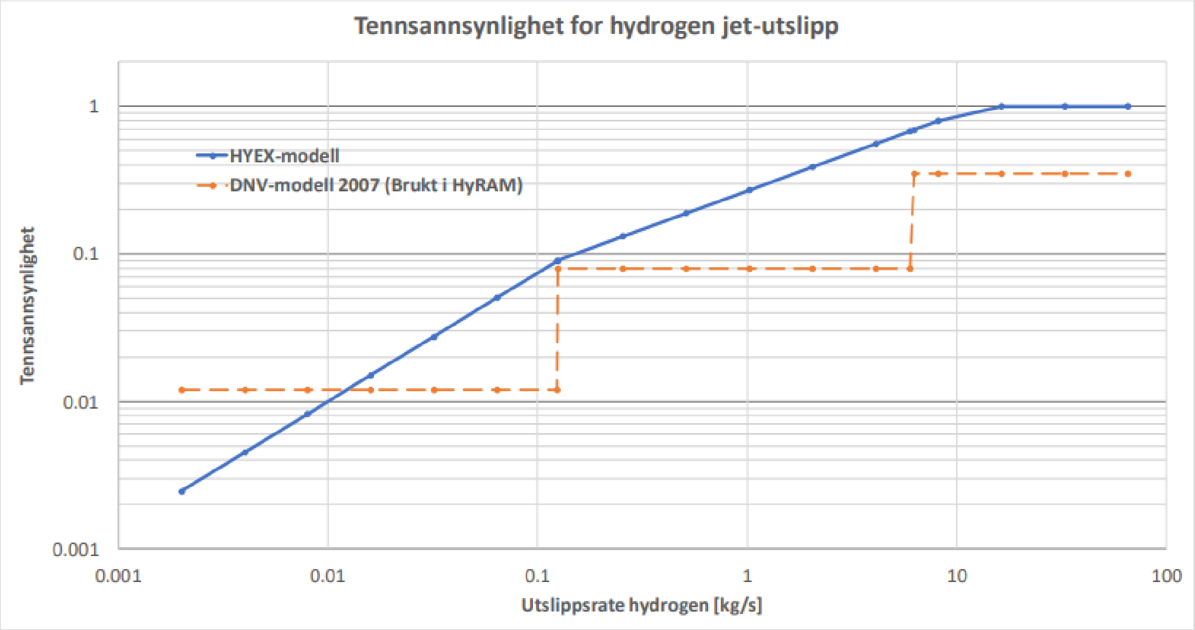

Figure 3-2: Ignition probabilities as functions of release rate (kg/s) according to the HyRAM and HYEX models. *Source:* [3]

3.6 Consequence modelling

3.6.1 Modelling tools

Potential consequences of leakages have been modelled with Gexcon's empirical tool EFFECTS/RISKCURVES version 12 (hereby referred to as RISKCURVES). Originally based on the TNO Colored Books, RISKCURVES has been expanded and improved for more than 35 years, and is accepted and used worldwide for a wide variety of risk studies.

3.6.2 Leak rates

Representative leak rates have been calculated by RISKCURVES for each segment and each hole diameter category in Table 3-2. These are calculated as initial rates through a hole with diameter given by the arithmetic mean of the category limits, from a reservoir with process conditions given by Table 3-1, and with a discharge coefficient of 0.85. (Releases in the category "Rupture" from the buffer tank have been modelled as an instantaneous release of the entire tank inventory.) This is a conservative approach, which does not take into account that the rate may drop due to decreasing pressure, especially if the available volume is small and the release rate higher than the normal flow rate of the system. An exception has been made for the electrolysers and compressors, where the largest applied release rate is calculated based on a release of the entire container inventory in 3 seconds.

