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Review article

Enhancing safety in nuclear-powered water electrolysis for low-carbon hydrogen production: A process safety approach

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ABSTRACT

The global transition away from fossil fuels has piqued interest in hydrogen as a low carbon energy carrier. Incorporating meaningful quantities of low-carbon hydrogen into the energy mix requires safe, cost-effective production at scale. This can be realized through utilization of electricity, steam and waste heat from nuclear power plants to power hydrogen production via water electrolysis. Nuclear power plants have critical safety systems to prevent radioactive releases. Concerns arise over the safe operation of pink hydrogen facilities, as usage of highly flammable hydrogen near nuclear facilities may increase fire and explosion risks. This work undertakes a comprehensive identification and review of hazards linked to hydrogen release, separating management strategies by incident prevention and severity limitation. Available data on the size of this fire and explosion risk is limited, and uncertain component failure rates impedes attempts to execute the quantitative risk assessment required for close integration of nuclear and hydrogen systems. However, close integration facilitates usage of nuclear waste heat, increases electrolyzer efficiency, and supports hydrogen production at a cost competitive with that produced using fossil fuels. This paper reviews the relevant works and identifies safe integration of nuclear and hydrogen systems as a key challenge for economical pink hydrogen production and proposes a series of mitigation strategies focused on leak prevention and detection. This supports a better-informed basis of safety for pink hydrogen projects and innovative design recommendations such as those related to spatial configuration.

1. Introduction

Combatting climate change is the defining issue of modern times. Continuing global temperature increases threaten catastrophic harm to people and ecosystems worldwide. Incidents of extreme weather events increase with every increment of temperature, threatening direct harm. Shifting weather patterns threaten food and water security, with the greatest effect on the most vulnerable people and societies. Restricting global temperature increase to 1.5 °C above preindustrial levels is vital to limit irreversible changes in major ecosystems and the planetary climate system [1,2]. Reducing the concentration of greenhouse gases in the atmosphere is key to halting the increase in global temperature. There is an urgent need to radically reconsider the global energy mix, reducing emissions linked to the combustion of fossil fuels [3].

1.1. Hydrogen and the energy transition

Hydrogen has emerged as a promising energy carrier to support this vital energy transition, capable of reducing reliance on fossil fuels and replacing them with lower carbon energy sources [4].

Importantly, hydrogen could play a key role in a decarbonized energy portfolio as a form of long-term energy storage to support grid stability. This can provide flexibility to intermittent energy sources and minimize losses when renewable or nuclear energy generation exceeds demand [5]. Hydrogen is a well-established industrial gas, with well-developed storage and transportation methods [6]. With supporting legislation and investment, this makes the hydrogen gas well positioned to provide power and security for energy transition [7]. The environmental benefits of using hydrogen are inextricably tied to the carbon footprint of its production method.

1.2. Hydrogen production methods

Hydrogen can be produced from a diverse range of processes, using a variety of energy sources and feedstocks. Each production pathway corresponds to a wide range of emissions, relating to the energy sources and technology employed [10].

Hydrogen production from fossil fuels with no carbon dioxide emission control (grey hydrogen) is by far the most common hydrogen production method, responsible for 830 Mt of carbon dioxide each year

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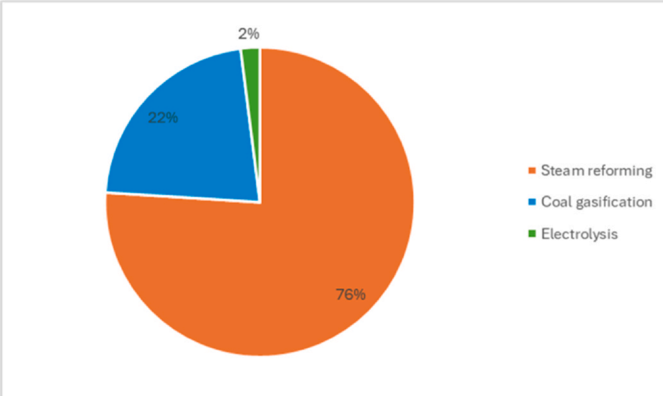

Fig. 1. Global hydrogen production methods. Data taken from the Center on Global Energy Policy at Columbia [8].

[8]. These processes are energy intensive and use non-renewable feedstocks. Production of hydrogen is largely carried out via steam reforming, where methane is split into carbon dioxide and hydrogen, this is currently the most economical and developed commercial method of hydrogen method to produce hydrogen [9]. Turning a grey hydrogen process blue, through addition of Carbon Capture, Usage, and Storage increases the cost of hydrogen production by 20–80%, depending on the production method [8]. For this reason, less than 1% of total hydrogen production utilizes Carbon Capture, Usage, and Storage to reduce emissions [10]. Currently only 2% of the world's hydrogen is produced via electrolysis of water [7]. (Fig. 1).

Water electrolysis is a suitable method for production of clean hydrogen. If the input electrical power required has no associated greenhouse gas emissions, then the hydrogen produced can be considered zero-carbon [11]. The cost of energy to produce green hydrogen from renewable sources such as wind and solar is currently too high to compete with grey hydrogen. This cost will reduce over time with technological advancements [9].

Pink hydrogen is hydrogen produced through water electrolysis using nuclear resources. Nuclear power plants produce no carbon emissions during operation but have a small quantity of emissions associated with their life cycle. The UN Intergovernmental Panel on Climate Change (IPCC) estimates the median life-cycle carbon-dioxide-equivalent emissions of nuclear power to be 12 g of carbon dioxide per kWh electricity, similar to wind power [12,13]. Energy prices from nuclear power are lower than renewable power sources, allowing pink hydrogen to better compete financially with fossil-based hydrogen production. Nuclear power has the potential to deliver hydrogen production through water electrolysis at scale, with large capacity nuclear plants a key factor in this lower cost [14]. Energy for electrolysis can be provided through the heat of fission, or from electricity generated using turbines [4]. Combining the nuclear and water splitting technologies presents an opportunity to utilize waste heat to carry out electrolysis at higher temperatures, increasing the efficiency of both systems [15]. (Fig. 2).

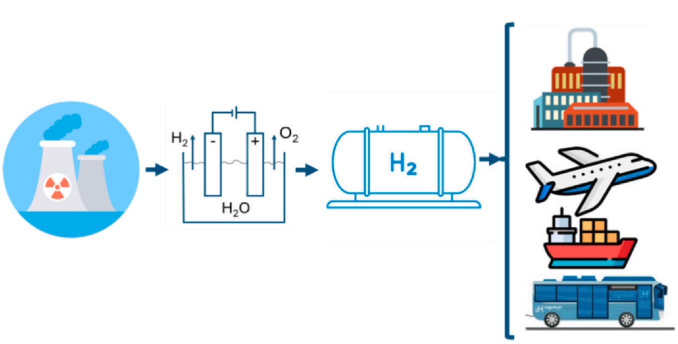

Fig. 2. Pink hydrogen production and usage pathway.

This paper recognizes the value of pink hydrogen technology development and considers the process safety challenges associated with production of hydrogen via this method. It is vital that process safety is considered early in the design and conceptualization stages to ensure that a risk which may appear small at the demonstration stage, does not become inhibitory when developing larger commercial projects [16]. Low carbon hydrogen production is a vital tool to support energy transition. Hydrogen technology must be socially viable if a hydrogen economy is to be successful, this necessitates safe and reliable production to gain public and governmental support, safety incidents have in the past resulted in large scale withdrawals from usage of such technologies [17]. Both hydrogen and nuclear technologies evoke safety concerns among the public, which has hindered the usage of fissionable material and hydrogen and energy sources [18]. The Hindenburg disaster of 1937, which killed 36 people when a hydrogen filled blimp exploded, continues to dominate the view of hydrogen, despite a substantial record of industrial safety [19]. Similarly, the Chernobyl nuclear accident was a key factor in Germany's anti-nuclear sentiment and the Fukushima Daiichi incident prompted the country's renewed commitment to phase out of nuclear power in 2011. It is vital that a serious pink hydrogen incident is avoided, for the protection of people and the environment, but also to ensure that this technology remains an available tool for energy transition.

