SITING AND CO-LOCATION WITH HYDROGEN: WHAT ARE THE RISKS?

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ABSTRACT

The demand for hydrogen has grown more than threefold since 1975 [1], and price is expected to significantly decrease by 2030 [2] concluding in an expected continual increase in demand. HyLaw, defined by Hydrogen Europe, lays out recommendations for hydrogen applications using identified Legal and Administrative Processes (LAPs) across 18 European countries. Regarding site location, HyLaw refers to the land use plan. This defines the production and storage of hydrogen as an industrial activity and therefore, regardless of the specific site methods of production or use, the hydrogen site must be within a permitted industrial zone or under specific condition commercial areas [3]. Local authorities, fire departments and other concerned parties may need to be consulted on site suitability for the project. Risktec explores a range of considerations for siting and layout of hydrogen developments, including co-location with other assets, for example with renewable energy sources, hazardous facilities or public structures. Good practice tools and assessment techniques are presented to mitigate the risks associated with the production, storage and use of hydrogen not just the surrounding site and environment, but the operatives of the facility.

1.0 INTRODUCTION

Hydrogen has been long recognised as an alternative to fossil fuels and a potentially valuable tool for tackling climate change. A hydrogen economy is a priority for the EU's post-COVID-19 economic recovery package; guided by the European Green Deal, which commits Europe to become the world's first climate neutral continent by 2050 [4].

Given the primary role hydrogen can potentially play in decarbonisation, there is rapid growth in new locations to account for the increased production, storage and use of hydrogen in high quantities. While centralised production of hydrogen at large scale can generate large amounts of hydrogen at low costs, in some cases, the production of hydrogen on-site (e.g. at a hydrogen refuelling station), in sufficient quantities to meet the demand of the site or to reduce the need of frequent distribution by truck and tube trailers, represents the better (or only) option [5]. In addition, green hydrogen generation may require co-location of the hydrogen production and storage units with renewable energy sources.

The production of hydrogen is still regarded as an industrial activity in all of the EU countries covered by the HyLaw project, irrespective of the production method, hence such activity would only be permitted in an area designated as an industrial zone or in commercial areas under specific conditions. The consequence of this is it would hamper the commercialisation and market reach of hydrogen as an alternative fuel [5].

Currently, there are no established guidance or standards regarding siting, co-location and layout of hydrogen developments covering both industrial and non-industrial hydrogen sites. This paper explores a range of considerations for siting hydrogen developments, including co-location with other assets e.g. with renewable energy sources, hazardous facilities or public structures. The scope of considerations presented in this paper have been majorly limited to production, storage and use of gaseous hydrogen as liquid hydrogen is still currently an area where significant uncertainties remain and further experimental work is required. Notwithstanding, much of the *process* discussed in this paper is equally applicable to liquid as gaseous hydrogen.

Good practice siting tools and guidance developed for the process industry i.e. oil, gas and chemical, and assessment techniques are presented to mitigate the risks associated with siting, co-location and layout of hydrogen facilities. While a majority of the considerations discussed in this paper are relevant to other hazardous fuels as well as hydrogen, factors specific to hydrogen have been highlighted. Facility siting and layout for hydrogen would generally follow the same processes as for other dangerous substances; however, the properties of hydrogen introduce different considerations. In some cases, these differences make siting and layout for hydrogen more difficult whilst in others, they make siting easier. It is possible to take advantage of the inherent properties of hydrogen, through siting and layout design, to embody the principles of inherent safety in design and significantly reduce risk.

2. FACILITY SITING

Siting involves finding an optimal site location for a facility. Given that it is among the earliest steps in the design of any high hazardous facility, appropriate siting consideration establishes a foundation for a well laid out site with a lower level of risk. As illustrated in Figure 1, some risk reduction measures are better than others and reduction is most effective at the earliest stages of design.