3.6.3 Leak durations

The duration of a leak will depend on the time to detection and shutdown, as well as the remaining segment inventory after shutdown. The hydrogen system is subject to a comprehensive process control system, and leakages are in general assumed to cause shutdown within short time due to deviating process conditions. The electrolyser and compressor containers are equipped with hydrogen detection. Filling operations of containers will be monitored by personnel, which may initiate shutdown manually. When evaluating the leak durations for different parts of the facility, the following assumptions have been applied:

- For leaks from the buffer tank and the storage containers, where shutdown will have limited effect, the leak is assumed to last until the leaking battery/tank is empty.
- For leaks from piping outdoors, where leak detection may be difficult, the leak is assumed to last until the flammable cloud reaches steady state.
- For leakages from the transfer system during filling of containers, shutdown within 20 s is assumed, due to process or manual detection.
- For leakages inside the electrolyser and compressor containers, leak rates below 10 g/s are assumed to cause shutdown before build-up of an explosive cloud which may harm third parties. For leak rates of at least 10 g/s, shutdown is assumed to occur within 20 s.

3.6.4 Gas dispersion

Gas dispersion from the different leak scenarios is modelled with an ambient temperature of 15 deg C, which is considered typical for Eigerøya. Leakages from the buffer tank and other equipment/piping located outdoors are modelled directly as horizontal jet releases 1 m above the ground. Leakages from the electrolysers and compressors are also modelled as horizontal releases 1 m above ground. However, while the release rates correspond to the actual hole size, these releases are modelled with hole diameters based on the area of the vent openings of the containers. Leakages from the storage containers are modelled in a similar way, but are located 2.5 m above the ground and directed upwards, as they are assumed to be obstructed by the walls surrounding the storage area and/or neighboring storage containers.

3.6.5 Ignited events

Ignited events which may be caused by a hydrogen leakage at the facility are jet fires, flash fires, and explosions. Immediate ignition of the leakage will result in a jet fire. Delayed ignition, where a flammable gas cloud has developed over time, will cause a flash fire or explosion, which may burn back to the source and continue as a jet fire. If the gas cloud is located in an open area, a flash fire will occur, which is characterized by a short-term heat radiation without significant overpressures. A gas cloud in a congested and/or confined area may on the other hand cause an explosion, which also represents an overpressure hazard.

Jet fires considered in this analysis are modelled in a similar manner as gas dispersion: Jet fires from outdoor equipment/piping are modelled directly from horizontal jet releases 1 m above ground, while jet fires from the electrolysers and compressors are modelled with adjusted hole diameters based on the vent openings. Finally, jet fires from the storage containers, which are assumed to be obstructed by walls and/or neighboring containers, are located 2.5 m above the ground and directed upwards.

For delayed ignition, the general assumption applied in the QRA is that the flammable cloud ignites at its largest extent. Furthermore, to reflect that hydrogen is a highly explosive gas, delayed ignition is assumed to always cause an explosion. Overpressure from explosions is estimated by the TNO Multi-Energy method, which is implemented in RISKCURVES. For leakages inside the electrolyser and compressor containers, it is assumed that the source pressure will primarily be generated by hydrogen gas inside the container. For such explosions the hydrogen mass in the flammable cloud is calculated based on estimated hydrogen concentration inside the container at the assumed shutdown time. It should be noted that flash fires are not included in the risk calculations for such scenarios, as the overpressure from the explosion is assumed to cause worse consequences. (RISKCURVES gives relatively short distances to flammable concentrations for the modelled low momentum releases from the vent openings.) For explosions inside the storage containers, it is assumed that hydrogen gas fills the entire open volume, and the explosive mass is calculated based on this volume, in addition to the flammable cloud calculated for the vent release. (The latter is added to reflect that the cloud outside the container may be confined by walls and/or containers, and thus cause significant overpressure upon ignition.) If an explosion occurs inside a storage container, it is considered likely that the hinged doors at the back of the container will be blown open. For an unfavorable release location and direction this may lead to an unobstructed jet fire pointing out through the open doors. This has been accounted for by direct modelling of horizontal jet fires 1 m above the ground for these specific scenarios.

An important input parameter to the Multi-Energy method is the curve number describing the type of explosion. This number, which is specified by the user, may vary from 1 (“Very weak deflagration”) to 10 (“Detonation”). A study has been performed by Air Liquide [6] for evaluating which curve number best represents different types of hydrogen leakages. The conclusion from the study is that, for free jet releases, curve number 4 should be used for release rates below 100 g/s, 5 for rates between 100 and 1000 g/s, and 6 for rates above 1000 g/s. For obstructed jet releases curve number 10 is recommended.