This work discusses the existing knowledge of safe usage of water electrolysis in combination with nuclear power plants to generate hydrogen. The suitability of common electrolyzer and nuclear power plant types, in combination for pink hydrogen production are evaluated in Section 2.2. Recommendations are made in Sections 2.3 and 3.1 as to the safety and ease of integration of different technology combinations.

In Sections 3.1 and 3.2, this paper demonstrates where existing knowledge from separate hydrogen, nuclear and water electrolysis industries can be used to identify hazardous scenarios in a pink hydrogen production process. An event tree is used as a tool to demonstrate the consequences of hydrogen release in Section 3.2. This work considers each hazard posed by the combination of nuclear and hydrogen production facilities and identifies an elevated fire and explosion risk as a key hazard. The is due to the flammability properties of hydrogen and the possibility of radioactive release if nuclear safety systems were damaged in an incident. In Section 3.3, mitigation strategies are considered to reduce the likelihood and severity of a hydrogen leak. This incorporates safer by design principles and suggests that material selection considers hydrogens embrittlement properties, and that welded fittings are used over flanges to combat hydrogen high diffusivity. An integrated safety system is proposed where, if a hydrogen leak is detected, ventilation should be increase and air and electricity supply should cease to rapidly cease hydrogen production, preventing the accumulation of an explosive atmosphere.

In Section 3.4, existing pink hydrogen demonstrations are identified and their safety and licencing approaches considered. In Section 3.5 these safety cases are used to make targeted recommendations for areas in which process safety research could accelerate the development of large-scale pink hydrogen production facilities. At present, insufficient data is available as to the size of the fire and explosion risk at such facilities, in part due to a lack of available data. This work sets out a comprehensive, qualitative review of pink hydrogen hazards and establishes an important framework from which a safer design recommendation can be made. The report finds that despite an elevated explosion risk, there is evidence to suggest that the electrolyzer could be positioned more closely to the nuclear plant than has been achieved previously and recommends that this qualitative assessment of hazards is supported by a quantitative risk assessment which calculates this distance. Close integration of nuclear and hydrogen systems is vital for heat integration supporting high temperature electrolysis at a price competitive with cheaper, polluting, grey hydrogen alternatives. Conclusions such as these are facilitated by the new framework developed through this report.

There are some other references which have recently studied pink hydrogen's role in a hydrogen economy [20–26].

2. Pink hydrogen

2.1. Hazards of hydrogen

Hydrogen is highly flammable with a low minimum ignition energy of 0.019 mJ [27], only 4% of that of methane. Combustion of hydrogen produces high pressures and temperatures, further escalating these flammability hazards. The instability of the flame and interaction of various pressure waves results in turbulent combustion - this can escalate with increasing flame speed creating a detonation [28].

Hydrogen's high diffusivity and embrittlement compromises the strength of materials, this can cause cracking which increases propensity to leakage [29]. In the event of a leak however, hydrogen rapidly dissipates reducing the risk of ignition. Hydrogen's flammability is so great that a high-pressure release can cause a jet fire – the movement of the gas itself provides sufficient kinetic energy to cause ignition. Slower releases and delayed ignition can result in a flash fire or explosion [28,30].

2.2. System components

2.2.1. Types of nuclear power plant

The 2 most common types of reactor are light water pressurized water reactors (PWRs) and boiling water reactors (BWRs), these make up 70 and 15 percent respectively of the global reactor fleet [31]. This paper focuses on light water BWRs and PWRs in detail and additionally touches on the role of small modular reactors (SMRs) for pink hydrogen production.

2.2.1.1. Pressurized water reactors. PWRs are characterized by having 2 separate water circuits. They comprise of a primary circuit which flows through the core of the reactor, this is pressurized so that it does not boil at elevated temperatures, and a secondary circuit which is heated to steam via heat exchange with the primary circuit. Water in the secondary circuit boils as it is held at a lower pressure [31]. A diagram of a PWR is shown in Fig. 3. The steam in the secondary circuit is fed into the turbine to generate electricity [32].

2.2.1.2. Boiling water reactors. BWRs utilize a single circuit of water which passes through the reactor and turbine. This is shown in Fig. 4. Here, the water is held at a pressure which allows it to boil.

Both BWRs and PWRs have been shown to be compatible with a water electrolyzer, provided careful consideration is made for the heating and steam requirements of the electrolyzer and steam provision from the nuclear plant [36,37].

2.2.2. Types of electrolyzer

In electrolysis, water is split into its constituent molecules by means of an electrical potential. A membrane or diaphragm separates the evolved gases and mechanically supports the cell, enabling it to withstand pressure differences between the 2 sides [38,39]. This is vital in water electrolysis as the evolved gases (hydrogen and oxygen) have potential to form an explosive mixture [40].

There are 4 main electrolyzer technologies. These are:

- Alkaline Water Electrolyzer (AWE)
- Proton Exchange Membrane (PEM)
- Solid Oxide Electrolysis Cells (SOEC)
- Anion exchange membrane (AEM)

AEM technology is the at the earliest development stage, and demonstrations currently produce hydrogen but only at the kilowatt scale [41] – too small to be considered for pink hydrogen trials [42]. This research focusses on the 3 better established technologies; AWE, PEM and SOEC. Key operational differences are given in Table 1.

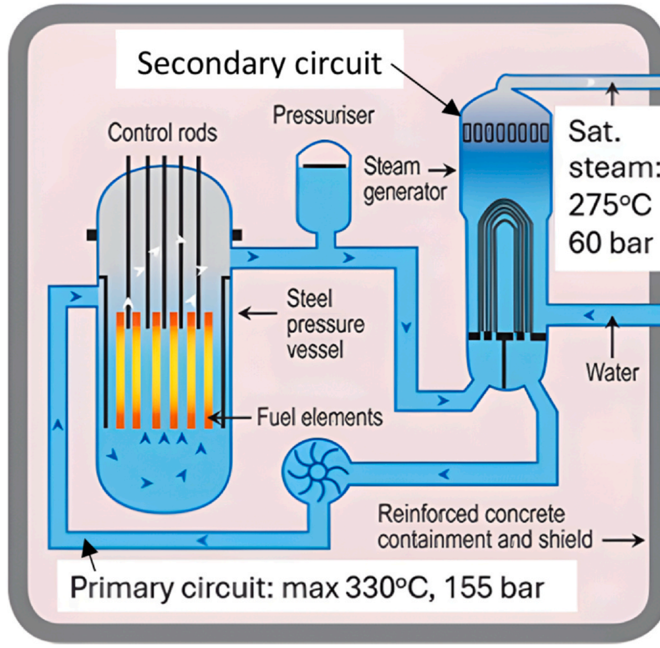

Fig. 3. Diagram of PWR taken from World Nuclear Association [31]. With annotations [33,34], where Sat. steam is an abbreviation of saturated steam. PWR = pressurized water reactor.

