# Why Proactive Assessment of Hydrogen Fuelling Risks Is Essential

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This paper focuses on the use of hydrogen as a fuel source and the challenges associated with assessing risk for hydrogen vehicle fuelling operations. With a shift towards clean energy and the projection that hydrogen production will be cost competitive before 2030 (if properly implemented), many companies are investing in this technology as part of their overall corporate portfolios. It is essential to define the right approach to safety in the initial hydrogen network design and implementation in order to mitigate the potential for a negative perception towards the technology.

Currently, the commonly used method for assessing risks involves a PHA/LOPA approach to identify potential consequences and associated frequencies to determine scenario-based operational risks. In addition, the "worst credible case consequence" event(s) is typically reviewed to determine the level of safeguards required for safe operation. However, this approach to quantifying hydrogen fuelling operational risk fails to address not only the catastrophic, low frequency events but also the lower consequences, higher frequency events that may drive site risk profiles.

Historically, the oil and gas industry has experienced a range of hydrogen vapour cloud explosions (VCEs). Hydrogen, which is unique due to its explosion energy and high ignition probability, has the possibility of undergoing a deflagration-to-detonation (DDT) transition. Detonation events result in high energy explosions, which can be devastating due to the high-pressure nature of the explosion. This paper will discuss historical hydrogen explosions and the resulting damage in order to cover the potential impacts of a catastrophic release of hydrogen, both with respect to physical damage as well as public perception.

A properly conducted risk analysis for hydrogen fuelling systems should incorporate the best practice work currently performed during the PHA/LOPA process with more quantitative approaches to better understand the risk profile of hydrogen fuelling systems. This paper specifically addresses how a comprehensive scenario-based approach that considers existing process safeguards can be utilized to determine quantitative risk profiles. The proposed approach enables optimisation of station locations, station layouts, and selection of safeguards to provide decision-makers with an objective framework to manage risk exposure to a tolerable level.

Keywords: Hydrogen Fuelling, Clean Energy, Alternative Fuels, Facility Siting, Quantitively Risk Assessment, Hazard Mitigation, Explosion

## Introduction

### Carbon and Climate Change

In order to avoid the worst climate impacts, studies show that global greenhouse gas (GHG) emissions need to drop 50% by 2030 and reach net-zero around mid-century. (Levin, 2019). With this urgency in mind, an increasing number of countries are setting goals for net-zero emissions. At the United Nations Climate Action Summit in September 2019, several countries and some states, cities, and companies pledged to reach net-zero by 2050. This list includes the United Kingdom, Norway, Finland, Iceland, Sweden, Denmark, France, Portugal, and Switzerland, as well as proposed adoption by the European Union (EU) and New Zealand. Unfortunately, major emitters such as the United States and China are missing from this pledge, greatly limiting the overall global impact of what other countries achieve by 2050.

What does it mean to be net-zero? Net-zero emissions is reached when human-caused GHG emissions are balanced by removing GHGs from the atmosphere through carbon removal (see Figure 1). This balance requires driving human-caused emissions from sources like fossil-fuelled vehicles and factories to as close to zero as possible while restoring forests and removing carbon through direct air capture and storage (DACS) technology (Levin, 2019). In other words, achieving climate neutrality. Along with investing in clean and efficient energy and reducing food waste and loss, zero emission vehicles are considered a top 10 key solution needed to reduce GHG emissions according to the World Resources Institute. (WRI, 2020).

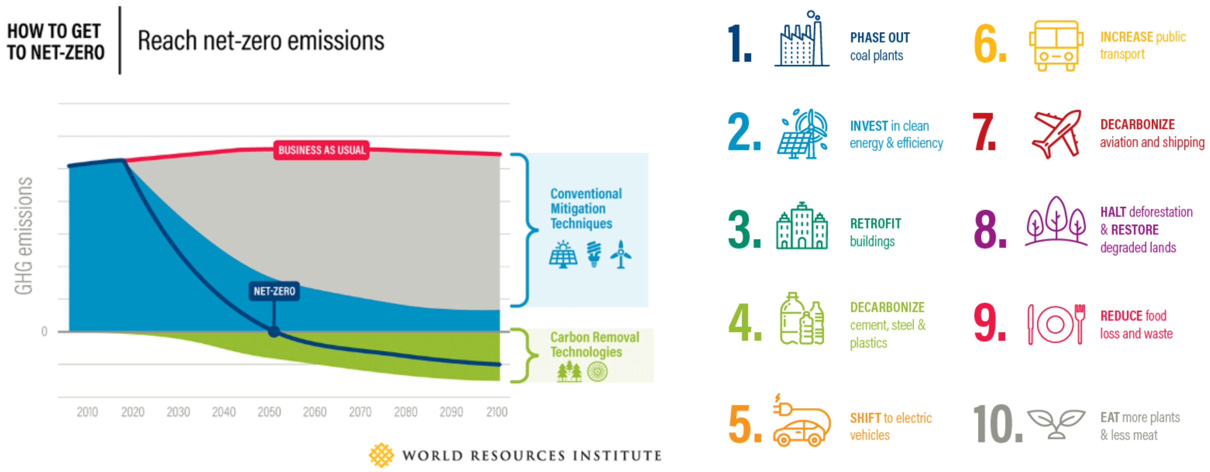


**Figure 1: Reaching Net Zero and Top 10 Key Solutions to Getting There (WRI, 2020)**

## Hydrogen Fuelling Technology

With zero emissions vehicles playing a key role in the reduction of GHG, electric vehicles (Figure 2) and hydrogen fuel cell vehicles (Figure 3) are being looked to as viable alternatives to the gasoline and diesel combustion engines. While Tesla CEO Elon Musk has championed his battery-powered electric vehicles over hydrogen fuel cell vehicles with statements about “fool cells” including “success is simply not possible” and “*[they are]* mind-bogglingly stupid”, a 2017 survey of 1,000 global auto executives concluded hydrogen fuel cell technology will ultimately outperform battery-powered electric vehicles (D’Allegro, 2019).

**Figure 2: Tesla Model S - Battery (CEN Online, 2014)**

**Figure 3: Toyota Murai - Hydrogen (Toyota, 2019)**

Fuel cell electric vehicles (FCEVs) combine hydrogen with oxygen (from the air) to produce electricity, with water vapour as the only by-product. FCEVs don’t need to charge like battery-powered electric vehicles and have a range of over 300 miles on a full tank. Additionally, they fill up via nozzle, only slightly slower than traditional gas and diesel vehicles (D’Allegro, 2019). While critics say that most hydrogen for FCEVs is produced from traditional natural gas extraction, the impact on the environment is still less than gasoline and diesel combustion engines.