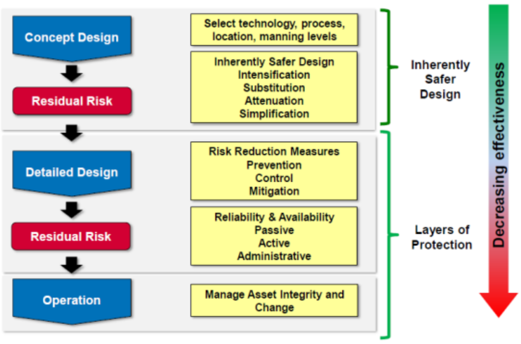


Figure 1. Risk reduction through a project lifecycle [6]

Factors associated with siting in this paper were derived from the guidance published by the Centre for Chemical Process Safety (CCPS) guidelines on facility siting and layout [7] which outlines key elements for siting of processing plants. However, given that the guidance was predominately aimed at siting oil and gas facilities, the characteristics of hydrogen have been taken into account for each factor and discussed here.

Hydrogen is highly reactive, diffusive, and 8 times more buoyant than methane. It has a broad flammability range (~4 to 74%) and a minimum ignition energy of 0.02 millijoules of energy to ignite a stoichiometric hydrogen–air mixture, which is less than 7 percent of the energy needed to ignite natural gas at stoichiometric mixture. As presented in Figure 2, a source with ignition energy of 0.24 mJ will not ignite methane or propane but it will ignite a mixture of hydrogen and air within the concentration range of 6.5 to 58 vol. % of hydrogen.

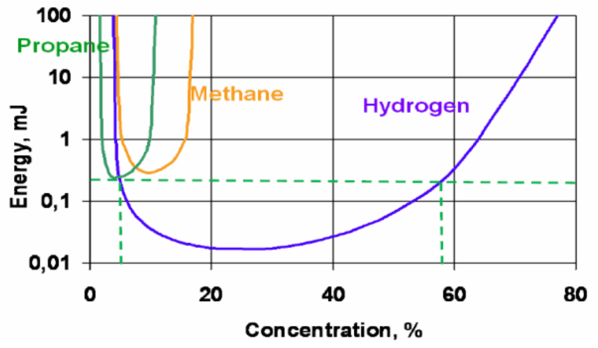


Figure 2. The dependence of the ignition energy on the concentration of a fuel (hydrogen, propane or methane) in the air [8]

2.1 Sensitive receptors

Ideally sites should be located in areas remote to sensitive neighbouring populations such as schools, hospitals or care homes, but this may not always be practical. In the event that a site selected is adjacent to sensitive areas, the potential consequences to these receptors need to be determined to identify the steps that need to be taken to reduce risk to acceptable levels. An iterative consequence analysis process involving sensitivity analysis and remodelling should be carried out to identify an optimised set of siting options. The consequence analysis of hydrogen release, however, must take a pragmatic approach, while applying modelling assumptions.

Following the iterative process, risk reduction options would need to be identified based on a hierarchy of risk control measures (Figure 1). The options could include reducing hydrogen storage inventory/pressure, changing storage location, or by adding a buffer zone i.e. a separation area from the site from potential receptors for the purposes of mitigation of conflicts. In the event that a buffer zone is not practical, especially in areas where there are space restrictions, alternative siting locations need to be considered.

Hydrogen is odourless and therefore is not detectable by the human olfactory system in the case of a leak. In hydrogen facilities, particularly near sensitive receptors, the facility should consider using hydrogen with an odorant so as to act as an inherent warning system in the event of a gas release, prior to dangerous levels being reached. An odorising compound is generally added to natural gas for domestic gas distribution; however, this may not be possible in fuel cell applications. These compounds usually exhibit an unpleasant odour that is detectable at minute concentrations. Currently there is active research being carried out by gas distribution companies in the UK such as SGN and Cadent in identifying a suitable odorant for use in a 100% hydrogen gas grid for domestic use [9]. The research involves a review of existing odorants (used primarily for natural gas), and the selection of suitable odorants based on experimentation. The results have so far confirmed that Odorant NB (new blend) could be a potential candidate, as it meets the minimum requirements for odorants already used in natural gas.

2.2 Prevailing wind and weather conditions

Given gaseous hydrogen has high buoyancy and diffusivity, and as such leaking hydrogen will rise and disperse quickly in air, prevailing site specific wind direction data can assist in siting to account for the potential release points downwind of potential ignition sources. Given that hydrogen may need to be stored at high pressures, the momentum driven phase of dispersion is likely to be significant. Identifying potentially impacted populations/assets who may be affected by momentum driven dispersion downwind may help determine whether or not a site is appropriate or if additional measures are required.