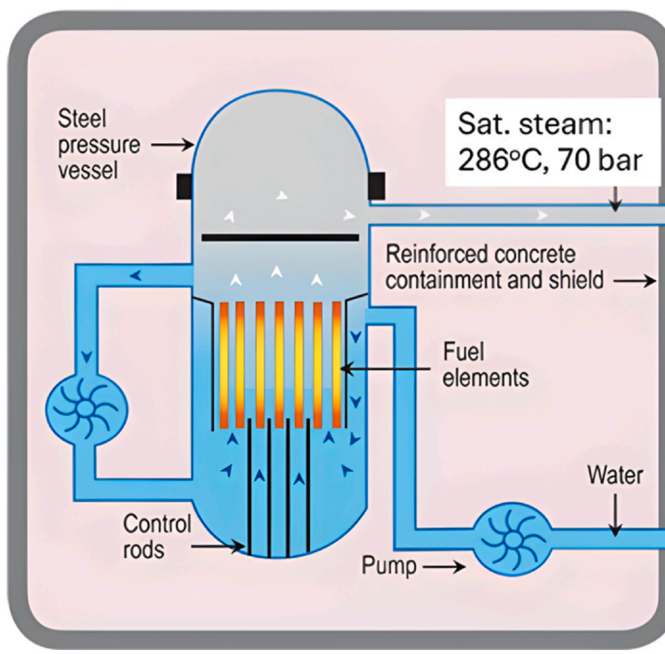

Fig. 4. Diagram of boiling water reactor taken for World Nuclear Association [31]. With annotations [35], where Sat. steam is an abbreviation of saturated steam.

The 3 electrolyzer types differ in their chemical and physical properties. It is these characteristics that determine the inherent safety of a particular technology and its suitability for a certain application.

AWE cells are the most established technology for water electrolysis and have proven over decades to be reliable and safe over an extended life span of around 20–30 years. They have the lowest capital cost of the 3 technologies and the greatest current commercial scope as they can be deployed in capacities over 100 MW [15]. The key drawbacks of AWE

Table 1
Comparison between electrolyzer types

	Alkaline water electrolyzer (AWE)	Proton electron membrane (PEM)	Solid oxide electrolysis cells (SOEC)
Electrolyte [4]	NaOH/KOH (liquid)	Polymer (solid)	Ceramic (solid)
Efficiency (%) [43]	60–80	80	> 90
Temperature (°C) [43]	60–80	50–90	500–1000
Readiness [43]	Mature	Commercial	Demonstration
CAPEX ($/kWe) [15]	500–1400	1100–1800	2800–5600
Current maximum demonstrated capacity (MW)	150 MW (Baofeng Energy, China) [44]	20 MW (Air Liquide, Quebec) [45]	4 MW (NASA, California) [41]

cells are that they operate at lower efficiency (60–70%) than PEM or SOEC types and the current density is also lower, limited to 0.45 A/cm^2 [11]. This means that a lower hydrogen production rate is possible [46]. Alkaline fog in the generated gas makes AWE electrolyzers less environmentally friendly than systems such as PEM which do not require caustic solutions [47]. For intermittent renewables applications, a key challenge of AWE's is the long start up time and slow response to load [38]. Power fluctuations are not seen to the same degree in nuclear power plants, reducing the need for rapid response times in an accompanying electrolyzer. For economic reasons, nuclear power plants tend to be operated continuously around their maximum output, to provide base-load power to the grid [48]. Therefore, rapid response times provided by PEM electrolyzer types do not provide additional benefit to a pink hydrogen use case.

PEM electrolytic cells have fast response and start up times, this provides high load flexibility and can support grid balancing services [5]. A compact design with higher current densities (up to 10 A/cm^2) and efficiencies (circa 80%) provide significant advantage over traditional AWE systems, although both systems operate at similarly low temperatures. Higher output pressure of the gas reduces the compression costs of hydrogen storage downstream [11]. PEM electrolyzers contain Nobel metals such as platinum and iridium, utilizing their exceptional electrocatalytic properties [4]. However, these metals are susceptible to corrosion, and cost and scarcity issues limit large scale commercial applications [49]. Alternative catalytic materials are being developed to safeguard technologies from these challenges [50].

SOECs operate at elevated temperatures which aid ion transfer and can achieve electrolysis at very high efficiencies; up to 100% (at 1 A/cm^2) [11]. Capital cost of installation of an SOEC system remain high, but as the technology becomes more established this is predicted to fall. Over time SOEC could be available for lower capital costs then PEM or AWE systems in certain circumstances [51,52]. Of the 3 technologies, this is the least developed and remains in the demonstration stage, although larger scale (1 MW) trails are planned in conjunction with nuclear plants over the next few years [41]. The key advantage of SOEC is that the cells can utilize industrial waste heat to provide the elevated temperatures required (500–1000 °C), increasing the efficiency of both operations [53]. This higher efficiency and reduced electricity demand means that SOEC electrolyzers could produce hydrogen at lower operating costs [54]. This has led to growing interest in SOEC in conjunction with existing sources of process heat [55]. Steam and heat are abundant in nuclear plants, which typically release around 67% of their thermal energy as waste heat [56].

Of course, electrolyzers do not exist as units in isolation. They require associated subsystems and auxiliary components to function properly. For water electrolysis these typically include pumps, water demineralization equipment, separation equipment, transformers, system controls and many more [51]. Each electrolyzer type has different "Balance of Plant" requirements, each incurring different costs and installation challenges. A PEM system is generally seen to be straightforward to balance, while an SOEC is much more challenging [11]. SOECs have a more extensive system of associated components due to their high operating temperatures; heat exchangers are required to recycle heat, and a top up heater is required to bring the feed temperature up to that of the SOEC stack and to prevent temperature gradients. This all has an associated cost and ground footprint. A PEM system is also the most compact and can generally deliver the same production capacity at an AWE or SOEC, with half of the footprint [51]. These are important considerations for space restricted use cases. Deficiencies in associated systems can cause premature degradation of the electrolyzer and hinder system efficiencies and hydrogen purities. From a safety perspective, it is vital that supporting systems are properly designed and maintained [57].

All 3 electrolyzer types can produce high purity hydrogen [11,58], and have been demonstrated as viable technologies for pink hydrogen applications [15,37]. They have been commercialized or demonstrated at varying scales (see Table 1).

Additional sources were used to support this comparison electrolyzer technologies [59–61].

2.3. Retrofitting water electrolyzers to BWR and PWR nuclear power plants

2.3.1. The advantages and schemes of heat utilization for high temperature electrolysis

A nuclear plant can provide energy required for water splitting as electrical energy and/or thermal energy. For conventional, low temperature electrolysis (PEM or AWE types), the electrolyzer can be located outside of the nuclear plant boundary, minimizing risk to nuclear safety. However, efficiency improves if waste heat from the reactor is utilized to preheat the feed. This enables high temperate electrolysis through SOECs without excess heating cost [15].

Electricity can be easily transferred across large distances with minimal losses, steam succumbs to significant thermal energy losses which increase proportionally with distance traveled. Without an external heat source to generate steam however, the potential 20% efficiency advantage of SOEC over lower temperature electrolyzer types disappears [51].

Unlike conventional low temperature electrolysis, high temperature electrolysis takes place well above the boiling point of water. Superheated steam reduces the energy requirement for water splitting, as the total energy demand excludes the heat of vaporization. Thermal energy is a more economical means of providing energy for this purpose than electricity, making heat integration a key benefit of combining a nuclear process with high temperature electrolysis using SOECs [62].

Heat integration can either be direct (heat is transferred directly from the stream of one process to another via a heat exchanger), or indirectly (an intermediate loop containing a heat exchange fluid is used to transfer heat between the streams of different processes).