Setting aside the questions on pricing and cost (which varies by location, subsidies, and incentives), there are three main reasons why adoption is low; lack of fuelling infrastructure, public perception of hydrogen safety, and confidence in technology. To overcome this widespread reluctance of adoption, consumer education and demonstration of robust infrastructure are key. This paper introduces a platform to address these needs through a discussion of historical hydrogen incidents and objectively addresses hydrogen infrastructure hazards and risks to limit potential adverse public perception.

## Current Hydrogen Fuelling Landscape

As the market continues to grow for FCEVs in places like the United Kingdom, European Union, Asia, and North America, so does the need for comprehensive hydrogen fuelling infrastructure. Around the world, governments are struggling to overcome the barriers to widespread adoption of FCEVs. Hydrogen fuelling infrastructure is limited, the cost of producing and delivering hydrogen to service stations is high at low volumes, and it is currently much cheaper to produce hydrogen from fossil fuels than renewable energy. Furthermore, production costs of fuel cell vehicles will need to drop considerably from current levels and consumer knowledge of the benefits will need to improve for this technology to reach the mainstream market (Isenstadt, 2017).

The 2017 Hydrogen Infrastructure Update by The International Council on Clean Transportation (ICCT) assesses the development of infrastructure networks around the world. This research is based on work in California, Europe, Japan, and Korea, which are regions of extensive study and activity. Hydrogen fuelling technology has seen faster growth in heavy and medium-duty vehicle markets, including transit buses, rail, and truck markets partially due to a strong value proposition and centralized depot refuelling. In 2018, China became a medium- and heavy-duty leader with around 1,500 fuel cell trucks and buses. In addition, transit and fleet operators are becoming increasingly interested in the technology due to the improved efficiencies and, in some cases, subsidies. As for light-duty vehicles, in 2018 it was estimated that worldwide there were over 10,000 hydrogen passenger cars on the road – 5,899 of these in the United States (mostly California) and over 2,500 in Japan (MacEwen, 2019).

Depending on the location, infrastructure projects differ in their hydrogen delivery systems, with a mix of liquid hydrogen delivery common in California, on-site electrolysis of hydrogen from grid electricity and solar power common in the United Kingdom and European Union, and on-site natural gas reforming common in Asia. Regardless of the delivery system, vehicles are about 30% more efficient than gasoline and diesel combustion engines, have ranges of over 300 miles, and refuel in 3 to 5 minutes. With vehicle production costs dropping and more renewable energy sources coming online for carbon free hydrogen production via electrolysis, the Hydrogen Council has set 2050 targets at 12-20 million commercial trucks, 5 million buses, 20% of trains, and 400 million passenger cars (MacEwen, 2019).

Infrastructure networks are currently being developed in areas where vehicle manufacturers, hydrogen providers, and governments share the common goal of increasing fuel cell vehicle deployment. Companies leading equipment and station construction worldwide include Air Products, Linde, Air Liquide, Shell, TOTAL, and several others. At the end of 2016, at least 150 hydrogen fuelling stations had been built or funded, with more than 50 each in California, Germany, and Japan (Idenstadt, 2017). In 2018, another 77 stations went into operation globally, raising the total number to 337 with estimates of over 3,600 by 2033. For current station locations in the US, UK and EU, and Japan, see Figure 4. While this sounds and looks promising, projections for technology adoption are decreasing due to failure of countries to meet their own goals (Research and Markets, 2019). The question that needs to be answered is why is there a lack of widespread FCEV adoption by the public?

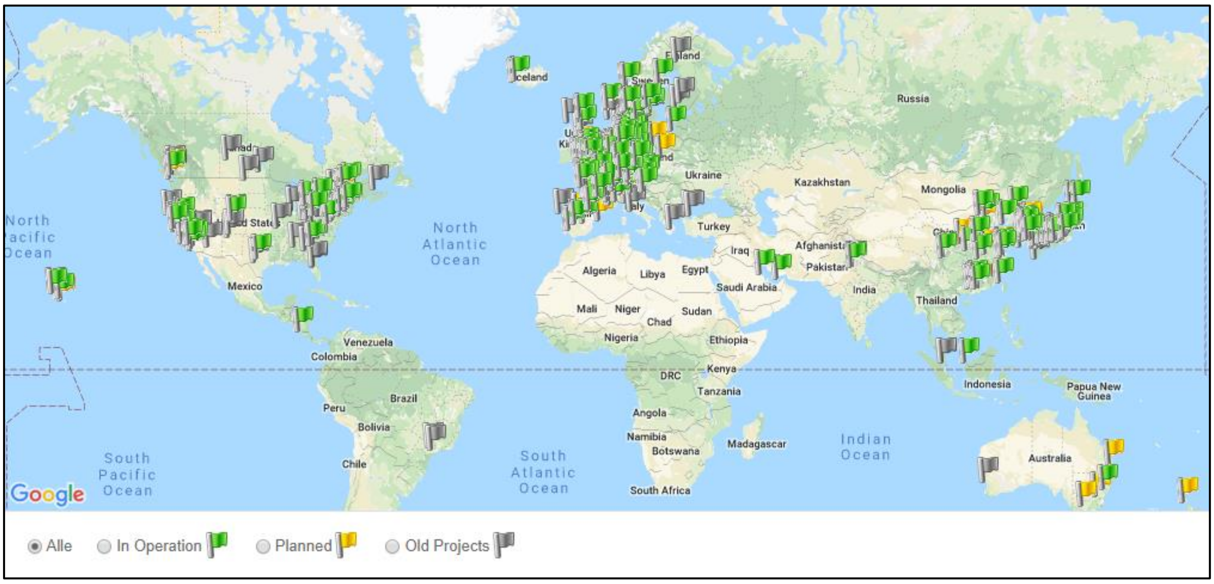


**Figure 4: Hydrogen Fuelling Station Map January 2020 (H2Stations.org, 2020)**

## Hydrogen Fuelling Safety Concerns

For hydrogen fuelling to become financially viable by 2030, public adoption and acceptability is essential. To date, government incentives and investments have been instrumental in assisting with the advancement of hydrogen fuelling technology and infrastructure. However, research suggests that state aid to co-fund the hydrogen network is not enough to drive the build-out of the technology and the costs will need to shift to private industry and the public. Industry has reported difficulties keeping small stations profitable due to the large capital and operating costs as well as the limited opportunity to generate income through fuel sales (CARB, 2019). In order to achieve and grow public adoption of hydrogen technology, education on the safety aspects of hydrogen and objectively addressing risks associated with the technology is of utmost importance.

