Hazards from Emerging Technologies in the Energy Transition

Background

The IChemE Safety Centre (ISC) undertook a member survey to understand the hazards associated with emerging technologies and reviewed whether we have the right tools to manage them. The survey found that the current methods used in risk assessments are valid though continued application is needed. The survey highlights that existing risk assessment methods are effective for identifying and mitigating hazards associated with emerging technologies and that organisations should continue to utilise these methods to ensure safe and responsible development and implementation of emerging technology hazards.

Many renewable energy systems can be safer than traditional fossil fuel technologies and the benefits of renewable energy systems far outweigh the potential hazards. However, proper training and safety measures are still necessary to prevent accidents and injuries from occurring. As the technologies advance and come to fruition it is imperative to reassess the current risk assessment tools being used while ensuring the provision of comprehensive training for workers and engineers involved in renewable projects

Introduction

Climate change is occurring at an increased rate due to the use of fossil fuels such as coal, oil and gas. The United Nations (2023) regard fossil fuels as the leading contributors to climate change with 75% of greenhouse gases and approximately 90% of carbon monoxide coming from this source of energy

As the world and organisations transition towards renewable technologies and energy sources we need to consider if we are transitioning in a safe, reliable, and sustainable way. As markets have emerged to meet the goal of trying to half emissions by 2030, we have seen some leading renewables come to fruition such as;

- Hydrogen – Green and Blue
- Nuclear
- Solar Power
- Wind Power
- Biofuels
- Electrification – Battery Storage

Some of the emerging threats to this transition are;

- Hydrogen – Highly flammable gas

- Nuclear – Radiation containment and waste treatment
- Solar Power – Fire risk
- Wind Power – Injuries from confined space entry and working from height
- Electrification – Battery degradation resulting in thermal runaway

During the third ISC Advisory Board meeting on 17 August 2021 the operating partners requested a research project into emerging hazards in the next 5 – 10 years associated with emerging technologies and the energy transition underway. Our operating partners felt they would like to see a range of topics including hydrogen technology, energy transition, battery safety and cyber security with an insight into what other organisations are doing (*minute no: 8-08/2021*).

During the initial research phase of the project, we consistently see four technologies come to the forefront by 2030 to assist in achieving net zero by 2050 *(figure 1)* with two complimentary utilities to those four technologies. This report focuses on these technologies.

Source	Hazards
Solar	The main hazard surrounding solar on a global scale is failure of the DC isolator switch which can then result in significant fire damage to buildings or surrounding areas, depending on the mounted location. Additional hazards include occupational challenges in manual handling and working at height.
Wind	Access and egress to wind turbines for maintenance is a major concern in the offshore floating wind farms. Currently the Nacelle area of the turbine contains the largest number of hazards and poses the highest risk to personnel. Falls from height, electrical hazards, crushing injuries, confined spaces, rotating hazards. Although these are more occupational hazards these can impact the reputation of future development.
Hydrogen	Highly volatile and many areas to cover from green/blue/grey to hydrogen storage offshore/infrastructure etc. Hydrogen is known to be extremely volatile gas. The molecular weight for hydrogen is very light being at 2 on the periodic table, natural gas is 16 which would mean hydrogen is a smaller molecule thus the potential for leakage is enhanced. The flammability limit of hydrogen is 4%/75% vs natural gas at 7% and 20%. The flame speed of hydrogen is ~200 – 300 cm/sec vs natural gas of ~30 – 40cm/sec. Adiabatic flame temperature – the temperature of the flame in combustion process emits is circa 223.89°C higher for hydrogen than natural gas. As hydrogen is lighter than natural gas you need approximately 3 times the volume to achieve the same amount of energy, this poses additional hazards of storing larger volumes of hydrogen at increased pressure and/or operating at increase flow rates over natural gas. Hydrogen will combust with both higher and lower concentrations of air present, has a quicker flame speed and will burn hotter than natural gas making it a more challenging molecule to control.