2.3.1.1. Indirect heat integration

- Advantages: Enhanced safety through physical separation (no direct contact between heat source and sink); radioactive leaks can be isolated and detected in the intermediate loop. Enables greater design flexibility (e.g choice of heat transfer fluid) and supports continued electrolyzer operation during nuclear plant maintenance (if backup heaters are used). The intermediate loop could collect heat from different streams if multiple heat sources are required.

- Disadvantages: Addition of an additional intermediate loop would incur higher capital costs for piping and pumping; lower thermal efficiency due to additional heat loss in transfer.

2.3.1.2. Direct heat integration

- Advantages: Higher thermal efficiency due to fewer transfer steps.
- Disadvantages: Safety concerns due to potential radioactive contamination and the physical proximity required between systems.

For a combined nuclear and high temperature electrolysis system, indirect heat integration is preferred [63]. The physical separation of the nuclear and electrolysis processes reduces the risk of safety incidents and provides an additional barrier to inclusion of radioactive contaminants in the hydrogen production process [64].

2.3.2. Ease of co-fitting an SOEC electrolyzer with heat integration with a PWR and BWR

Water streams passing through the core of the reactor contain radioactive contaminants [65] such as Nitrogen-16; a radioactive isotope with a high activity and short half-life that is produced when oxygen in the cooling water captures a neutron and emits a beta particle [48]. Radioactive isotopes must be removed before steam enters the electrolyzer system so that radiation hazards are contained within the shielding of the reactor [66]. This can be achieved through shielded heat exchanger, or through extensive filtration and purification of the steam.

In a PWR, this shielding is inbuilt between the primary and secondary circuits significantly reducing steam radioactivity, although some small and more difficult to remove radionuclides such as tritium may remain. The small size of tritium means that it can permeate through process piping. Integration of electrolyzers with a BWR is more complex and these reactors do not have a secondary loop which acts as a physical barrier to contaminants. Therefore, use of the steam requires this additional processing since it has directly passed through the reactor core [65,66]. The allowable limits of radioactivity in discharge material are generally specified by regulatory bodies, and vary by use case – for example, levels in material used in a desalination plant to provide drinking water will be lower than for district heating [64].

In the pink hydrogen case, it is possible that tritium could migrate from the nuclear cooling circuits into the hydrogen production facility and into the hydrogen product stream [63]. The allowable limit for tritium contamination should be provisionally set to the U.S. Environmental Protection Agency standard for drinking water (0.74 Bq/g), with an exposure pathway analysis to be carried out to determine to what level this could be relaxed. Licensing usage of nuclear generated process heat is a challenge. Within item 4.4 of SECY-10-0034, Potential Policy, Licensing, and Key Technical Issues for Small Modular Nuclear Reactor Designs, the Nuclear Regulatory Commission (NRC) sets out its guidance on licencing facilities that utilize nuclear generated process heat [64,67].

Limits vary significantly between countries with range from 100 mBq/g in France, to 76 Bq/g in Australia. Tritium can be removed through separation of tritiated water from water via isotope exchange, electrolysis and distillation methods. Levels of radioactivity in the nuclear process stream proposed for use as process heat should be measured and the stages of separation required calculated based on this [64].

Where waste process heat is to be utilized from an existing nuclear reactor, it may be more efficient to integrate the electrolyzer with a PWR to aid the provision of the high temperature, low-radioactivity steam [66,68]. The heat exchanger between loops on a PWR shields the secondary loop from much radiation, whereas BWRs require costly retrofitting of shielded heat exchangers. Electrolyzer-nuclear plant combinations must be considered on a case-by-case basis.

The success of a low carbon hydrogen economy is strongly dependant on the cost of the hydrogen produced being competitive with that from fossil-based production [9]. Different electrolyzer types incur different costs, and the suitability of each is highly dependent on the chosen application and scales involved. The vicinity of the hydrogen production facility to its target market should be considered as storage and transportation of hydrogen incur separate and significant costs [6]. For pink hydrogen applications, licensing restrictions limit how closely linked the nuclear and hydrogen production areas of the plant may be [69]. These restrictions are in place to ensure that changes to the original plant do not compromise its safety systems. Large distances between systems can incur significant heat losses, limiting any economic advantage brought about through use of waste heat [15]. This is of greatest issue for SOEC electrolyzers, given they require much higher temperatures than the other types to operate at efficiencies which make them economical [51]. This presents a process safety challenge of ensuring that the electrolyzer can be positioned in close vicinity of a nuclear plant without compromising safety.

The thermal requirements of the electrolyzer determine the temperature of the process water used from the nuclear power plant. Should a large amount of thermal energy be required (high temperature electrolysis), this may be tapped from before the turbine. This would however affect turbine control and electrical power capacity of the nuclear reactor. Smaller thermal requirements can be provided by steam take-off after the first turbine minimizing these disruptions. In a BWR, to prevent creation of a route for contaminated fluids to leave the facility, steam take-off would likely take place within the turbine building [70]. Alongside the safety assessment, a monetary calculation considering electrolyzer efficiency gains against the thermal load on the nuclear reactor would be required. In the case of an incident, an integrated steam pathway may present an additional route for contaminated coolant to escape (e.g, a steam pipe breakage).

2.3.3. A note on small modular reactors (SMRs)

Small modular reactors (SMRs) are nuclear reactors which are smaller than 300 MWe – around a third of a traditional nuclear power plant. There are around 80 different designs, and reactors may be cooled by water, gas, liquid metal, molten salt and more. Of these, most are in the design or licencing stage, but some are operational. Specific hazards relate to the design and safety basis of the individual SMR. A key advantage of SMRs is that they are modular and scalable – components can be assembled at a factory and then transported to site. This makes SMRs flexible and suited to supplying power to remote regions. They are also available at a much lower cost than traditional nuclear reactors [71].

SMRs have many inherent safety characteristics based on their reduced operating capacity, and low core power and pressure. The safety concept for an SMR relies upon passive systems. The proportion of coolant to fuel is much greater for an SMR than larger reactors reducing the scale of a possible incident. Furthermore, SMRs are able to use natural circulation to cool the reactor core, this means that even in the case of an incident, little to no operator involvement is required to return the reactor to a safe state [71].

There is potential for a SMR – SOEC combination to produce hydrogen at a lower cost than other electrolysis methods [72]. It is important to mention SMRs within this paper, although the focus is on hydrogen production introduced alongside existing, larger scale nuclear power plants.

3. Hazard identification of nuclear, water electrolysis and combined pink hydrogen production systems

This research looks at the hazards associated with each part separately and considered the combined hazards brought about by carrying out all parts in proximity. By considering safety from the concept selection and employing inherently safer design principles, risk can be better managed throughout the product lifecycle [73]. There are significant safety challenges to overcome in the development of a commercial pink hydrogen production system. Lessons should be taken from existing nuclear power plants, hydrogen handling and electrolysis sites and uses to accelerate the progress and improve the safety protocols for pink hydrogen production.

3.1. Safety challenges of nuclear power and water electrolysis

3.1.1. Nuclear safety

Nuclear plants are operated under rigorous safety procedure to protect human health and prevent the release of radioactive materials into the environment. These procedures reduce the likelihood of events that may result in loss of control of the reactor core, uncontrolled fission reactions and subsequent meltdown. An international guideline as to the high levels of safety required for safe nuclear operations is set out by the International Atomic Energy Agency [74].

Pink hydrogen production risks arise from either electrolysis, nuclear energy production, or the flammability properties of hydrogen. These parts in isolation are established industries, with associated regulation and safe operating procedure. This work considers areas of increased risk associated with handling, storing and producing highly flammable hydrogen in the vicinity of radioactive material.