## An Overview of Hydrogen Safety

The key to hydrogen safety is to be aware of all hazards related to the handling and use of the material. Due to historical incidents such as the Hindenberg disaster (Figure 5) and the public perception of hydrogen bombs, it is a common misconception that hydrogen is much more dangerous than gasoline/diesel or natural gas. It is natural for people to be wary of a material often associated with a weapon as devastating as the H-Bomb (Figure 6). However, in general, hydrogen safety concerns, which can be physiological, physical, or chemical, are simply different and not necessarily more severe. The primary hydrogen hazard is the production of a flammable or explosive mixture in air (Rigas, 2013), which is discussed in the subsequent sections of this paper.

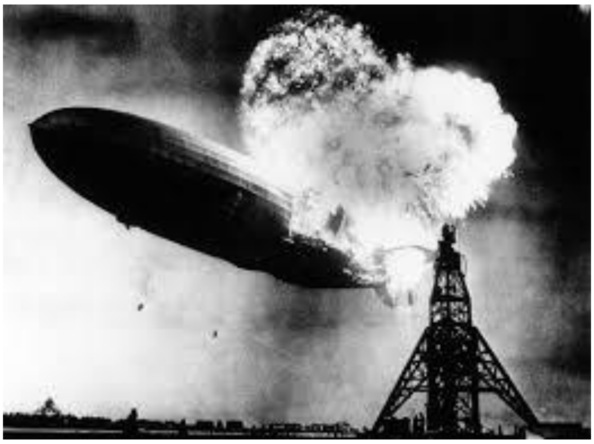


**Figure 5: 1937 Hindenberg Disaster (de Syon, 2017)**

**Figure 6: 1946-1958 Marshall Islands Testing (Abadi, 2016)**

Hydrogen has a very low minimum energy for ignition (0.02 mJ) meaning that it is very easily ignited. Hydrogen-air mixtures have nearly an order of magnitude lower ignition energy and much wider flammability range than methane-air mixtures. Therefore, a major emphasis needs to be placed on containment, leak detection, and ventilation. While in chemical processing facilities safety measures, such as elimination of likely sources of ignition, frequency of inspection and maintenance, and education of safe handling, can significantly limit the likelihood of ignition, leaks do occur even with the best practices applied to containment. This inevitability becomes increasingly problematic for hydrogen vehicle fuelling due to the involvement of the public as the operators as well as the fact that while both hydrogen and natural gas are colourless and odourless, hydrogen cannot be odorized with mercaptans for early detection like natural gas due to fouling of the vehicle fuel cells (Rigas, 2013).

## Historical Industry Hydrogen Events

For the time period from 1965 to 1977, over 400 hydrogen related incidents were reviewed by Zalosh and Short (Zalosh, 1978). They concluded from this analysis that in terms of the number of incidents, deaths, and property damage, hydrogen explosions were a more serious problem than other types of hydrogen events (fires, asphyxiation, etc.). Zalosh and Short's conclusion was based on over half of the hydrogen related incidents reviewed being hydrogen explosions, which accounted for three quarters of the injuries and fatalities reported. This research revealed that three quarters of the incidents reviewed involved hydrogen gas with the majority of the remaining incidents involving a liquid, which contradicted the Factory Mutual (FM) Global Data Sheet for the evaluation of VCEs that specifically excludes consideration of VCEs due to gaseous hydrogen releases (FM Global, 2013).

Zalosh and Short's research raises the interesting question: Why would FM Global exclude evaluation of gaseous releases even though they recognized that 3% of the VCEs reviewed were from gaseous hydrogen or syngas? The real answer is likely that FM Global is focused on maximum property damage events and not facility siting and impacts to people; however, the more interesting answer is that while most companies recognize early ignition fires and late ignition confined hydrogen VCEs as credible events, many question the validity of unconfined hydrogen VCEs (Thomas, 2014).

In their 2014 paper, Moosemiller and Galindo dive into how subject matter experts (SMEs) can have such vastly differing opinions on hydrogen releases varying from 0% and 100% hydrogen ignition (Moosemiller, 2014). Their analysis concludes that the variance in opinions arises from an individual's experience because with hydrogen, depending on the configuration of the discharge area, very different ignition probabilities are realized for identical conditions. However, data shows that while hydrogen does have unique ignition probability characteristics, unconfined VCEs should not be ignored any more than immediate ignition or delayed confined ignition should. This is especially true as the hole sizes for release increase and ignitions near release locations are increasingly controlled/eliminated (Moosemiller, 2014).

In their 2014 paper for the American Institute of Chemical Engineers, Thomas, Eastwood, and Goodrich examine the credibility of unconfined hydrogen vapor cloud explosions (Thomas, 2014). They conclude that hydrogen's buoyancy does not prevent the formation of a large flammable mixture and that credible hydrogen releases can form significant flammable gas clouds and should be considered when examining potential hazards and risks. Furthermore, based on a review of historical incidents and hydrogen VCE test programs, Thomas et al. conclude that hydrogen-air mixture VCEs can result in damaging blast loads, particularly where the release and congestion/confinement would support a deflagration-to-detonation transition (DDT). Two of the incidents they reviewed, Jackass Flats, Nevada and Hanau, Germany, are summarized here due to the conditions being similar in some respects to hydrogen fuelling station operations.

*Jackass Flats VCE*

Hydrogen was one of the fuels being tested for rocket motors in Jackass Flats, Nevada in 1964. In one of the tests, the hydrogen was intentionally not ignited to evaluate the sound pressure (noise) levels. Hydrogen was released in this test from an initial pressure of 3,400 psi (approximately 234 bar) from a storage tank through a nozzle venting upward into the atmosphere. This pressure is similar to that utilised in medium- and heavy-duty vehicle fuelling. After 13 seconds, this release was unintentionally ignited resulting in a VCE of about 200 lbm (90kg) of hydrogen. This VCE was reported to be a deflagration without congestion due to preignition turbulence and resulted in limited damage to surrounding buildings (Thomas, 2014).

*Hanau VCE*

In 1991, there was a release of hydrogen from a 100 cubic meter cylindrical storage tank in Hanau, Germany. This tank ruptured at a pressure of 45 bar (650 psi), resulting in the ignition of the subsequent flammable cloud and an unconfined hydrogen VCE. The blast wave from this explosion caused significant property damage to the vicinity and window damage to buildings near the facility (Thomas, 2014). The storage vessel size and pressure involved in this incident is similar to those of hydrogen fuelling facilities.