Nuclear	It has seen significant gains in the political and business drive towards renewable energy, still suffering from reputational damage. However, we have potential to utilise previous incidents in 'lessons learned' to make nuclear safer. Radioactive waste can create challenges for economies going forward to ensure they have adequate resources for safe disposal and storage.
Battery Storage	The main hazards are surrounding Lithium-Ion and thermal runaway. Once the chemical reaction initiates it can have catastrophic consequences, this issue is yet to be solved from a safety mitigation perspective.
Carbon Capture Usage and Storage	CO_2 storage at high pressure in tanks. Retrofitting to operational industrial plants or facilities can result in fire and explosion risk to existing assets being enhanced. Leaks – CO_2 has the potential to cause cracks in steel pipes, tanks, and vessels when they reach low temperatures. Should CO_2 come into contact with water it forms carbo0nic acid which can cause corrosion.

Solar and Wind

The International Energy Agency (IEA) World Energy Outlook 2022 report suggests that within ten years the world will be deploying around 210 gigawatts (GW) of wind capacity and 370 GW of solar if countries are taking the necessary action to deliver on their climate pledges. It is believed that in countries such as United States and India, solar is the dominate renewable technology and the European Union is moving towards electrification dominated by onshore and offshore wind.

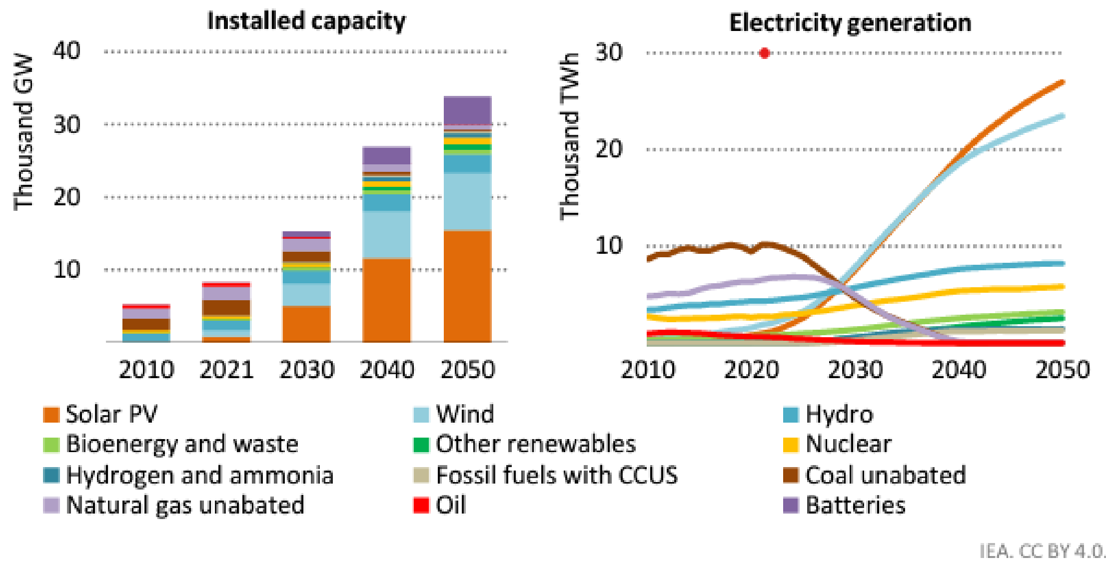
Hydrogen

Undeniably one of the most widely discussed renewable energies of the future through its unprecedented political and business momentum. Topics on hydrogen are often discussed from its vulnerability through to how effective it can be in cutting emissions, although this is not as mature a source as others and there are a lot of unanswered questions in the safety of this highly discussed fuel.

Nuclear

It is also reported that nuclear power is seeing an uptrend in investment as a renewable energy through the construction of nuclear power plants in France through to Japan. Currently, China has the largest nuclear programme to be carbon neutral by 2060 with Japan also seeking to restart historical nuclear plants. The United States are currently looking into policy changes to extend the lifetime of their current ageing nuclear power plants.

Figure 3.10 ▷ Total installed capacity and electricity generation by source in the NZE Scenario, 2010-2050



Total electricity generation nearly triples to 2050, with a rapid shift away from unabated coal and natural gas to low-emissions sources, led by solar PV and wind

Figure 1 International Energy Agency (2022) highlights in Figure 1 the total installed capacity and electricity generation by source in the net zero emission (NZE) scenario by 2050.