3.1.1.1. Impacts of fire and explosion on critical nuclear safety systems. Both fire safety assessment and operational knowledge have shown that fire and/or explosion on a nuclear power plant can seriously affect plant safety [75]. Due to the increased risk presented by colocation of a hydrogen electrolyzer and nuclear plant, it is important to discuss here the potential effect of a hydrogen explosion on the nuclear power plant, particularly possible damages to critical equipment.

The International Atomic Energy Agency's analysis of historic fire and explosion incidents identified design flaws (e.g, steam pipes located adjacent to cables) and human factors as major contributors to an incident. This highlights the importance of careful safety by design consideration, particularly in the positioning of an intermediate heat exchange loop to provide nuclear process heat for high temperature electrolysis.

The consequences of fire and explosion events [75]

- A change of plant status (e.g, reactor scram/change of power level) due to failure of safety related items such as, diesel generators, off site power, degradation of the containment and/or fire boundary and failure of heat removal capability.
- The key functions (core heat removal, confinement of radioactive material) have previously been affected by fires even in cases where the fire has begun in a location where safety related items are not present.
- Undesired transient effects. Where nuclear waste heat is used for water electrolysis, and this places a high thermal load on the power plant (circa 30%), there is a risk that prompt loss of this thermal load could trigger a transient [70].
- Negative environmental impact (radiological/non-radiological).

Loss of key functions such as core heat removal (e.g, through loss of feedwater and emergency pumps) has potential to result in nuclear meltdown or necessitate reactor shutdown to prevent core damage from overheating.

3.1.2. Electrolyzer safety and comparison of electrolyzer types

Of the 3 technologies discussed, PEM electrolyzers are considered the safest electrolyzer type [4,76]. This does not however mean that other electrolyzers are unsafe, but there are additional risks to consider. Choices of nuclear-electrolysis technology combinations generally relate to the simplicity and cost of integration [6,66]. Key risks associated with hydrogen production via electrolysis are discussed in this section.

3.1.2.1. Gas crossover and formation of an explosive mixture. The primary safety challenge within an electrolyzer is to produce both oxygen and hydrogen, while preventing the formation of an explosive mixture of the 2 gases. The gas permeability of a diaphragm within an AWE cell is much higher than a PEM cell. In PEM electrolyzers, $H+$ ions diffuse across the cell to the cathode. Protons are the smallest ions and so can diffuse through solid polymers which resist the flow of other materials. This means that the membrane is able to completely separate the oxygen and hydrogen in the 2 sides of the cell while still allowing electrolysis to take place [38]. The porous diaphragm in an AWE cell must have larger pores to allow OH- ions to pass through. This also means that small amounts of oxygen may pass across the diaphragm and leave the cell at the cathode alongside the hydrogen gas [76].

However, if the membrane of a PEM electrolyzer is improperly maintained, exposure to elevated temperatures, feedwater impurities and high current densities within the electrolyzer can cause it to degrade over time [77]. This poses a risk of crossover of hydrogen onto the oxygen side and the same associated risks of an explosive mixture forming.

SOECs operate at temperatures above the autoignition temperature of hydrogen increasing the ease of ignition of hydrogen. A leak at this temperature would immediately ignite without an additional ignition source. This however means that any gas crossover which may occur is less of an issue, since it would immediately auto ignite, and thus not accumulate in any large quantity [78].

3.1.2.2. Chemical hazards. Hydrogen is a non-toxic, odorless and colorless gas which burns with an invisible flame. It can cause asphyxiation in confined spaces but tends to readily dissipate due to its high diffusivity [79]. Hydrogens major chemical hazards relate to its flammability properties (refer to Section 2.1).

PEM or SOEC electrolyzer components don't pose the chemical hazards that potassium hydroxide does in an alkaline AWE system. Potassium hydroxide is corrosive and toxic to humans and the environment if loss of containment occurs. These caustic solutions can also degrade the diaphragm, further increasing the risk of gas permeation [77].

3.1.2.3. Propensity to leakage. The high temperatures used within SOECs place thermal stresses on equipment, reducing component life span and increasing the risk of cracking [77]. SOECs have presented issues around delamination of electrodes and improper sealing [80]. These issues pose safety concerns for SOECs as they increase the likelihood of material release and explosive mixture formation.

3.1.3. Safety challenges of pink hydrogen production

The primary safety concern for all electrolyzer systems is the risk of fire or explosion due to the formation of an explosive hydrogen-air mixture [40]. This risk is also present for all handling and storage of hydrogen on site. It must be ensured that an incident on the hydrogen side of the process cannot compromise the structural integrity of the nuclear side, leading to release of contained radioactive material. This combined hazard is the focus of this section. Hazards associated with chemical usage and disposal are well considered in existing documentation for water electrolysis systems. These will be the same regardless of the power source and so are not the focus here.

3.2. Consequences of hydrogen release

Fire and explosion hazards are a concern in all processes which handle hydrogen, and historic incidents have cause severe damage to equipment and loss of life. Existing resources such the Hydrogen Incidents and Accidents Database (HIAD), and the French Authority for Nuclear Safety's database should be utilized to inform risk assessments of pink hydrogen projects [81]. The vicinity of a nuclear power plant to explosive material leads to concerns around the damage that a