## Hydrogen Fuelling Industry Incidents

As stated previously, there are three main reasons why adoption of FCEVs is low: lack of fuelling infrastructure, public perception of hydrogen safety, and confidence in technology. These concepts are exhibited through three industry incidents in 2019. The limitations of the hydrogen vehicle fuelling infrastructure was demonstrated by the network impacts following the Santa Clara, California explosion; the poor public perception of hydrogen safety was evident in protests following the explosion in Gangneung, Korea; and the lack of confidence in technology caused multiple station closures across Europe following the station explosion in Baerum, Norway.

*Santa Clara, California*

On June 1, 2019, there was a hydrogen explosion at the Air Products chemical, gas storage, and transportation facility in Santa Clara. In this incident, a hydrogen tanker truck was being filled when a leak occurred. During the shutdown of the hydrogen transfer to the tanker truck, an explosion occurred that damaged the emergency shutoff panel and valve near the tanker. While two valves were shut off, the valve closest to the original tanker truck could not be closed and the fire continued to burn for nearly two hours (Santa Clara Weekly, 2019). This fire, which was not visible to the human eye, resulted in the shutdown of the Air Products facility through September 2019.

As the only provider of hydrogen for hydrogen fuelling in the Bay Area region, the shutdown of the Air Products facility resulted in a disruption in the distribution network lasting for months. While a small supply was available from southern California, the limited availability of fuel was not enough to meet demand. By September 2019, left with no reasonable choice but to abandon their vehicles until fuel supplies returned, local FCEV owners were trading cars for other low carbon options such as electric vehicles and hybrids (Evarts, 2019).

*Gangneung, Korea*

In May 2019, a hydrogen tank explosion destroyed a complex half the size of a soccer field, killing two people and injuring six more at Gangwon Technopark. Preliminary investigations suggest the explosion resulted from a spark after oxygen found its way into the tank. This event resulted in hampering South Korea's goal of a million-plus FCEVs on the road when resident groups began protesting stations both planned and under construction around the country (Figure 7). South Korea is significantly behind the goal of 114 stations by end of 2019 with only 29 built as of September 2019, and will become further behind due to the lack of local government funding and companies having to shoulder the costs. Further slowdowns from public protests and refusal to incorporate hydrogen technology into existing stations by station owners have been recognized as a show of resistance due to safety concerns (Le Sage, 2019).

**Figure 7: South Korea Protests Against Hydrogen Fuel Cell Technology (Jin, 2019)**

*Baerum, Norway*

An Uno-X fuelling station experienced an explosion event on June 10, 2019 due to a leak from an improperly installed plug on a high-pressure storage tank. The explosion resulted in two airbag related injuries from a nearby car and a subsequent fire that burned for approximately three hours. Not only did this incident result in a distribution network interruption in Norway, but due to public concern, resulted in the closure of ten similar stations throughout the Uno-X distribution network. The public, who did not understand or trust the technology, were reluctant to accept the similar stations as safe until an inspection and integrity testing scheme was completed (Randall, 2019). Knock-on effects continued with Toyota and Hyundai both halting sales of FCEVs in Norway, virtually eliminating the market since they were the only two vehicle providers in the country.

With three hydrogen fuelling technology safety incidents occurring within a month of each other in 2019, how do regulators and owner operators cultivate public support and adoption? Looking to other alternative fuel safety regulations may provide a framework for proactively addressing safety and network concerns rather than reactively addressing public concerns and implementing lessons learned. If a reactive approach is taken, which is common practice for regulatory agencies, hydrogen technology may either never gain the momentum necessary to be financially viable or, alternatively, hit a significant roadblock in the future.

## Initiatives for Hydrogen Fuelling Technology Safety

Internationally, flagship programs for establishing, promoting, and regulating hydrogen fuel cell vehicle technology are gaining momentum. In Europe, Hydrogen Mobility Europe (H2ME) is a flagship program aimed towards giving FCEV drivers access to a pan-European network of refuelling stations. Currently, H2ME has a planned network of 45+ stations to allow an uninterrupted ability to operate FCEVs across borders. In the United States, Hydrogen USA (H2USA) had over 50 stations online in 2019 and is supported by the US Department of Energy as well as public-private partnerships with FCEV equipment manufacturers. The goal of H2USA is to promote the adoption of FCEVs and hydrogen infrastructure across America. A final example is in Canada, the Hydrogen Fuel Cell Association has the goal of raising awareness to accelerate commercialization of FCEV technology.

Interestingly, although each geographic region appears to have unique flagship programs, all have three things in common: building out of the FCEV infrastructure to promote uninterrupted service, public education for technology acceptance/adoption, and establishment of regulatory requirements.

### DifCurrent Practices for Assessing Risks

While it is promising to see flagship programs growing around the world, hazards and risks are assessed based on local regulatory requirements and are different in each country. This lack of consistency in approach to safety results in three main problems. The first is that the ability to standardize technology for vehicles, as well as for hydrogen generation, storage, transportation, and fuelling, is compromised. The second is that a thorough and consistent approach to analysing hazards and risks is prohibitive; generic safety studies are likely to be adapted in a minimalist manner (i.e., limited rigorous site specific analysis) to meet a range of local regulatory requirements. And finally, because hydrogen fuelling facilities tend to be modularized units coming from different manufacturers, the final owner/operator may not have the knowledge and detailed process safety information (PSI) necessary to understand the safety concerns, and as a consequence may adjust safeguards/operations on an ad-hoc basis without knowing the implications.

Regardless of location, safety requirements tend to incorporate one or more of the following approaches to siting: spacing distances, HAZOP/LOPA, and/or select detailed modelling. With regards to spacing distances, a number of international standards exist for various parts of the hydrogen technology process including SAE TIR J2601 *Hydrogen Fuel Dispensers*, ISO/TS 19880-1:2016 *Minimum Design Characteristics*, and ISO/FDIS 19880-1 *Hydrogen Technologies*. These are often supplemented by local regulatory requirements for minimum design spacing for facility layouts (Vilas, 2019).

Countries with specific regulatory and permitting requirements tend to also require a qualitative hazard review process such as HAZOP or LOPA. These techniques were originally developed for reviewing steady state process facilities. While this type of analysis can be used for looking at operational risks of hydrogen fuelling stations, using these methodologies to apply order of magnitude consequences and frequency to hazardous events can be challenging with this type of operating regime. This often involves defining a one or more “maximum credible events” (MCEs) and has the unintended consequence of missing low frequency, catastrophic events as well as high frequency, low impact events. As a result, safeguards are identified and selected based on MCEs rather than a full risk profile. This is especially worrying for a technology where the public is the ‘operator’ making the high frequency, non-catastrophic risks associated with improper fuelling operations a concern to be safeguarded for – a traditionally applied HAZOP/LOPA methodology may struggle to account for these risks in a meaningful way.