It is considered that leakages from outdoor equipment/piping, which are modelled as direct jet releases, to a large extent will be free, but that some obstruction may occur from the ground and nearby equipment/walls. Based on this curve number 7 has been used for these leakages. Leakages inside containers are considered as obstructed jet releases, thus curve number 10 has been used for these scenarios.

3.7 Vulnerability

Lethality from jet fires has been calculated by RISKCURVES based on a threshold value for heat radiation of 35 kW/m^2, which implies a lethality of 1, in addition to a probit function. The probit function, which also accounts for the duration of the heat exposure, is based on the TNO Green Book (11), and is defined by:

$Pr = -36.38 + 2.56 \ln (q^{4/3} * t)$,

where q denotes the heat radiation level in W/m2, and t denotes the exposure duration in seconds. The maximum heat exposure duration has been set to 30 s, and no protection from clothing has been assumed.

For flash fires, the lethality has been set to 1 within the flame contour and 0 elsewhere. For explosions, lethality from overpressure effects has been set to 1 for areas with overpressure above 400 mbar, and 0 elsewhere.

The above assumptions are in line with the recommendations given by DSB’s guideline for evaluation of lethality from ignited events.

4 Results

4.1 Consideration zones

DSB has defined consideration zones for facilities handling hazardous substances. The definitions are based on location specific individual risk (hereby referred to as *individual risk*), e.g. assuming that a third party is constantly present and exposed to the risk:

- **Inner zone (inside the 10^{-5} contour for individual risk per year):**
  This is primarily the organisation's own area, but may also include e.g. agricultural, natural and recreational areas (LNF-områder). Only momentary bypass for third parties (footpaths etc.) can be included in this zone. The population of concern in this area is the personnel at the facility.

- **Central zone (between the 10^{-5} and 10^{-6} contour for individual risk per year):**
  Public road, railway, quay and the like. Permanent jobs in industrial and office operations can also reside here. In this zone, there shall be no accommodation or housing. Scattered residential buildings may be accepted in some cases. Central zone is mainly designated to personnel on businesses near the plant (adjacent plants) and sometimes arterial roads, and random residence of people.

- **Outer zone (between the 10^{-6} and 10^{-7} contour for individual risk per year):**
  Areas regulated for residential purposes and other uses of the general population may be included in the outer zone, including stores and smaller accommodations. Outer zone considers areas where the population normally reside.

- **Outside outer zone (outside the 10^{-7} contour for individual risk per year):**
  Schools, kindergartens, nursing homes, hospitals and similar institutions, shopping centres, hotels or large public venues must normally be placed outside the outer zone. Individuals who are particularly vulnerable are expected to be placed here.

4.2 Risk contours

Individual risk for third parties has been calculated by RISKCURVES based on:

- Weather data as described in Section 2.3
- Initiating events as described in Section 3.2
- Leak frequencies as described in Section 3.4
- Ignition probabilities as described in Section 3.5
- Consequence modelling as described in Section 3.6
- Vulnerability as described in Section 3.7

RISKCURVES collects frequency contributions to lethality from all consequences and combines these into an overview of individual risk at all points. Based on this overview contours may be drawn that correspond to the consideration zone limits described above.

Estimated individual risk contours for the hydrogen facility are shown in Figure 4-1 and indicate that:

- The new public road is located outside the 10^{-5} contour
- The nearest industrial building is located outside the 10^{-9} contour
- The nearest residential building is located outside the 10^{-9} contour
- The building containing public restrooms is located outside the 10^{-5} contour

The results suggest that, based on the current objects and activities around the facility, the calculated risk is acceptable according to the criteria set forth by DSB.