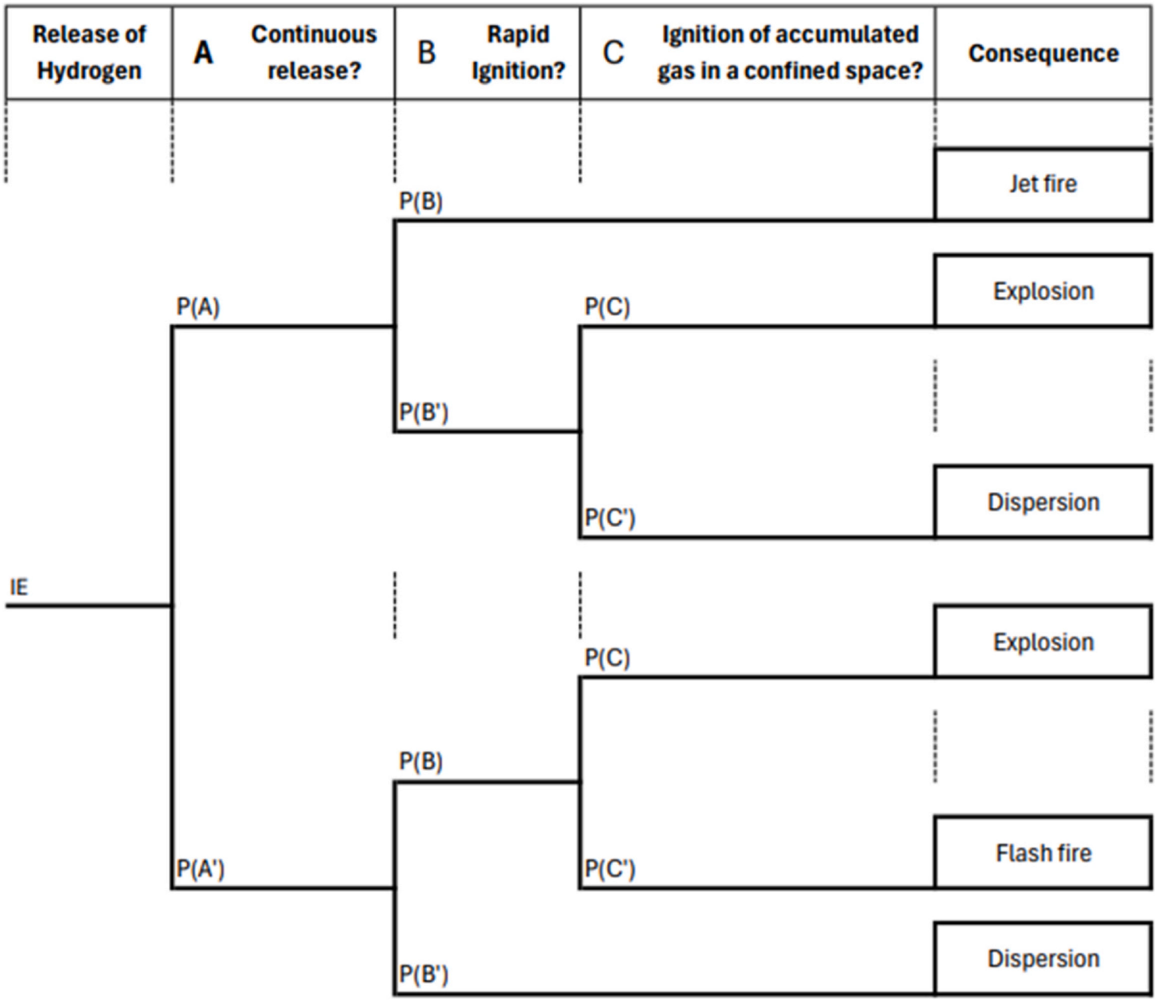

Fig. 5. Event tree showing consequences of hydrogen release under different scenarios [28], resulting from incident conditions A, B and C.

hydrogen fire or explosion could do to this infrastructure [82], possible consequences of a hydrogen release are described by the event tree in Fig. 5, with their effect of nuclear plant operation laid out in Section 3.1.1.

Fig. 5 lays out the consequences of hydrogen release, conditional on the probabilities of subsequent events (A, B and C) taking place. For condition A, where a release is not continuous (A'), it is assumed to be instantaneous (e.g, vessel rupture). For condition C, if hydrogen is released into a confined space, it accumulates. In this scenario, if ignition occurs it is assumed to be delayed, with a considerable quantity of accumulated gas. If the release takes place in an open space (C'), ignition is assumed to not create overpressure. If ignition does not occur, the diffusivity of hydrogen allows the gas to dissipate. The outcome of a hydrogen release is dependant on whether the release is continuous (leak), or instantaneous (vessel rupture), and on any delays in ignition:

- If the leak is continuous and ignition is rapid, the result is a jet fire. Hydrogen gas continues to be fed and fuels the flame which was likely ignited by its own kinetic energy.
- If hydrogen is not ignited following its release it will rapidly disperse into the atmosphere. If hydrogen was released into a confined space, this will take place over an extended period during which the accumulated gas may ignite (delayed ignition).
- If a large quantity of hydrogen gas rapidly ignites in an open space, the result is flash fire.
- If ignition of a large quantity of hydrogen gas takes place in a confined space, for example from the accumulation of gas from a leak over time, and the fire causes overpressure, the result is an explosion [28].

3.3. Mitigating hydrogen releases within electrolyzer systems

Hydrogen has a broad flammability range (4–74% in air) and a low minimum ignition energy (MIE) [79]. Once hydrogen gas accumulates it is challenging to prevent ignition since the source of ignition could be very small or difficult to identify [83]. Reducing the risk of an incident is 2-fold; leak prevention and prevention of hydrogen accumulation in the case of a leak. The latter is particularly important giving the susceptibility of hydrogen to leakage due to its small molecule size and tendency to embrittle materials [84]. Due to the low MIE of hydrogen, it is more straightforward to prevent development of an explosive atmosphere than it is to prevent the ignition of one which is already established. Statistical data has shown that the most prevalent hydrogen related incidents can be linked to failures in components such as valves, pipes and fittings, resulting in the release of material [28]. Components should be evaluated as to their leakage rate in the case of failure [85], this should be used as a tool to quantify the severity of the leak.

During leak detection and fault diagnosis, focus should be on components such as pipe valve filters that are prone to failure [28]. Event trees such as in Fig. 5 can be used to determine the probability of a major ignition event, with severity calculated using component leakage rates. Likelihood of component failure should be considered during system risk assessment, and safety by design techniques should be employed to select components with a lower likelihood of failure. Furthermore, the probability of an explosion can

Table 2
Systematic layers of protection for a hydrogen electrolyzer "hot box" to prevent hydrogen leakage and to reduce the likelihood of an ignition incident in the case of a leak

Purpose of safety measure	Leak causes and mitigation strategies
Leak prevention	• Leaks may be caused by over pressure leading to component failure. Implement pressure relief to avoid undue stress on components [86]. • Leaks may be caused by the embrittlement of materials. Use embrittlement resistant materials and ensure all components are regularly checked for signs of wear and replaced or repaired as necessary [87]. • Components may not be leak tight. Ensure components are selected with their functionality to hydrogen handling considered. Leak tightness must be guaranteed, and for hydrogen applications welded connections are preferred over mechanical joiners such as threaded fittings or flanges (this reduces the leak potential of the connection) [87].
Leak detection	• Hydrogen sensors for wide area monitoring. • Pressure sensors to detect gas losses on a system level. • High level hydrogen and low system pressure sensors should link to safety systems and trigger automatic shutdown of the hydrogen production system [86].
Prevention of accumulation of explosive atmosphere outside of the electrolyzer, in case of a leak (leak out).	• Ventilation system which switches to full speed if hydrogen is detected in an unexpected area. Hydrogen production should shutdown automatically in the case of a ventilation failure or detection of a hydrogen release [85,86].
Prevention of accumulation of explosive atmosphere within the electrolyzer (leak through).	• Hydrogen sensors in the oxygen gas stream to detect any gas permeation. • Membranes/diaphragms must be regularly inspected for damage/wear as this increases the potential for gas crossover [77].

be limited by preventing the accumulation of hydrogen gas in the case of a release, through gas monitoring and ventilation systems [86].

Mitigation strategies such as those laid out in Table 2 can be used to add layers of protection to a system, reducing the likelihood and severity of an incident through successive rounds of risk assessment. For these mitigation strategies to be successful in preventing incidents, it is vital that equipment is routinely checked and proactively maintained. Operators and regulators should move towards risk informed preventative maintenance as opposed to relying on emergency corrective measures. This improves safety while reducing unplanned downtime and improves the reliability of the system, reducing cost [85].

Leaks may be categorized as leak through or leak out. A leak out failure releases hydrogen into the atmosphere. A leak through failure involves the release of hydrogen into areas of the system where it is not anticipated – for example it may flow past a valve but remains within the piping. The risk of each leak is dependent on its location, but a leak out scenario is generally higher risk as there is a higher potential for ignition outside of the closed system [85].

SOEC electrolyzer units are typically located within a 'hot box'. This is a contained system which aids safety controls. The likelihood of leakage should be reduced to as low as reasonably achievable through safer design and well considered component choice [51]. Controls and ventilation systems should be designed so that in the case of a leakage event, flammable hydrogen gas is not able to accumulate in quantities which could cause a serious incident.

Uncertainties as to the rate and frequency of hydrogen leakage events from failed components creates a need for conservative design, increasing the size and cost of facilities. It also limits the understanding of the hazards such events pose on plant [85]. Expanding of the research in this area is important to make risk informed choices, supported by safety standards detailing the design and operation of such systems. Development of regulation and guidance specific to pink hydrogen applications would support the development of safe and efficient systems. There should be industry wide reporting of observations, near misses and incidents to provide valuable insights into potential hazards.