The research did not find any abnormalities in assessing risks associated with any renewable fuels or the tools used to assess those risks. The project re-emphasised the importance of using the risk assessment techniques in a structured process to better identify and assess the hazards associated with the renewable energies along with a lesson learned approach from historical events. However, importance should be placed on reassessing hazards as the renewable energy industries upscale from 2030 and beyond. Ensuring we include individuals from all levels within the organisation during risk assessment reviews may assist in reducing the risks associated with emerging renewable energies.

Hydrogen

Electrolysis uses electricity to produce hydrogen which is a process that splits hydrogen from water using an electric current. Electrolysis does not produce any by-products or emissions other than hydrogen and oxygen. The electricity for electrolysis can come from renewable sources such as wind and solar, nuclear energy or fossil fuels. If the electricity for electrolysis is produced from fossil fuels or biomass combustion, then the related emissions are indirectly associated with that hydrogen. We often see green hydrogen where renewable sources are used to generate the electricity to be used in the electrolysis process of producing hydrogen as the most sustainable option.

Hydrogen Tools (2023) outline the characteristics of utilising hydrogen as a fuel as;

- Colourless, odourless, and non-toxic
- Propensity to leak – can diffuse through many materials considered airtight or impermeable to other gases
- Buoyant – hydrogen is the lightest gas and will rise quickly under atmospheric conditions accumulating at the ceiling in indoor environments.
- Flammable – the flammability range is between 4% and 75% in air.
- Burns with an invisible flame and gives off little radiant heat
- Can cause hydrogen embrittlement in metals leading to component failure. Hydrogen is known to accelerate the corrosion process.
- It is a very small molecule with low viscosity prone to leakage.
- Liquid hydrogen has to be stored at -253°C which causes other concerns with infrastructure to become brittle of friable. High Temperature Hydrogen Attack (HTHA) - a phenomenon or reaction that occurs within process equipment exposed to high temperature in hydrogen-rich conditions such as oil refineries, chemical manufacturing facilities and steam boilers. HTHA should result in the use of hydrogen taking into consideration their process and equipment that may not be rated for HTHA situations.

There are a significant number of incidents involving hydrogen that we can learn from. A selection of incidents is described below;

- 1937 : Zeppelin Hindenburg - during the approach for landing a fire detonated one of the rear hydrogen cells, rupturing adjacent cells and causing the airship to fall to the ground
- 2011: Fukushima, Japan – a reaction occurred between the fuel rods and water vapour producing hydrogen during the Fukushima nuclear disaster. Hydrogen explosions occurred in Units 1, 3 and 4
- 2019: Uno-X fuelling station, Sandvika near Oslo, Norway - an incorrectly installed plug was found to be the source of the hydrogen leak which then exploded at the hydrogen fuelling station. This resulted in another 10 stations being closed until the investigation was completed

- 2020: OneH2 Hydrogen Fuel Plant, Long View North Carolina - an explosion so fierce it was felt in neighbouring towns approximately 10 miles away. The blast punched a hole in the wall of the plant and shattered the windows of 60 nearby homes
- 2023: Delaware County, Ohio - a truck transporting hydrogen fuel in a rear trailer collided with a car causing the trailer to burst into flames.

Hydrogen Tools A (2023) continue to provide more detailed descriptions of the hazards associated with hydrogen which are shown in *figures 2, 3 and 4* below. Hazards such as hydrogen are 57 times lighter than gasoline vapour and 14 times lighter than air. Hydrogen is debatably more suited to an outside environment as should a loss of containment occur it will typically rise and disperse rapidly. Figure X highlights the relative vapour density of hydrogen in comparison to natural gas, propane, and gasoline vapour relative to air.