In addition, given the low density of hydrogen, hydrogen equipment generally incorporates a vent system to relieve excess hydrogen to the atmosphere at high level. Therefore, prevailing wind direction data should be taken into account when deciding the direction of the vent lines to ensure venting to the atmosphere is done safely.

2.3 Emergency response capabilities

Like with any facility handling hazardous fluids, siting should review the adequacy of existing local emergency response capabilities including firefighting, coastguard, police, and medical facilities capable of handling the hazards associated with hydrogen release. In the event that a particular site is chosen, an engagement process with emergency response organisations would need to be undertaken share a common understanding of the hazards posed by a hydrogen release.

2.4 Transportation routes

Transportation routes around the potential site and increased traffic on them may present a risk to the neighbouring areas/sites and to the hydrogen site by limiting access and egress both normally and during an emergency situation. Therefore, ensuring that sufficient emergency response access will be available after the addition of transportation routes for the new site and increased traffic on these routes is taken into account is important. In addition, considerations should also be given to the threat of static charges and other ignition sources from vehicles which could ignite a hydrogen cloud.

2.5 Co-location with Renewables

Green hydrogen, i.e. generation of hydrogen by electrolysis using surplus renewable power is a key pillar of the EU strategy [4] and technologies for electrolysis are improving all the time, as are renewable technologies. Green hydrogen generation may require co-location of the hydrogen production and storage units with wind turbines, solar panels or tidal power systems. Some of the co-location considerations that can be undertaken to ensure that the units can simultaneously operate safely are discussed below.

By integrating the arrangements for emergency response management between the sites, it ensures that the response to an emergency is done in a co-ordinated way. For instance, in the event of a hydrogen gas leak in the hydrogen production plant, maintenance personnel working at a wind turbine (who might not be aware of the release) could be notified through a common communication system to initiate their own emergency response and evacuate the turbine.

In addition, there is a degree of complementarity between Battery Energy Storage Systems (BESS) and green hydrogen facilities as both are diverse forms of energy storage and both may release hydrogen under fault conditions (such as BESS over temperature leading to thermal runaway reaction). In one sense there is synergy, in that hydrogen detectors would be needed for both systems; however, this could give rise to potential issues with determination of where detected hydrogen initiates from.

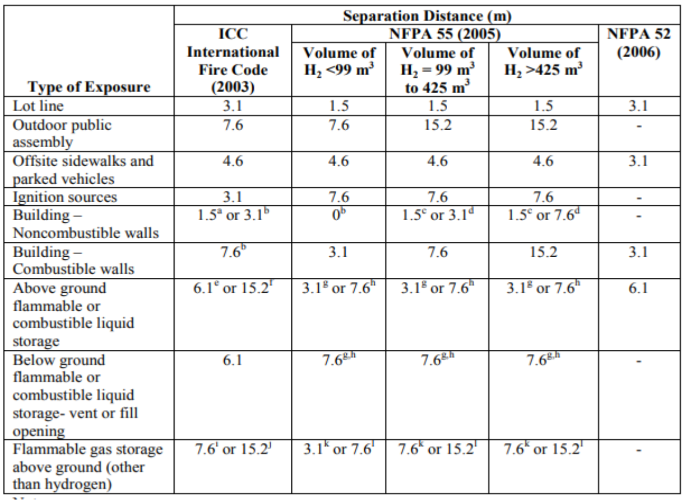
3. LAYOUT AND SPACING CONSIDERATIONS

As part of developing the layout of a facility, calculation of separation distances between equipment inside a hydrogen facility, adjacent facilities and the public at large is critical, as the findings can be used to implement measures to reduce the risks of a hydrogen release. Separation distances also prevent escalation of a hazardous event in a facility i.e. a minor event at one portion of a facility propagates to another part of the facility increasing the resulting consequences. They can also help to facilitate accessibility for maintenance and operations and safe egress in an emergency. This is important for hydrogen storage where higher pressures are required to prevent high pressure releases (even if unignited) through equipment damage and mitigate the potential consequences by provision of space to escape.

Separation distances for hydrogen facilities can be determined using several approaches currently used in the process industry:

- The “spacing tables” approach uses established tables/codes to determine minimum separation distances between equipment, units and buildings intended for occupancy.
- The “consequence-based” approach takes into consideration the impact of jet fire, flash fire and explosion events using empirical correlations or Computational Fluid Dynamics (CFD) numerical equations
- The risk-based approach is quantitative and takes into consideration numerical values for both the consequences and the frequencies of the events.