In infrequent instances, detailed modelling is conducted to quantitatively address the hazard and/or risk impacts of a facility. Detailed modelling may include select consequence analysis or full facility siting studies (either consequence or risk based). Studies of this level of detail are typically limited to instances where a hydrogen fuelling station may be located near a sensitive neighbouring property, a potential worst-case event may expose sensitive populations, or there is an increased public concern. To date, hazard and risk criteria is limited if available at all; therefore, risk assessment is compared to company guidelines or applicable best practice rather than reviewed critically against a given standard. Furthermore, due to the unique properties of hydrogen with respect to ignition and explosion characteristics, care must be taken when doing detailed hazard and risk modelling to ensure results are representative of current knowledge and technology.

## Lessons Learned from Existing Fuelling Regulations

While hydrogen fuelling is "new" technology, vehicle fuelling is not. The most common vehicle fuels are gasoline and diesel, both of which are readily accepted materials for combustion engines. Individuals do not question driving to the nearest petrol station and "filling up" on a material that is flammable, combustible, and emits flammable vapours. We should take a step back to remember that there are inherent risks associated with gasoline and diesel fuelling operations as demonstrated throughout history (Figure 8). As incidents occurred, governments began instituting regulatory requirements such as the Environmental Protection Agency (EPA) *Fuel Handling and Storage* Regulations in the US, and the Petroleum (Consolidation) Regulations and Dangerous Substances and Explosive Atmosphere Regulations in the UK.

**Figure 8: Petrol Station Fire in St. Louis (Wicentowski, 2018)**

With respect to hydrogen fuelling, one can look to the propane fuelling market for lessons learned. In Canada, auto propane is the most popular alternative fuel and is primarily used by high consumption public and private fleets (i.e., taxis, couriers, school buses, and transit vehicles). Demand for auto propane increased dramatically in the 1980s due to the government's introduction of CA$400 in 1981 in response to national energy security concerns to encourage conversion of vehicles to propane fuel (Wikipedia, 2019). However, due to low gasoline and diesel prices in the 1990s, auto propane demand began to decline. Regardless, the station fuelling infrastructure had already gained traction and naturally followed the bulk storage and loading infrastructure for traditional propane markets.

On August 10, 2008, a Boiling Liquid Expanding Vapor Explosion (BLEVE) at the Sunrise Propane plant rocked Toronto (Figure 9). This explosion was the result of the illegal practice of swapping propane loads between trucks, which was faster than unloading to and loading from storage tanks. The event forced 12,000 residents to evacuate and resulted in two deaths and dozens of injuries. Houses and businesses near the blast site were destroyed and the total clean-up bill was approximately 1.8 million Canadian dollars with an additional multi-million dollar class-action lawsuit settlement (Doherty, 2016). Most importantly, the Sunrise propane event caused a high reaction from regulators and the public, ultimately resulting in new regulations.

**Figure 9: Sunrise Propane BLEVE (Alchetron, 2018)**

The Technical Standards and Safety Authority (TSSA) for the Ontario Province responded to the incident with *Ontario Regulation 211/01: Propane Storage and Handling,* which requires propane facilities to have Risk and Safety Management Plans (RSMPs) in place to ensure public safety (TSSA, 2017). The Propane RSMP requires strict risk criteria to be met for offsite impacts as part of a detailed site risk assessment. Unfortunately, because this standard was reactive instead of proactive, it meant that a portion of the propane auto filling infrastructure was not compliant and either had to be taken out of the network (shutdown) or heavy investment was required to make stations safety compliant.

## Objective Risk Assessment for Hydrogen Fuelling

The hydrogen fuelling infrastructure can take note of the lessons learned by the Canadian propane auto filling industry and proactively establish a regulatory requirement for objective risk assessment as part of the siting and operating of stations. While short term rigorous risk assessment requirements may add some complication to the buildout of infrastructure, long term it may aid in limiting future infrastructure disruption and support long-term public acceptance of technology.

While there are different designs for hydrogen fuelling stations based on production, delivery, storage, and dispensing, most stations include the following (Qin, 2014):

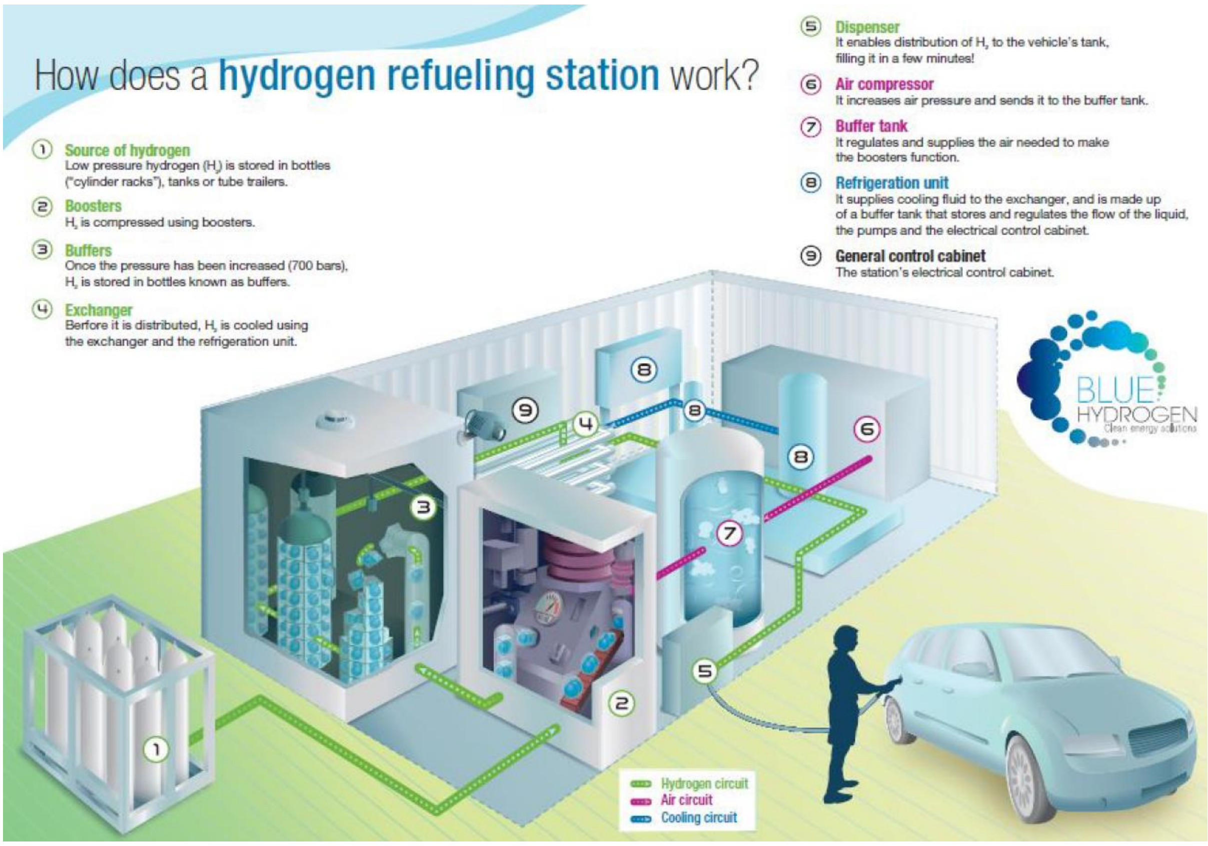
- Hydrogen production equipment for onsite production station only such as SMR and electrolysis
- Purification system to purify hydrogen to FCEV quality
- Hydrogen storage vessels, may be either gaseous (low or high pressure) or liquid form
- Compressor(s) to minimize storage volume and prepare gas for vehicle fuelling
- Cooling systems for hydrogen chilling
- Dispensing systems for vehicle filling (10,000 psi for light-duty vehicles and 5,000 psi for medium- and heavy-duty vehicles)
- Safety equipment (e.g., pressure relief valves, vent stack, sensors, security fencing, etc.)
- Mechanical equipment
- Electrical equipment