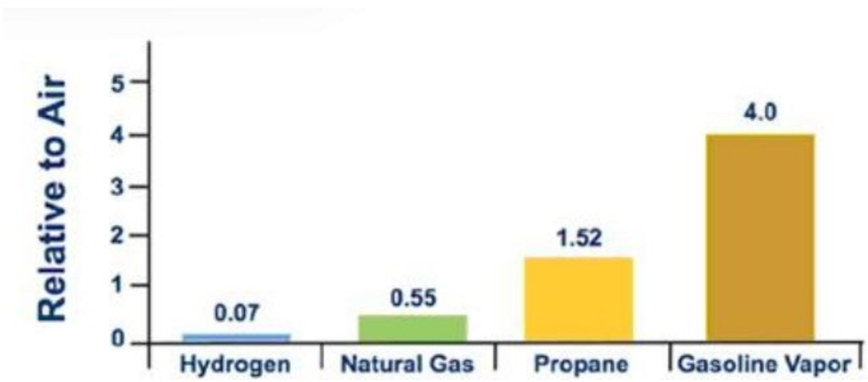


Figure 2 Hydrogen Tools A (2023)

The hydrogen flammability range is between 4% and 75% in air which is rather wide compared with other fuels. For example, Koestner P.E, J (2021) advises that natural gas flammability range is 7% and 20%.

Under the optimal combustion condition of 29% hydrogen-to-ai volume ratio the energy required to initiate hydrogen combustion is much lower than that required for other common fuels. *Figure 3* shows the combustion ratio with *figure 4* (second one below) highlighting the minimum ignition energy required for hydrogen in comparison to other fuels.

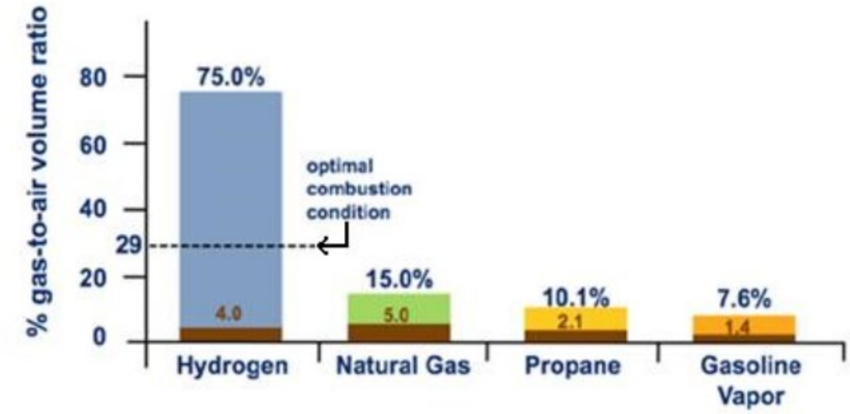


Figure 3 Hydrogen Tools A (2023)

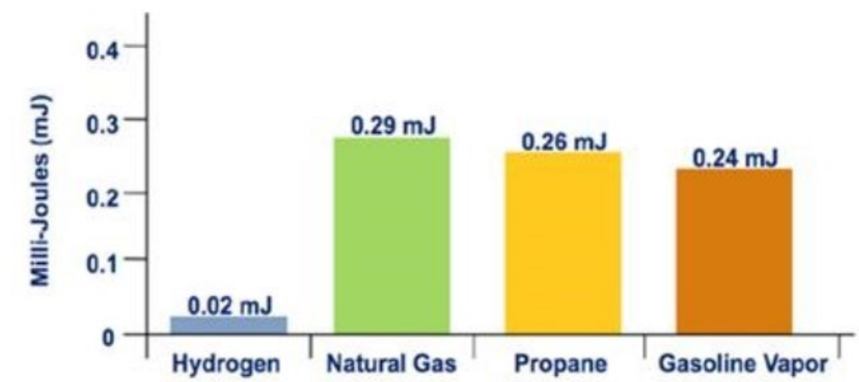


Figure 4 Hydrogen Tools A (2023)

The three main colours of hydrogen generation are grey, blue and green. However, it is critical to provide the additional colours of hydrogen generation should they increase in popularity within the coming years such as pink which is nuclear generated. *Figure 5* provides a breakdown of the eight colours of hydrogen, the technology required to make it, the feedstock and a guide with regards to the potential greenhouse gas footprint.

The research project by the IChemE Safety Centre found no deficiencies or missing tools for assessing the risks for hydrogen generation. However, as technologies and demand for increased hydrogen production change in the future, this should be reassessed to see if alternative methods have been used and if modelling techniques and tools are sufficient. The research survey did not identify any anomalies with current practices within the IChemE Safety Centre membership which would identify current practices for current hazards are sufficient if applied correctly.