Using the “spacing tables” approach, the separation distances can vary from one code or standard to another (Figure 3). In addition, whether the parameters currently being used to differentiate separation distances in these codes are adequate for future hydrogen facilities is uncertain. Specifically, higher gas storage and dispensing pressures than contemplated during the creation of the current codes are being considered for current gaseous hydrogen facilities. A consequence of these higher pressures is that the required separation distances may be significantly larger than currently specified [10].



Type of Exposure	Separation Distance (m)				
	ICC International Fire Code (2003)	**NFPA 55 (2005)**			**NFPA 52 (2006)**
		Volume of H_2 <99 m^3	**Volume of H_2 = 99 m^3 to 425 m^3**	**Volume of H_2 >425 m^3**	
Lot line	3.1	1.5	1.5	1.5	3.1
Outdoor public assembly	7.6	7.6	15.2	15.2	-
Offsite sidewalks and parked vehicles	4.6	4.6	4.6	4.6	3.1
Ignition sources	3.1	7.6	7.6	7.6	-
Building – Noncombustible walls	1.5[a] or 3.1[b]	0[b]	1.5[c] or 3.1[d]	1.5[c] or 7.6[d]	-
Building – Combustible walls	7.6[b]	3.1	7.6	15.2	3.1
Above ground flammable or combustible liquid storage	6.1[e] or 15.2[f]	3.1[g] or 7.6[h]	3.1[g] or 7.6[h]	3.1[g] or 7.6[h]	6.1
Below ground flammable or combustible liquid storage- vent or fill opening	6.1	7.6[g,h]	7.6[g,h]	7.6[g,h]	-
Flammable gas storage above ground (other than hydrogen)	7.6[i] or 15.2[j]	3.1[k] or 7.6[l]	7.6[k] or 15.2[l]	7.6[k] or 15.2[l]	-

Figure 3. Example separation distances for gaseous hydrogen storage currently specified in codes and standards [10].

The consequence based approach derives spacing distances for the site's specific layout and process parameters through fire and explosion consequence modelling. This relies either on empirical correlations or CFD numerical equations. An outline of the approach by CCPS [7] is presented in Figure 4 below.

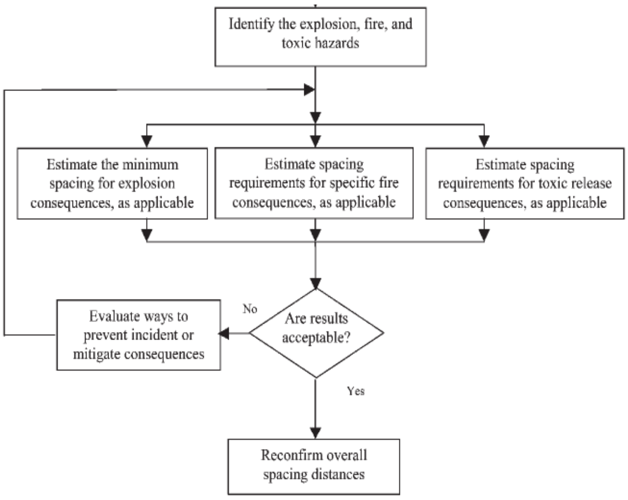


Figure 4. Approach to calculating separation distances using consequence modelling [11]

As briefly described in Section 2.1, existing consequence modelling of hydrogen release has limitations because it is carried out mostly by tools based on research, experimentation and validation of hydrocarbons. There is limited experimental data available for hydrogen. This means that the results of modelling can be inaccurate; therefore, conservative modelling assumptions must be made, refining with CFD where such conservatism is impractical. Such impracticalities may arise if conservative spacing in layout design results in failure to reduce risks associated with siting separation from external receptors to acceptable levels.

The risk-based approach, commonly used in the hydrocarbon industry is primarily based around the findings of a Quantitative Risk Assessments (QRA) study. QRA requires input of ignition probabilities and equipment leak frequency data. However, ignition probability of hydrogen release is currently insufficiently understood and there is a limited track record of hydrogen equipment and pipeline leak frequency data. A risk-informed process (proposed by Sandia National Laboratories [10]) as opposed to the risk-based process could potentially be a better approach, as it utilizes the risk insights obtained from QRAs combined with results of deterministic analyses of selected accidents scenarios, the frequency of leakage events at current hydrogen facilities, and the use of safety margins to account for uncertainties.