3.3.1. Key safety improvement recommendations

In summary, the key recommendations that can be made, considering the integrated safety systems detailed in Table 2 are as follows:

- Leak prevention is key to preventing hydrogen fire and explosion in electrolyzer systems. The risk of leakage should be considered at the design stage when selecting materials and fittings.
- Electrolyzer "hot boxes" should be fitted with an integrated system of sensors, ventilators and emergency gas shut off valves. These must be regularly checked and maintained.
- Hydrogen gas sensors and pressure sensors should be used in the area surrounding the electrolyzer and in the oxygen outlet to detect hydrogen leakage or crossover.
- Where a leak is detected, the ventilator should automatically switch to full, and hydrogen production should be stopped immediately to prevent accumulation of the fuel.

3.4. The safety case for existing large scale hydrogen projects

Nuclear plants are robust systems with very well-established safety protocols. There is a concern that the installation of an electrolysis plant alongside existing nuclear infrastructure could affect the integrity of the plants safety systems [69]. Existing pink hydrogen trials have approached this by positioning the electrolyzer units outside of the nuclear plant boundary to remove this risk, simultaneously removing the requirement for relicensing of the nuclear plant [51]. Trials follow guidance for changes to an existing plant, keeping within limits for hydrogen storage. These are small trials, designed primarily to provide hydrogen for use within nuclear power plants to cool generator and to deoxygenate the core [15]. (Fig. 6).

Existing pink hydrogen trials seek to supply this hydrogen requirement in house, with plans to scale up to supply the grid at a later stage if this is successful. Some sites are located near to major industries which require hydrogen such as oil refining to allow access to these markets if desired. Some projects aim to utilize hydrogen production as a storage mechanism to support energy balancing; when grid demand can be fulfilled by renewables and required nuclear output is less, this nuclear energy can be converted into hydrogen rather than ramping down the nuclear power plant or dispelling the excess energy. Hydrogen generation rather than nuclear plant curtailment could take place during low demand periods [15].

Projects listed in Table 3 show a variety of nuclear power plant and electrolyzer types. Within the USA there is a preference towards PEM electrolyzers, this is because the Department of Energy part funded these projects, and they placed emphasis on SOEC and PEM electrolyzers. A PEM electrolyzer was chosen as it is simpler to commission (no steam is requirement), and PEM electrolyzers are further along the development curve, meaning that they are more straightforward choice for higher MW applications [66,68].

The projects detailed in Table 2 all involve the retrofitting of a nuclear power plant with an electrolyzer for hydrogen generation. This

Fig. 6. Depiction of the location of large scale pink hydrogen pilots with existing BWR and PWR nuclear power plants given in Table 3. BWR = boiling water reactor; PWR = pressurized water reactor.

requires consideration of the changes permitted under the existing licence for the nuclear plant. A modification to an existing site is allowable provided an appropriate guideline is followed. For example, construction and operation on a 1.25 MW electrolyzer supplying a BWR at Nine Mile Point in the USA followed guideline 10 CFR 50.59 set out by the NRC to make this modification in accordance with these guidelines. This involved calculation of the blast radius of the electrolyzer [69]. Regulations in 10 CFR 50.59, "Changes, tests and experiments," sets out when licence holders can make changes to their facility without licence amendment [70].

At Nine Mile Point, Constellation Energy kept the electrolyzer small enough as not to affect the blast calculation, and to ensure that the quantity of hydrogen kept on site was within the existing licence limits [66]. This approach was taken by other trials due to the cost and time intensive nature of relicensing.

Installation of a hydrogen production facility co-located with a nuclear facility impacts the risk of fire and is therefore subject to site specific licence conditions to protect from this fire hazards. While specific regulations for co-located nuclear - hydrogen production facilities have not yet been realized, changes are governed by existing guidelines, and site-specific protection programmes. This includes changes to fire and explosion risk of a site, and the emergency operating procedures. Such guidance from the NRC can be found in RG 1.189, "Fire Protection for Nuclear Power Plants", and RG 1.205 "Risk-Informed, Performance-Based Fire Protection for Existing Light-Water Nuclear Power Plants" for fires. Ten CFR 50.54 "Conditions of licenses" (section q) and RG 1.219, "Guidance on Making Changes to Emergency Plans for Nuclear Power Reactors" consider emergency plans.

Changes to plant layout required by co-location of an electrolyzer, must be integrated into the plant safety basis. Different changes increase the probability or severity of an incident and this must be considered.

3.5. The future of electrolyzer and nuclear plant integration to support pink hydrogen production

To ensure compliance with licencing regulations for an existing nuclear plant, the electrolyzer must be located several hundred meters away or licensing is required (UK regulations) [51]. This distance places the electrolyzer outside the nuclear plant's protected zone, meaning any incident involving the electrolyzer will not impact the nuclear safety systems. While this distance doesn't pose issues if the electrolyzer is solely powered by electricity from the nuclear plant, it limits the potential for heat integration - this is a key advantage of SOEC's that supports their economic viability [69].

Several hundred meters separation between the source of process heat (the nuclear reactor), and the electrolyzer results in large heat losses. At this distance, the heat that could be transferred to an SOEC is only around 200 °C. PEM and AWE electrolyzers may utilize waste heat to preheat the feed, however the quantity of heat required is far less than for SOEC, due to the lower temperatures involved. Most if not all of the energy required for AWE and PEM electrolyzers is generally electrical. Heat losses are therefore less of a concern with these technologies and use of waste heat is subject to an economic viability assessment considering piping and integration costs. In contrast, the economic viability of SOEC electrolyzers relies heavily on their high-temperature efficiency and the availability and cost of heat [51]. Therefore, SOEC units must be closely integrated with the nuclear plant to minimize thermal losses.

Previous work by Vedros et al. (2023) suggests that the electrolyzer could be placed closer to the nuclear plant than previously demonstrated [69]. This work developed thermal hydraulic models for the heat extraction and delivery systems providing nuclear heat to preheat the electrolyzer feed. The determination of a steam bypass location and upper steam extraction rates provides a basis for risk calculations. To explore the possibility of positioning the electrolyzer closer to the nuclear plant, a thorough assessment is needed to evaluate the frequency and potential consequences of overpressure events for various nuclear plant targets and safety systems. Assessment of the vulnerability of each target requires use of standard hydrogen leakage rates for different components, along with severity calculations for maximum credible accident (MCA) scenarios considering the volume of hydrogen released. Scenarios include a hydrogen explosion from the electrolyzer or damage from external threats such as natural disasters. Vedros et al. calculated the overpressure curve if a blast was to occur at a distance of 1 km and determined that only the switchyard components have a significant probability of failure should the MCA occur. None of the safety critical nuclear Currently, regulation guides management of change and fire safety risk. The changes allowable under these regulations without relicensing are small. Should regulatory bodies and governments wish to support this technology at a scale which plant components were shown to be vulnerable to the overpressure produced by this hydrogen explosion [69]. The qualitative hazard assessment laid out in Section 3.1 should be complemented by a quantitative risk assessment to determine the minimum safe distance between electrolyzer and nuclear reactor.

Considerable expertise exists in the safe handling of hydrogen gas and the operation of electrolyzers. Nuclear power plants are engineered for robustness, designed to maintain safety even during extreme events such as a terrorist attack. Databases such as HIAD 2.0 provide a detailed collection of historical data on hydrogen incidents, vital for proactive assessment of the fire and explosion risk of electrolyzers and any compromising effect this could have on nuclear safety systems [18,81]. Such databases should be extended to encompass combined nuclear hydrogen systems. As pink hydrogen projects increase in commercial scope, any accidents, incidents and near misses should be recorded within a database to inform the development of regulations. The recording of near misses is a key element of risk identification, crucial for improving root cause analysis and prevention of future accidents.