<table>
<tr><th></th><th>Terminology</th><th>Technology</th><th>Feedstock/ Electricity source</th><th>GHG footprint*</th></tr>
<tr><td rowspan="3">PRODUCTION VIA ELECTRICITY</td><td>Green Hydrogen</td><td rowspan="3">Electrolysis</td><td>Wind | Solar | Hydro Geothermal | Tidal</td><td rowspan="2">Minimal</td></tr>
<tr><td>Purple/Pink Hydrogen</td><td>Nuclear</td></tr>
<tr><td>Yellow Hydrogen</td><td>Mixed-origin grid energy</td><td>Medium</td></tr>
<tr><td rowspan="5">PRODUCTION VIA FOSSIL FUELS</td><td>Blue Hydrogen</td><td>Natural gas reforming + CCUS Gasification + CCUS</td><td>Natural gas | coal</td><td>Low</td></tr>
<tr><td>Turquoise Hydrogen</td><td>Pyrolysis</td><td rowspan="2">Natural gas</td><td>Solid carbon (by-product)</td></tr>
<tr><td>Grey Hydrogen</td><td>Natural gas reforming</td><td>Medium</td></tr>
<tr><td>Brown Hydrogen</td><td rowspan="2">Gasification</td><td>Brown coal (lignite)</td><td rowspan="2">High</td></tr>
<tr><td>Black Hydrogen</td><td>Black coal</td></tr>
</table>

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

Figure 5 https://globalenergyinfrastructure.com/articles/2021/03-march/hydrogen-data-telling-a-story/

An example of developing hydrogen markets would be the introduction of a new colour such as Gold Hydrogen. Gold Hydrogen (2022) highlights that gold hydrogen is naturally occurring and accumulates naturally under the ground, generated by geological processes. It can be produced using proven engineering practices with minimal environmental impacts, having a small footprint in comparison to other exploration activities. Gold hydrogen does not require fracking, or hydraulic stimulation to be produced while offering significant cost and emission advantage relative to other sources of hydrogen production due to is natural accumulation.

IEA (2021) highlight that Korea is regarded as being among the most active countries in adopting hydrogen technologies. In 2019 the government launched its Hydrogen Economy Roadmap, which outlines a vision for the role of hydrogen in the energy sector. The roadmap highlights two priorities, creation of a hydrogen market and the development of hydrogen utilising industries to create the world's largest market for fuel cells for transport and electricity generation.

Nuclear

The International Atomic Energy Agency (2021) refers to Nuclear Energy as a form of energy released from the nucleus, the core of atoms made up of protons and neutrons. The source of energy can be produced in two ways, fission – when nuclei of atoms split into several parts or fusion – when nuclei fuse together. The nuclear energy we know that is in use around the world to produce electricity is known as fission. Nuclear power is a low-carbon source of energy with nuclear reactors generating close to one-third of the world's carbon free electricity. Unlike fossil fuel power plants, nuclear power plants practically do not produce C02 during their operation and are critical in meeting climate change goals.

The International Atomic Energy Agency (2021) advises that the next generation of nuclear power plants, known as innovative advanced reactors, will generate much less nuclear waste than the reactors in use today. These are expected to be under construction by 2030.

The office of Nuclear Energy (2021) advises that nuclear fission occurs when a neutron slams into a larger atom (such as uranium-235 and plutonium as they are easy to initiate and control), forcing it to excite and split into two smaller atoms, also known as fission products. Additional neutrons are also released that can initiate a chain reaction. As each atom splits a large amount of energy is released in the form of heat and radiation. *Figure 6* provides the cycle of the neutron and proton.

Figure 7 shows a diagram of a typical nuclear reactor plant which is designed to contain and control the chain reactions previously discussed. The heat generated from the fission process warms the reactor's cooling agent which is typically water resulting in steam forming. The steam is then channelled to spin turbines which in turn generates low-carbon electricity.