3.1 Storage of Liquid Hydrogen

Liquid hydrogen is stored at cryogenic temperatures. The storage vessels have potential for Boiling Liquid Expanding Vapor Explosion (BLEVE) i.e. the vessels can fail catastrophically (upon exposure to external fire or mechanical impact) which can have consequences at distances. Like with gaseous hydrogen releases, hazard distances could be derived using consequence analysis, however there are currently few consequence modelling tools that claim to explicitly model liquid hydrogen as its release and dispersion is an area where a significant experimental work is required. Therefore, for these sorts of novel circumstances a risk based approach would not be appropriate and focus would need to be on modelled or putative consequences [11]. Acquiring additional land beyond that needed for the facilities at the time of siting the plant can also provide a buffer area between the liquid hydrogen vessels and surrounding habitations.

3.2 Hydrogen Explosions

Delayed ignition of a hydrogen gas accumulation in a congested and/or confined area could lead to a vapor cloud explosion (VCE), potentially producing damaging overpressures. A key requirement of National Fire Protection Association (NFPA) Hydrogen Code 2 [12] is that "the hydrogen facility design should provide an acceptable level of safety for occupants and for individuals immediately adjacent to the property from the effects of unintentional detonation or deflagration". As such, evaluation of NFPA Hydrogen Code 2's [12] performance criteria can be primarily conducted via characterization of accidental hydrogen releases using tenability or harm criteria such as gas concentrations and overpressure levels derived using empirical or CFD based applications.

Consequence analysis models developed for gas dispersion and vapor cloud explosions (congested and/or confined) can predict a rising flammable hydrogen cloud or overpressure levels, however, not all have been thoroughly validated. Moreover, the models do not allow consideration of local geometry. Therefore, a pragmatic approach, applying conservative modelling assumptions and refining with Computational fluid dynamics (CFD) modelling where conservatism is impractical is recommended.

Under certain conditions, the flame front travelling through a hydrogen-air or hydrogen-oxidant mixture could accelerate such that the ongoing deflagration transitions into a detonation (a process referred to as a deflagration-to-detonation transition, or DDT). Such events can produce high overpressures, several times those that are achievable from a simple deflagration. Therefore, all efforts should be made to ensure the layout has a low degree of confinement to reduce the potential for the presence of hydrogen-air mixtures during operation.

4. VENTILATION REQUIREMENTS

It is ideal to locate hydrogen storage/equipment in open, uncongested and unconfined locations to mitigate the risks of hydrogen releases accumulating to concentrations above the Lower Flammability Limit (LFL) of 4% to the Upper Flammability Limit (UFL) of 75%; however, this is not always practicable.

The potential for leakage from piping and equipment is higher with hydrogen due to its low molecular size and viscosity (when compared to other flammable fuels e.g. natural gas) and therefore ventilation arrangements should be in place to ensure that leaks/fugitive emissions do not accumulate. Calculation of ventilation requirements should take into account the sizes of the foreseeable leak wherein the hydrogen concentration is normally maintained below 10% of the LFL, with only occasional temporary increases to 25% of the LFL [13, 14].

The hierarchy of risk reduction with respect to ventilation selection as per DSEAR ACOP [15] positions natural ventilation as the first and preferred method due to its intrinsic reliability. If mechanical/forced ventilation is used, then the reliability of the system has to be considered e.g. forced mechanical ventilation system in a hydrogen electrolyser should be interlocked to shut down in the event of ventilation system failure.

To ensure that the hydrogen release is not ignited during mechanical extraction, all ventilation equipment should be appropriately rated as per its hazardous area classification.

Hydrogen is lighter and less dense than air and will generally accumulate near the ceiling or roof area of facility structures such as filling stations. Passive ventilation features such as roof or eave vents can prevent the build-up of hydrogen in the event of a leak or discharge. While co locating with existing refuelling facilities, existing roofing arrangements need to be thoroughly evaluated (and modified, if required) to ensure that a hydrogen leak from will be able to dissipate safely i.e. ensuring provision for inlets at low level and outlets at high level which should be located in two opposing exterior walls or in a door and an opposing exterior wall [13].