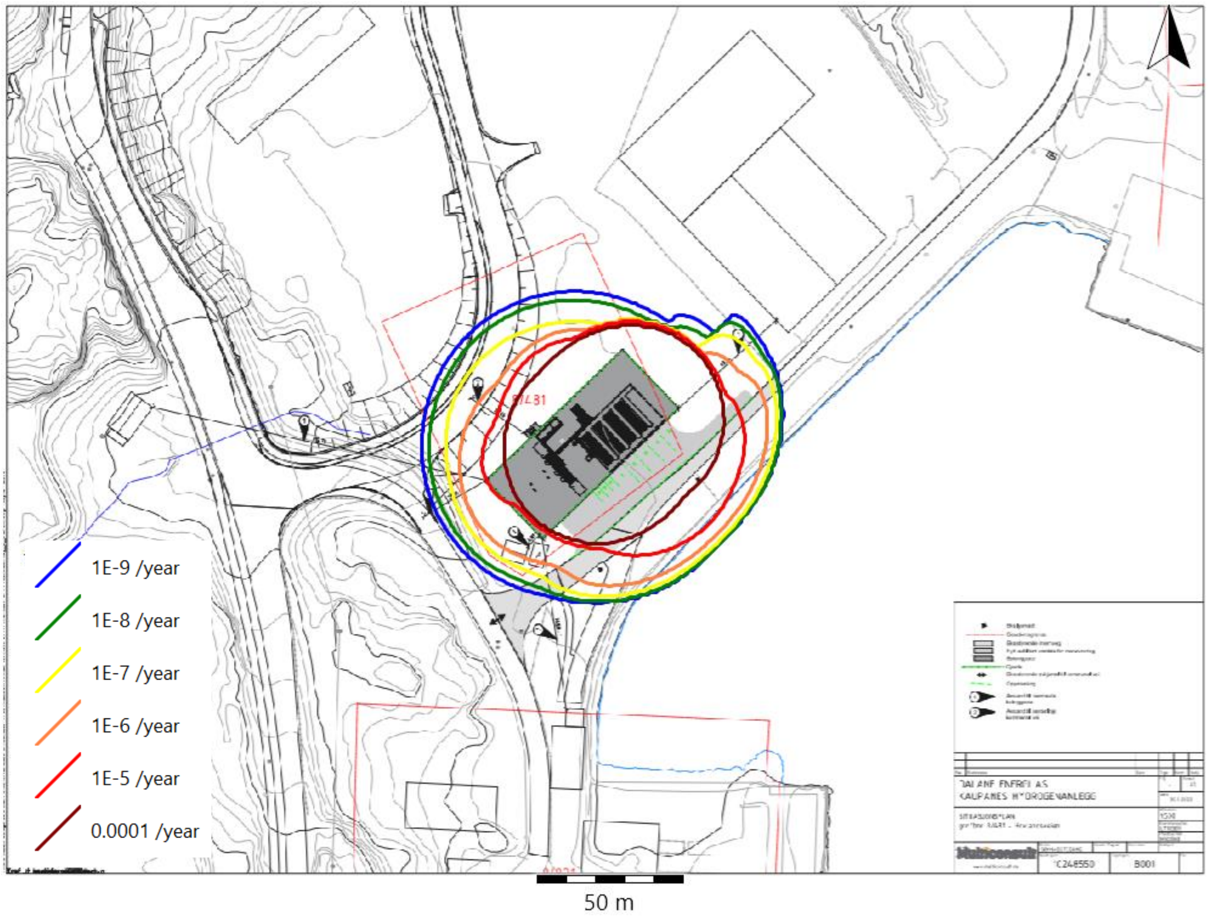

Figure 4-1: Estimated risk contours for the hydrogen facility: 10^{-4} (dark red), 10^{-5} (red), 10^{-6} (orange), 10^{-7} (yellow), 10^{-8} (green), 10^{-9} (blue).

4.3 Risk distribution

The contributions to the 10^{-5} risk contours from the different modules are shown in Figure 4-2, and indicate that the largest contribution is due to the storage containers.

The distribution of risk between different consequences may also be of interest. Figure 4-3 shows the 10^{-5} risk contour from flammable cloud exposure, the 10^{-5} risk contour from overpressure, and the 10^{-5} frequency contour for exposure to heat radiation of 15 kW/m^2 (which implies a lethality of approx. 50% for 30 s exposure). The contours suggest that overpressure (from explosions) and heat radiation (from jet fires) both give large contributions to risk, while the flammable cloud risk (from flash fires) is less significant.