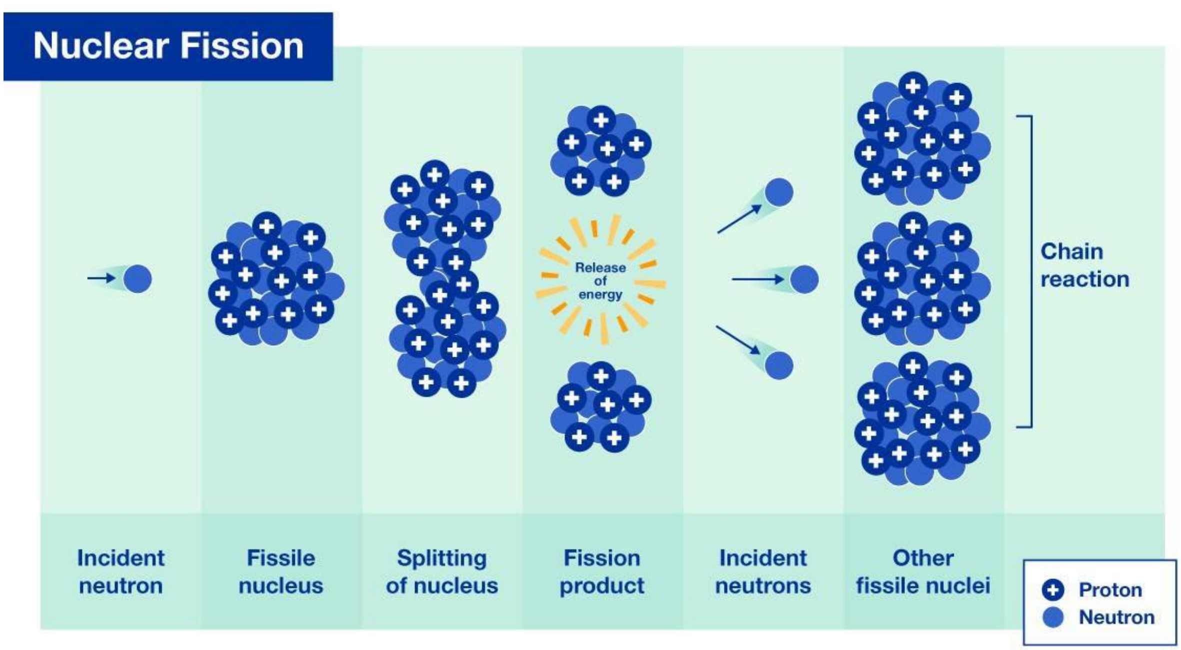


Figure 6 International Atomic Energy Agency (2021)

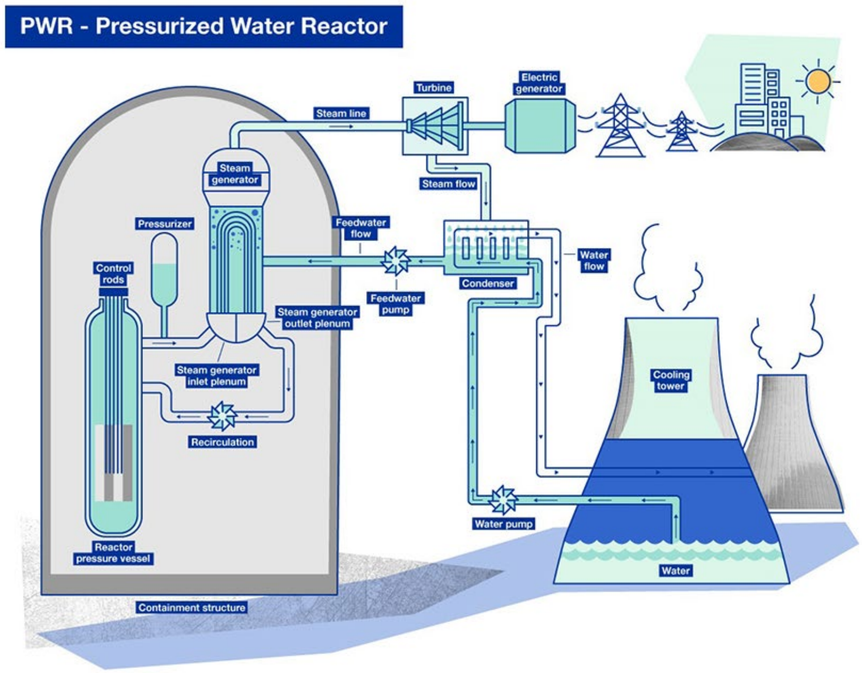


Figure 7 International Atomic Energy Agency (2021)

EDF (2023) advised that the nuclear industry has one of the best health and safety track records of any industry and provides some comparisons in Table 1 of fatality probabilities.