5. CONTROL OF IGNITION SOURCES

As described in section 2, the minimum ignition energy of hydrogen is low, compared to other fuel types. This introduces the possibility of ignition even from weak electrostatic discharges. Avoidance of ignition sources in areas where a flammable atmosphere due to Hydrogen release may occur is necessary. Therefore, the hazardous areas at a hydrogen development where explosive atmospheres could be formed need to be identified and classified according to the likelihood of an explosive atmosphere being present as per applicable regulations e.g. DSEAR ACOP [15].

Electrical and non-electrical equipment appropriate for use with hydrogen should be determined once the hazardous areas have been identified and classified. This is a critical point of consideration from a co-location perspective. For example, an existing facility that previously only handled natural gas, that is intended to also handle hydrogen, would need to ensure that the fixed electrical equipment design is reviewed. Hydrogen has a different gas class (IIc) to other fuel types (such as natural gas, which is IIa); therefore, the electrical equipment may need to be replaced if it is in the hazard radius for the hydrogen equipment.

5.1 Static Charges

Hydrogen can be ignited by low energy electrostatic charges. Static charges can be generated whenever surfaces come into contact and then separate, without effective earthing. This could include people walking near facility, nearby vehicles, roadways, railways or wind turbines. Maintaining a safe distance to such sources, is an important consideration for siting and layout design.

Precautions should be taken to prevent the build-up of static charges that may lead to a discharge and this may include ensuring that:

- all pipe work and equipment handling hydrogen is effectively earthed;
- personnel working in hazardous areas involving hydrogen wear antistatic clothing and footwear

6. FIRE AND GAS DETECTION

6.1 Gas Detection

Hydrogen is colourless, tasteless and odourless, which means hydrogen facilities should be provided with a detection system to detect the presence of hydrogen in locations where leaks and/or accumulations may occur, generally at high points. Early detection of leaks in is essential to facilitate the activation of alarms, shut down actions and if necessary emergency evacuation of people.

The general tendency is have as many detectors as possible to ensure all potential releases as soon as they occur are detected and also to guard against false trips/detector faults. To reduce conservatisms, hydrogen facilities could consider carrying out hydrogen specific fire and gas detector mapping studies (commonly carried out in the hydrocarbon industry) to analyse detector layouts and optimise the number of detectors needed to meet coverage targets.

6.2 Flame Detection

Hydrogen burns with an invisible flame making it difficult to detect a hydrogen fire, therefore the facility needs to take into account a combination of thermal and optical sensors to detect hydrogen flames.

Flame detection systems are not required by NFPA 55 [16], but NFPA 52 [17] does require them for hydrogen fuelling stations (i.e., hydrogen dispensing operations).

7. DISCUSSION

As discussed previously in this paper, even though experimental data for hydrogen releases is building and good practice is developing, there are currently consequence modelling limitations (specially with empirical models) when calculating separation distances of hydrogen equipment. To hedge against this uncertainty, risk assessors tend to adopt a conservative approach by introducing greater separation distances then required. Consequently, this has the potential to increase offsite risk i.e. sensitive neighbouring receptors. This is potentially more relevant to hydrogen than with other dangerous substances given that it has one of the lowest minimum ignition energies and is often stored at higher pressures.

One possibility, as described in Section 2, would be to produce hydrogen at source using electrolysis with power from the grid, BESS, and / or collocated renewable resources. This could be an effective inherent safety measures, potentially reducing both storage inventories and pressures.

Where this is not possible, a trade-off between siting and layout may need to be considered. This could include looking at opportunities for reduced conservatism in spacing and layout in order to build buffer zones to sensitive receptors or ignition sources over which the facilities have less control. A CFD based modelling tool coupled with a risk-informed decision making process could help reduce the conservatism and optimise siting while empirical models are developed further to improve their accuracy. The separation distance approach outlined by CCPS [7] has been modified to take into account for the renewed approach i.e. trade-off between siting and layout to spacing considerations and is presented in Figure 5.