There are also a number of aspects associated with the material, technology and operating regime that require particular attention when applying safety review processes normally applied to traditional process facilities. These include, but are not limited to:

- Material properties of hydrogen
    - Explosion characteristics; potential for VCE and DDT
    - Ignition probabilities; low ignition energy
    - Frequency of failure; increased leak potential
- “Operator” training and competency; facilities are operated by members of the public and thus more likely to be prone to operator error
- Population exposure (transient & offsite), fuelling facilities likely to be located in urban rather than industrial environment
- Offsite vs. onsite hydrogen production; production facility risk + transportation risk + fuelling risk compared against onsite production risk. Onsite production technology doubles the cost of a station, however cost and, more importantly, risk savings are made elsewhere.

## Staged Approach for Efficient Hydrogen Fuelling Risk Assessment

A typical hydrogen fuelling station is shown in Figure 10 (Awad, 2018). Due to the similarities between stations, an objective quantitative risk assessment (QRA) approach can be effectively and efficiently applied as a staged review cycle to help owners/operators design efficiently for safety. This staged review cycle follows a 5-stage cycle as shown in Figure 11 (Vilas, 2019). The process begins by master planning the infrastructure buildout and station locations, leveraging the “typical” fuelling station equipment and operations to create a “generic” risk model for decision making purposes. Following the process presented in Figure 11, the risk models can then be used to optimize station layout and select appropriate safeguards to optimize safety.



How does a **hydrogen refueling station** work?

① **Source of hydrogen**
Low pressure hydrogen ($H_2$) is stored in bottles ("cylinder racks"), tanks or tube trailers.

② **Boosters**
$H_2$ is compressed using boosters.

③ **Buffers**
Once the pressure has been increased (700 bars), $H_2$ is stored in bottles known as buffers.

④ **Exchanger**
Berfore it is distributed, $H_2$ is cooled using the exchanger and the refrigeration unit.

⑤ **Dispenser**
It enables distribution of $H_2$ to the vehicle's tank, filling it in a few minutes!

⑥ **Air compressor**
It increases air pressure and sends it to the buffer tank.

⑦ **Buffer tank**
It regulates and supplies the air needed to make the boosters function.

⑧ **Refrigeration unit**
It supplies cooling fluid to the exchanger, and is made up of a buffer tank that stores and regulates the flow of the liquid, the pumps and the electrical control cabinet.

⑨ **General control cabinet**
The station's electrical control cabinet.

**Figure 10: Overview of Hydrogen Fuelling Station (Awad, 2018)**

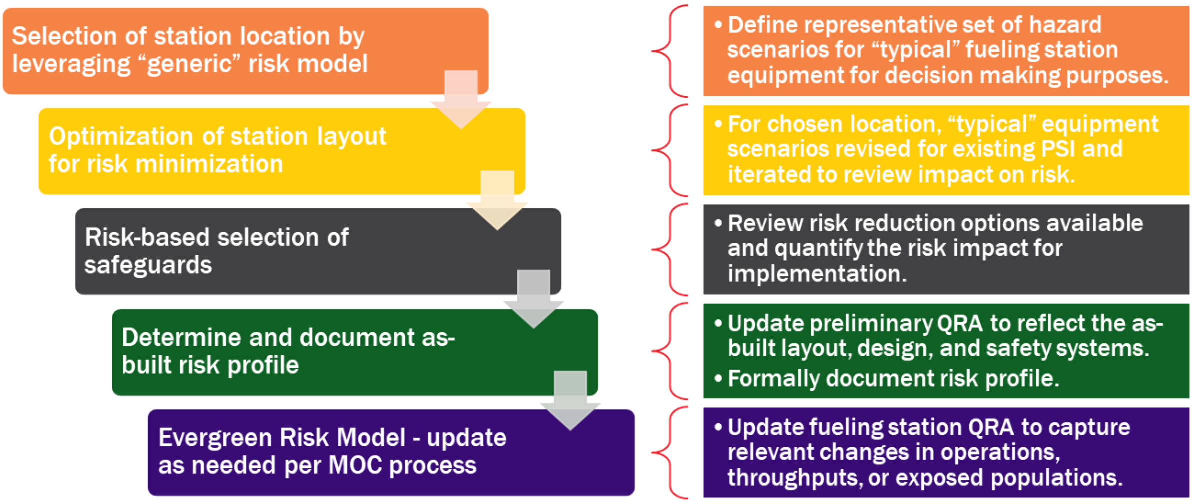


**Figure 11: Staged Risk Review Cycle – Design Efficiently for Safety (Vilas, 2019)**

Once the location is selected, the detailed design layout is determined, and the process data and safeguards are finalized, the site risk profile can be determined. Location specific individual risk contours (also known as geographic risk contours) can be utilized to ensure offsite populations are below specified risk criteria while fuelling operation population estimates can be utilized to determine a yearly onsite risk exposure. Finally, and most importantly, the risk assessment should not be shelved and determined complete; rather, it is an evergreen process that needs to be adapted and updated as the throughputs change with time, populations shift and/or encroach, and operations change to respond to demands.