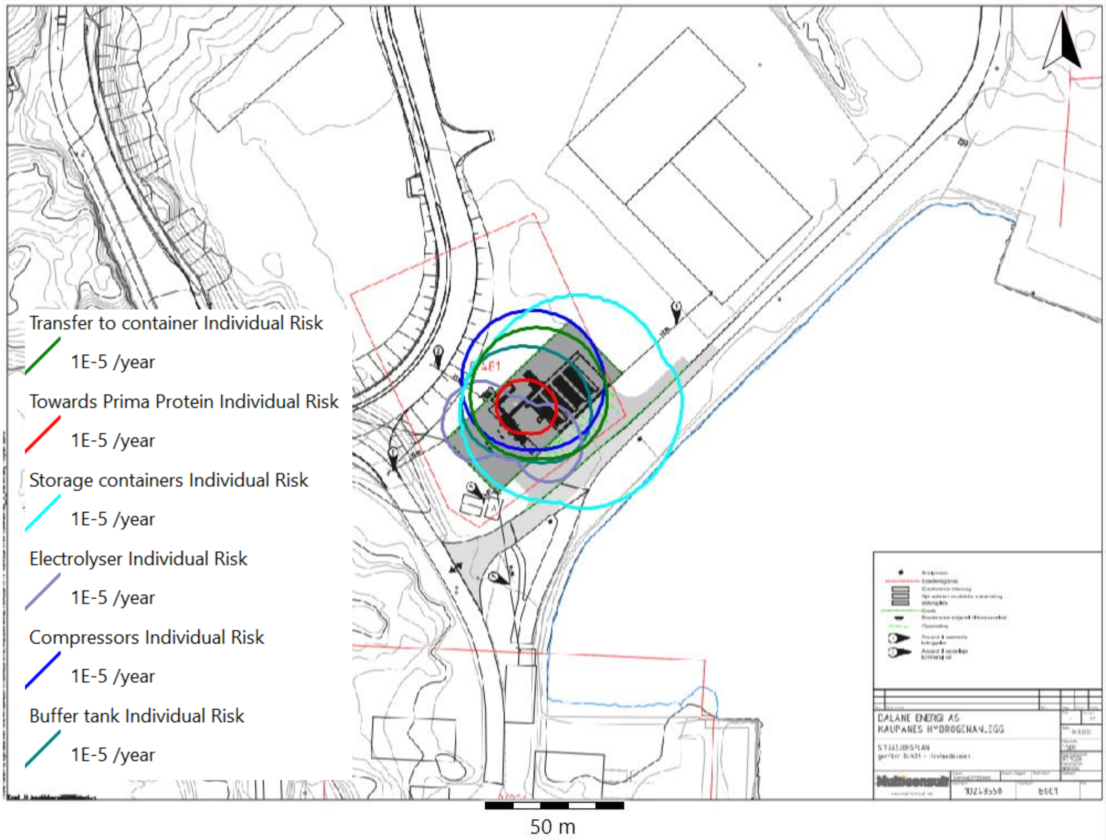

Figure 4-2: Contributions to the 10^{-5} risk contour from different modules.