Limiting the severity of a potential explosion should involve limiting the potential fuel which could feed an explosion and careful consideration of plant layout. In the case of co-location for waste heat utilization, the steam tap off and electrical system for the electrolyzer should be fitted with isolation valves which shut in the case of an incident, as the primary safety response. Such measures must be included within the nuclear plants emergency operating procedures [70]. In particular, the quantity of hydrogen stored on site should be minimized, with hydrogen moved rapidly away from the nuclear facility post-production. As the hydrogen economy continues to grow, further safety research and updated regulations on hydrogen production and usage at scale will be essential. Those that facilitate close integration of nuclear and water electrolysis systems will be effectual to enable investment in safe and efficient pink hydrogen operations [85]. The future success of hydrogen as an energy carrier in the energy transition depends on

Table 3
List of commercial pink hydrogen projects (not exhaustive) and their technologies, timescales and objectives [15]

Company	Location	Electrolyzer type	Nuclear plant type	Details and timeframe
Energy Harbour	Ohio, USA	PEM (2 MW)	Davis-Besse NPP, a 894 MW PWR	• A 2-year demonstration beginning in 2024. • Aims to explore the economic viability of pink hydrogen at the plant and to demonstrate the synergy of the technologies. • Electrolysis powered by electricity from NPP. • Site is located near to major hydrogen markets such as oil refineries, with a view to markets for future expansion.
Constellation Energy	New York, USA	PEM (1.25 MW)	Nine mile point a BWR (1890 MW)	• A successful project which currently supplies hydrogen for use within the nuclear plant. • Project began in 2020 and provided hydrogen to plant as of 2022.
Arizona Public Services	Arizona, USA	PEM (17 MW)	Palo Verde a PWR (3937 MW).	• This project is an example of how hydrogen could be used to balance power to the grid and prevent wastage during periods of fluctuating demand or supply with a portfolio of energy sources. • Project aimed to utilize surplus nuclear power to produce hydrogen. This would typically be in cases where the linked solar facility is able to provide the grid with a high-power output. • Hydrogen would be used to co fire natural gas turbines used to meet peak electricity loads. • The project secured 3 years worth of funding to commence in 2022 however the project was not carried through to production stage due to difficulties producing competitively priced hydrogen.
Bruce Power	Ontario, Canada	PEM (5 MW)	PHWR (6358 MW)	In exploration stage.
Rosatom	Murmansk, Russia	PEM (1 MW)	Kola nuclear plant a PWR (1644 MW)	Production planned to begin in 2025.
Xcel Energy	Minnesota, USA	SOEC (240 kW - 1 MW)	Prairie Island nuclear plant a PWR (1041 MW).	• An integrated system proposal with the electrolyzer using steam and heat and electricity from the PWR. • Project aims to generate hydrogen rather than curtailing the nuclear power plant during low priced hours. • Production expected to begin in 2024.
Vattenfall	Väröbacka, Sweden	Low temperature electrolysis (0.8 MW) – assumed to be an AWE due to age.	PWR (2202 MW)	• Uses electricity from plant, operational since 1997. • Produces $60-110$ m^3/h hydrogen which is used to cool nuclear generators.
OKG	Oskarshamn, Sweden	AWE (0.7 MW)	BWR (1450 MW)	• Uses electricity from plant, operational since 1992. • Produces 60-110 m^3/h hydrogen which is used to cool 3 nuclear generators. Since the projects inception, 2 generators have closed and this surplus hydrogen is sold.
EDF	Lancashire, UK	SOEC (1 MW)	Heysham 2 an advanced gas cooled reactor (1250 MW)	• Feasibility study complete with construction potentially beginning in 2024. However, Heysham 2 is due to begin decommissioning in 2028 [88]. • Proposal involves hydrogen being used to replace fossil fuels at partner asphalt and cement production plant [55].
EDF	Suffolk, UK	Low temperature electrolysis (2 MW)	Sizewell B PWR (1198 MW)	Proposal stage.
EDF	Suffolk, UK	SOEC	Sizewell C (3200 MW)	Proposal for a SOEC utilizing heat from the nuclear plant.

AWE = alkaline water electrolyzer; BWR = boiling water reactor; PEM = proton exchange membrane; PWR = pressurized water reactor; SOEC = solid oxide electrolysis cell; OKG = Oskarshamns Kraftgrupp; EDF = Électricité de France; NPP = Nuclear Power Plant; PHWR = Pressurized Heavy Water Reactor.

positive public perception and government backing. A process safety incident at a pink hydrogen plant could halt or curtail any future projects.

Low temperature electrolysis using electricity only from the nuclear power plant is straightforward as it doesn't require close integration. Close integration and co-location is required when the heat is needed for high temperature electrolysis, but this significantly increases the risk posed to critical nuclear safety systems. Utilization of waste heat is important when seeking to reduce costs of low-carbon hydrogen production.

Currently, regulation guides management of change and fire safety risk for nuclear power plants. The changes allowable under these regulations without relicensing are small. Should regulatory bodies and governments wish to support this technology at a scale which can make a meaningful contribution to the energy mix, it is recommended that they should streamline the process for co-locating an electrolyzer to allow heat integration. This currently requires re-licencing which is cost prohibitive to companies. However, the process of relicensing is important to ensure that changes made are safe. Researchers should seek to provide a quantitative analysis of the fire and explosion risk at such facilities, carefully considering effect of steam tap off position, electrolyzer size and location on safety. At present, insufficient data is available to calculate the size of this risk and solving this challenge is key to the development of regulation and enabling utilization of waste heat from nuclear power plants for electrolysis.

This paper explores the process safety approach for commercial water electrolysis and nuclear projects alongside new pink hydrogen demonstrations and provides recommendations for industry, regulators, and researchers to enable large-scale nuclear powered hydrogen production. This work examines the safety cases for existing pink hydrogen pilot projects and identifies areas for development to ensure cost-competitive, low-carbon hydrogen production. Additional sources were used to support this assessment of the safe integration and operation of nuclear and hydrogen technologies [89–102].

4. Conclusion

Safety is the top priority for pink hydrogen projects, and ensuring the protection of people and the environment is both a legal and moral responsibility. Increased risk of fire and explosion due to production, handling and storage of hydrogen in the vicinity of critical nuclear safety systems is identified as a significant challenge for safe pink hydrogen production. This work undertakes a thorough assessment of the literature detailing hazards associated with retrofitting an electrolyzer alongside an existing nuclear plant, using an event tree to study the consequences of hydrogen release and ignition under different scenarios. This work identifies existing pink hydrogen demonstrations and uses them to evidence a safety case. Having identified key hazards, the paper recommends mitigation strategies, focusing on safety by design to prevent leaks, implement effective leak detection, and avoid the accumulation of flammable hydrogen gas, thereby reducing the potential severity of incidents [86]. This enables design recommendations to be made which support the utilization of waste heat and energy to produce low carbon hydrogen.

Key recommendations include those relating to spatial configuration; the economic benefits of heat integration are undermined by heat losses during transportation between the nuclear plant and electrolyzer. Ensuring safety and close integration of the 2 systems is crucial to the success of pink hydrogen technology, particularly for high temperature electrolysis using solid oxide cells (SOECs) [15,51,69]. A key recommendation for regulators is to support and streamline the process for modifying nuclear power plants to enable pink hydrogen production. Doing so will require consideration of the electrolyzer blast radius and the vulnerability of specific nuclear targets. Hydrogen and nuclear incident databases should be used to inform risk strategies and expanded to encompass hazards specific to pink hydrogen [18,81]. The high cost of relicensing presents a barrier for many projects, preventing the adoption of efficient heat integration methods. Pink hydrogen processes must be highly efficient and leverage waste heat to remain competitive with cheaper, polluting grey hydrogen.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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