While Figure 11 shows the process from a site master planning and operating perspective, Figure 12 shows how that same process supports the project lifecycle. In the initial Stage 1 Select Front End Loading, risk profiles are conceptual and used to establish infrastructure support and site layout. As the project moves through Stage 2 Detailed Design Update, the study is updated to reflect the actual site details and moves from "conceptual" to site specific. Stage 3 is arguably the most crucial as it not only updates the risk assessment model to reflect the as-built design and operations, but also ensures proper handover of PSI for the technology design/manufacturers to the station owner/operators. Complete transfer of PSI and proper education/understanding of the information is essential for support of Stage 4, the Evergreen Risk model. Understanding that risk is dynamic and small changes over time can have a large impact on the risk profile is paramount for station owners/operators to understand.

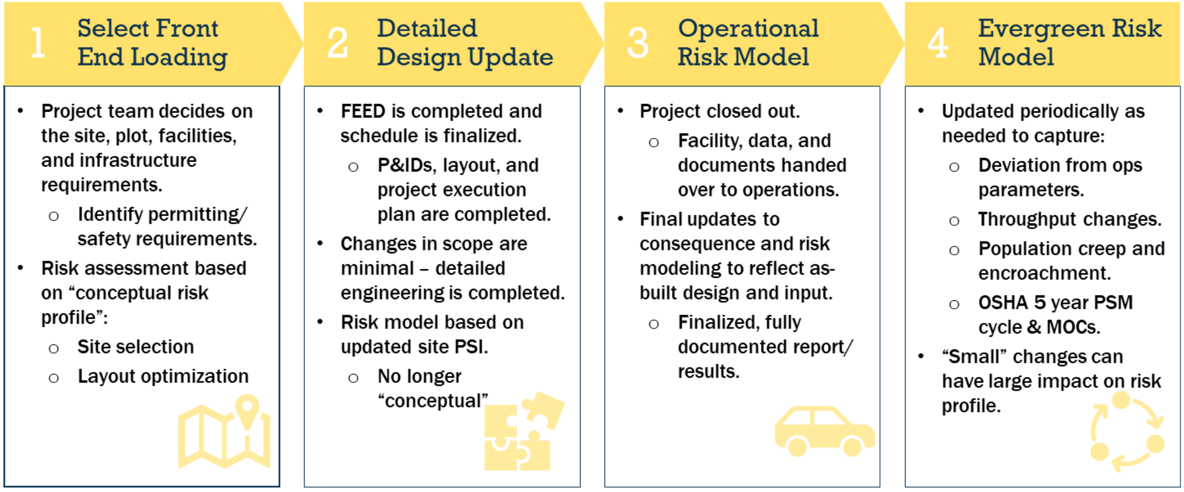


**Figure 12: Staged Review – Risk Assessment for Project Support (Vilas, 2019)**

A properly conducted, thorough risk assessment can be cost effectively and efficiently updated through this staged risk review cycle to objectively master plan, establish risk, and safeguard over time. If risk is properly addressed proactively in the infrastructure design and site selection, the likelihood of costly future changes is limited. It is up to the station owners/operators to facilitate transfer of PSI and ongoing communications to ensure risk understanding and ongoing operations. Furthermore, it is their responsibility to ensure site risk profiles remain evergreen and are updated when required.

It is important to note that proactive risk assessment can limit risk exposure and ensure safe siting, but risk, by definition, cannot be eliminated. The goal is to ensure that if an incident does happen, impacts are limited to the extent practicable.

## Conclusions

Countries around the world are actively adopting policies for GHG emission reductions with many moving towards goals of carbon neutrality. A large part of these efforts involves a shift away from gasoline and diesel combustion engine vehicles to alternative fuels such as battery powered and hydrogen fuel cell vehicles. FCEVs have the benefits of low to zero GHGs while maintaining high performance and comfort without compromising on range and refill time. Currently, governments are investing heavily through grants, subsidies, and incentives in the development of hydrogen fuelling technology infrastructure. However, to become financially viable, this burden will need to shift to technology owners and operators as well as the technology consumers. To achieve this shift, vehicles need to be cost competitive, renewable energy costs need to continue to drop, and the public must buy into FCEVs as a reliable and safe technology.

While we cannot directly affect the costs of technology, we can influence the public perception of technology reliability and safety. The main conclusion that can be drawn is that public perception needs to be changed; the idea of "normal" must be updated through exposure and education. Hydrogen is different; it behaves differently than typical publicly accepted products, and those differences need to be properly communicated to the public. If the public understands the properties and safe handling of hydrogen in the same way they do traditional vehicle fuels, barriers for adoption would be lower.

The media in today's societies ensure high profile, 24-hour news cycle on negative events. This high exposure to news means that one bad incident – one perceived threat – can influence the public against technological advancements. To get ahead and stay ahead of public perception of FCEV and hydrogen production/fuelling technology, a proactive and objective approach to risk assessment can ensure that when incidents do happen, impacts are limited due to preplanning with respect to infrastructure design and site selection and layout. While actively adopting regulatory requirements for risk assessments will likely have little impact on public perception, limiting future hazardous impacts or infrastructure disruptions will limit negative reactions to hydrogen fuelling technology.

> "Fuel cells will power cars with little or no waste at all. We happen to believe that fuel cells are the wave of the future, that fuel cells offer incredible opportunity."
>
> *President George W. Bush, February 25, 2002*

## References

Abadi, Mark, Business Insider. 2016. The US dropped 67 nuclear bombs on this tiny island nation – and now it’s far more radioactive than we thought. [ONLINE] Available at: https://www.businessinsider.com/marshall-islands-nuclear-bombs-radiation-2016-6. [Accessed 10 January 2020].

Alchetron. 2018. Toronto propane explosion. [ONLINE] Available at: https://alchetron.com/Toronto-propane-explosion. [Accessed 11 January 2020].

Awad, M. 2018. “Medium to long term development of Hydrogen Mobility in the UAE”, Hydrogen Mobility. Air Liquide / Khalifa University / Al Futtaim.

California Air Resources Board (CARB). 2019. Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development, July 2019. Available at: arb.ca.gov. [Accessed 10 January 2020].

CEN Online. 2014. Improving the Battery in the Tesla Model S Electric Car. [ONLINE]. Available at: https://www.youtube.com/watch?v=_MkPu6K0IIk. [Accessed 5 January 2020].

D’Allegro, Joe, CNBC. 2019. Elon Musk says the tech is ‘mind-bogglingly stupid,’ but hydrogen cars may yet threaten Tesla. [ONLINE] Available at: https://www.cnbc.com/2019/02/21/musk-calls-hydrogen-fuel-cells-stupid-but-tech-may-threaten-tesla.html. [Accessed 3 January 2020].

De Syon, Guillaume, Time. 2017. Why the Hindenburg Disaster Is Still Worth Remembering. [ONLINE] Available at: https://time.com/4764799/hindenburg-disaster-80-years/. [Accessed 10 January 2020].