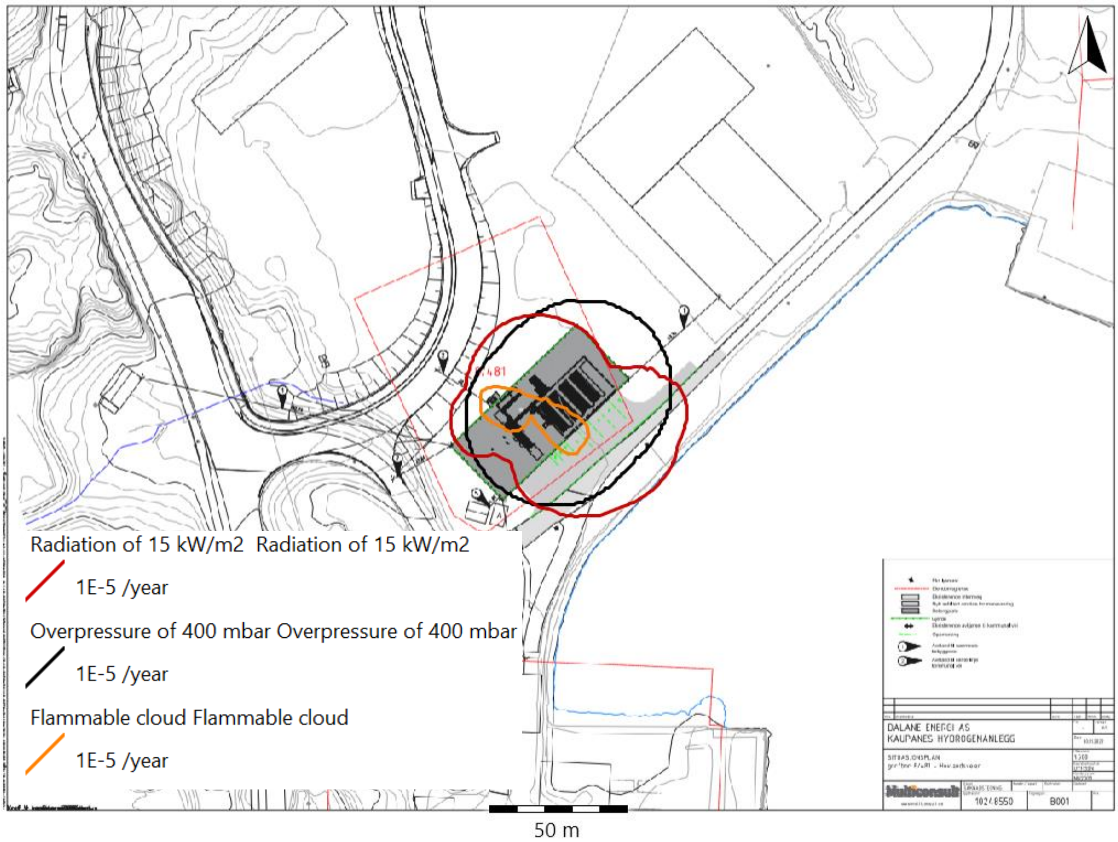

Figure 4-3: 10^{-5} frequency contours for different consequences.

5 Conclusions and recommendations

A QRA has been performed for a hydrogen facility planned built on Eigerøy as part of the ROBINSON project. Individual risk for third parties has been estimated and presented as risk contours, which may be used for establishing consideration zones around the facility. The risk contours indicate that, given the current objects and activities around the facility, the calculated risk is acceptable according to the criteria set forth by DSB.

The risk analysis has been performed using empirical consequence models, which give less accurate results than a CFD tool such as FLACS. In particular, the sloping terrain towards west has not been accounted for. The overall estimated risk is expected to be on the conservative side, e.g. due to conservative ignition probabilities and explosion modelling.

It should be noted that the ROBINSON project involves several other components handling hazardous substances. These components should be included in the QRA when their design has matured. However, since they are planned located at some distance from the hydrogen facility, the effect on risk around the hydrogen facility from the other components is expected to be limited.

The risk analysis has been performed before the design has been finalized. If significant design changes are considered, Gexcon should be notified, and the need for updating the risk analysis should be evaluated.

A premise for the validity of this report is that relevant rules and regulations are adhered to, and that engineering, construction, commissioning and operation of the facility will be based on best industry practises. In particular, the following assumptions are made, which should be verified at later stages of the project:

- The ATEX directive is adhered to with respect to zone classification and equipment to be used in ATEX zones.
- Pressure relief devices are provided for pressurized equipment in accordance with the PED directive.
- Grounding of equipment is provided according to NEK 400, and lightning protection is provided according to EN 62305 (or equivalent standards).
- Procedures will be established for minimizing risk related to loading and unloading of storage containers.
- Procedures will be established for regular inspection, pressure testing and replacement of filling hoses.

It should also be noted that the current risk calculations assume that the fenced area is extended by 3 m towards north-west, as this has been observed to give a significant reduction of the estimated risk (by reducing ignition probabilities).

With respect to reducing the risk to a level as low as reasonably practicable, the measures described below should be considered. (These measures are not assumed implemented in the risk analysis.)

- For limiting the duration of outdoor leakages, which may be hard to detect by gas detectors, acoustic sensors should be considered.
- For reducing the risk related to the buffer tank, a low physical barrier around the tank should be considered, for protection against collisions with vehicles.
- A closed construction of the fence should be considered, for reducing flammable gas exposure outside the facility.

6 References

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[4] Sandia National Laboratories, "Hydrogen Risk Assessment Model (HyRAM)," [Online]. Available: https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/hydrogen-risk-assessment-model-hyram/.

[5] H. M. a. F. LaChance, "Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen," Sandia National Laboratories, 2009.

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