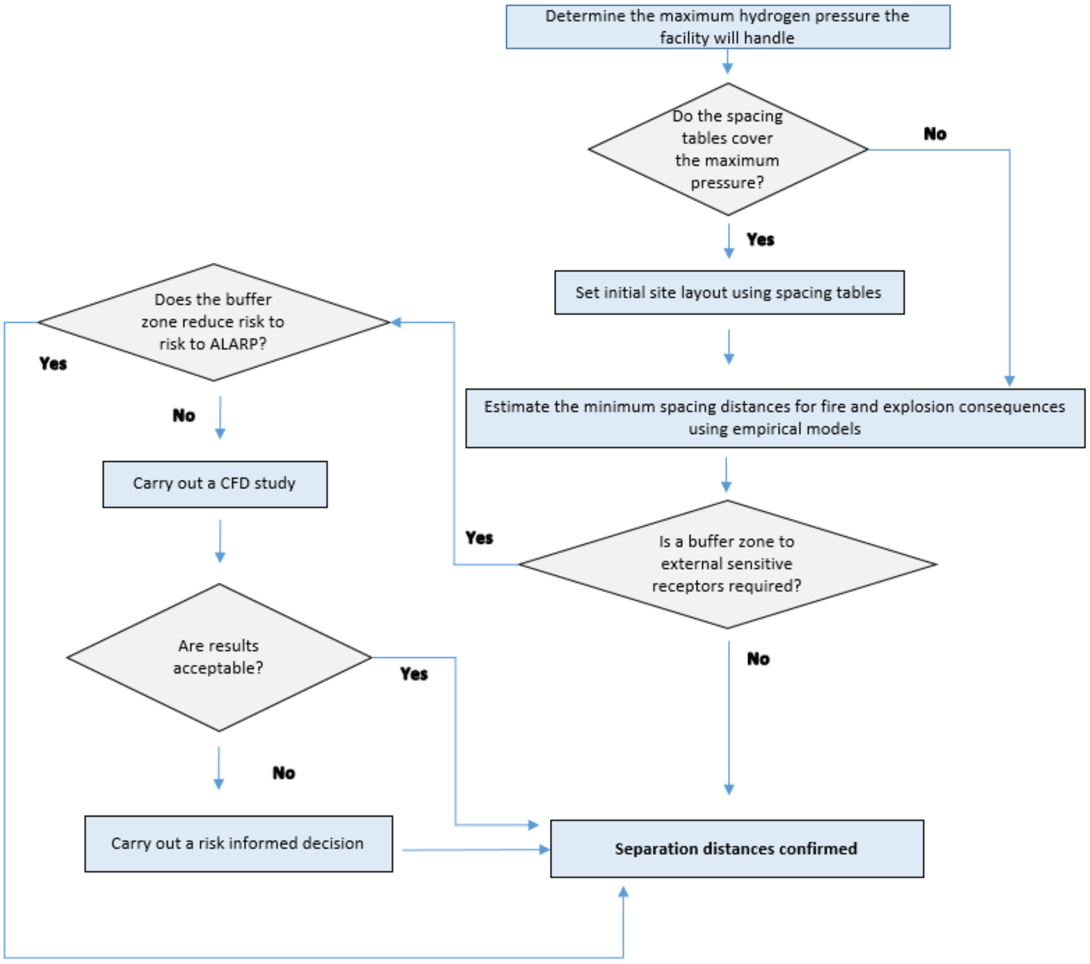


Figure 5. Possible approach to calculating separation distances

8. CONCLUSION

Production of hydrogen is still regarded as an industrial activity, irrespective of the production method, hence such activity would only be permitted in an area designated as an industrial zone thereby hampering commercialisation and market reach of hydrogen as an alternative fuel. Owing to a lack of established guidance on hydrogen facility siting, a range of considerations for siting hydrogen developments, including co-location with other assets, for example with renewable energy sources, hazardous facilities or public structures have been presented in this paper. Hydrogen has some distinctive attributes of makes siting a complex process fraught with uncertainties, however if the threats are identified and managed properly, commercialisation of hydrogen facilities can be enabled.

As part of the developing the layout of the facility, different approaches to calculation of separation distances between equipment in hydrogen storage facility, adjacent facilities and the public at large were discussed. While a conservative approach to calculating separation distances is currently the convenient option, it could have reduced conservatism and unacceptable offsite risk elsewhere. Therefore, a trade-off between siting and layout needs to be considered.

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