Doherty, B. for The Star. 2016. August 10, 2008: Sunrise Propane plant explodes. [ONLINE] Available at: https://www.thestar.com/news/gta/2016/08/10/august-10-2008-sunrise-propane-plant-explodes.html. [Accessed 11 January 2020].

Evarts, E. for Green Car Reports. 2019. Northern California fuel-cell drivers still felt dry since June explosion. [ONLINE] Available at: https://www.greencarreports.com/news/1124908_northern-california-fuel-cell-drivers-still-left-dry-since-june-explosion. [Accessed 11 January 2020].

FM Global. 2013. “Evaluating Vapor Cloud Explosions Using a Flame Acceleration Method”, Data Sheet 7-42.

H2Stations.org. 2020. Hydrogen Stations Map. [ONLINE] Available at: https://www.h2stations.org/stations-map/?lat=41.971744&lng=-100.105299&zoom=4. [Accessed 12 January 2020].

Isenstadt, A. and Lutsey, N. 2017. Developing hydrogen fuelling infrastructure for fuel cell vehicles: A status update. International Council on Clean Transportation, October 2017. Available at: www.theicct.org. [Accessed 5 January 2020].

LeSage, J. for Oilprice.com. 2019. Fatal Explosion Slams South Korea’s Hydrogen Future. [ONLINE] Available at: https://finance.yahoo.com/news/fatal-explosion-slams-south-korea-190000850.html?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmNvbS8&guce_referrer_sig=AQAAADkC1vpD53NNN1Wgc6adoI0_WZ8tdqdC5O2YMyx_p4XxWKkfytJhE_9JCWrXc61wiK52hA2N5kMiTJiGcil-PgVyS3IauKMOyHaQzXkp3HKuWQmu8T1BRattg6G58xzYlxtoHikkAWomLPEOtA67jyuZpkKAQrznpX8NSuuqjodM. [Accessed 11 January 2020].

Jin, H. and Chung, J for Reuters. 2019. Hydrogen hurdles: a deadly blast hampers South Korea's big fuel cell car bet. [ONLINE] Available at: https://www.reuters.com/article/us-autos-hydrogen-southkorea-insight/hydrogen-hurdles-a-deadly-blast-hampers-south-koreas-big-fuel-cell-car-bet-idUSKBN1W936A. [Accessed 11 January 2020].

Levin, K. and David, C., World Resources Institute. 2019. What Does "Net-Zero Emissions" Mean? 6 Common Questions, Answered. [ONLINE] Available at: https://www.wri.org/blog/2019/09/what-does-net-zero-emissions-mean-6-common-questions-answered. [Accessed 3 January 2020].

MacEwen, Randy, Ballard Blog. 2019. Our Countdown of the Top 5 Developments in the Hydrogen and Fuel Cell Industry in 2018. [ONLINE] Available at: https://blog.ballard.com/hydrogen-and-fuel-cell-industry. [Accessed 5 January 2020].

Moosemiller, M. and Galindo, B. 2014. “Hydrogen Ignitions – Wildly Differing Opinions, and Why Everyone Could be Right”, American Institute of Chemical Engineers 2014 Spring Annual Meeting. 10th Global Congress on Process Safety, New Orleans, LA.

Qin, N. and Brooker, P. 2014. “Hydrogen Fuelling Stations Infrastructure”, Electrical Vehicle Transportation Center Semi Annual Report. EVTC Report Number EVTC-RR-02-14.

Randall, C. for elective.com. 2019. Norway: Explosion at hydrogen filling station. [ONLINE] Available at: https://www.electrive.com/2019/06/11/norway-explosion-at-fuel-cell-filling-station/. [Accessed 11 January 2020].

Research and Markets. 2019. Global Hydrogen Fuelling Stations Market, 2019-2033. [ONLINE] Available at: https://www.prnewswire.com/news-releases/global-hydrogen-fuelling-stations-market-2019-2033---hydrogen-station-deployments-pick-up-in-several-regions-with-337-operating-worldwide-300817593.html. [Accessed 5 January 2020].

Santa Clara Weekly. 2019. Hydrogen Gas Explosion and Fire at Air Products and Chemicals, Inc. In Santa Clara. [ONLINE] Available at: https://www.svvoice.com/hydrogen-gas-explosion-and-fire-at-air-products-and-chemicals-inc-in-santa-clara/. [Accessed 11 January 2020].

Thomas, K., Eastwood, C. and Goodrich, M. 2014. "Are Unconfined Hydrogen Vapor Cloud Explosions Credible?" Process Safety Progress, 34(1), pp. 36-43. Doi: 10.1002/prs.11685.

Toyota. 2019. Coupe-Inspired Design Modernizes All-New 2021 Toyota Mirai Sedan Concept. [ONLINE] Available at: https://pressroom.toyota.com/coupe-inspired-design-modernizes-all-new-2021-toyota-mirai-sedan/. [Accessed 5 January 2020].

Technical Standards & Safety Authority (TSSA). 2017. Propane RSMP. [ONLINE] Available at: https://www.tssa.org/en/fuels/propane-rsmp.aspx. [Accessed 11 January 2020].

Vilas, K. 2019. Effective Application of QRA to Hydrogen Fuelling Operations. In Conference on Hydrogen Safety. Sacramento, CA USA, October 14-15, 2019.

Wicentowski, D. for Riverfront Times. 2018. Incredible Dumbass Turns Lamborghini into Fireball at St. Louis Gas Station. [ONLINE] Available at: https://www.riverfronttimes.com/newsblog/2018/07/09/incredible-dumbass-turns-lamborghini-into-fireball-at-kirkwood-gas-station. [Accessed 11 January 2020].

Wikipedia contributors, 'Autogas', Wikipedia, The Free Encyclopaedia, 27 December 2019, 02:15 UTC, <https://en.wikipedia.org/w/index.php?title=Autogas&oldid=932598990> [accessed 12 January 2020]

Wikipedia contributors, 'Electrolysis of water', Wikipedia, The Free Encyclopaedia, 2 January 2020, 08:29 UTC, <https://en.wikipedia.org/w/index.php?title=Electrolysis_of_water&oldid=933654041> [Accessed 3 January 2020]

World Resources Institute (WRI). 2020. Making Big Ideas Happen. [ONLINE] Available at https://www.wri.org. [Accessed 3 January 2020].

Zolash, R.G. and Short, T.P. 1978. "Compilation and Analysis of Hydrogen Accident Reports", Factor Mutual Research Corporation for the US Department of Energy. FMRC J.I. 4A7N0.RG, RC78-T-54.