Table 1

Examples of Fatality Probabilities

Source	Probability per annum[1]
Risk of death from five hours of rock climbing every weekend	1 in 100
Risk of death due to work in high-risk groups within relatively risky industries, such as mining	1 in 1000
General risk of death in a traffic accident	1 in 10,000
Risk of death in an accident in the very safest parts of industry (such as service industries)	1 in 100,000
General risk of death in a fire or explosion from gas at home	1 in 1 million
Risk of death by being struck by lightning	1 in 10 million
Risk of wide-spread radiation release from nuclear power plant failure (but may not result in fatality)	Less than 1 in 10 million

[1]Probability per annum is the chance of a particular event occurring within the space of one year. This could also be equated to the number of years required to for an event to occur. For example, a probability of 1 in 1 million per annum would also equal an event occurring once in the space of 1 million years.

Source: Tolerability of Risk from Nuclear Power Plants and Office for Nuclear Regulation (ONR)

EDF further explains that for every potential hazard, the types and amount of protection required are chosen according to the hazard type and its potential impact. The greater the hazard the more protection will be applied and included in the design. An example given is if a hazard can affect the health of the public a wide variety of protection is specified to prevent this occurring. This is compared to if a hazard would only have a financial impact, then very few layers of protection are used.

Managing the nuclear product and waste generated are some of the key hazards involved within the nuclear industry along with other more conventional hazards such as;

- Toxic substances such as Hydrazine or Ammonia – corrosion inhibitors and pH control for high quality, demineralised water supplies used in power generation processes.
- Corrosive substances such as Sulphuric Acid or Sodium Hydroxide – used to enable water demineralisation.
- Asphyxiant gases such as Carbon Dioxide or Nitrogen – used for gas-cooled reactor operation and for fire suppression.
- Explosive gases such as hydrogen – used in alternators connected to the turbine to improve efficiency.
- Flammable and carcinogenic oils, fuels, and lubricants – used for lubrication and for backup diesel generator operation.

A list of accidents that involved nuclear energy are;

1957: Wind Scale Fire, UK – the worst nuclear accident in the UK's history started with a routine annealing process that was carried out to regulate levels of Wigner energy stored in graphite moderators. Temperature control issues during the release of Wigner energy saw the uranium temperature increase to circa 400°C marking the highest temperature the reactor ever reached resulting in a fire and hazardous release.

1979: Three Mile Island, USA - the reactor was severely damaged due to a loss of coolant. This was the most serious accident in US commercial nuclear power plant operating history. A coolant pressure relief valve became stuck open after trying to relieve pressure due to the pressure build up in the system from the initial coolant water feed pumps failing.

1986: Chernobyl, Ukraine - asteam explosion and fire caused the destruction of the reactor initially killing 2 people plus a further 28 from radiation poisoning within three months. This event continues to have a significant environmental impact and reputational damage.

2011: Fukushima Daiichi, Japan - a loss of cooling due to a huge tsunami caused irreparable damage to four reactors. The backup generators which would have been used to pump cooling water through the reactor on plant shutdown were destroyed during the tsunami. As a result of no cooling, three cores melted over three days and there were several hydrogen explosions along with the release of nuclear material into the environment.

Solar

The Solar Energy Industries Association (2023) (SEIA) advises that solar power is energy from the sun that is converted into thermal or electrical energy. Solar energy is the cleanest and most abundant renewable energy source available with certain countries around the world being richest in solar resources. Solar technologies can harness the energy from the sun and utilise it by means of generating electricity, providing light and heating water for domestic, commercial, or industrial use.

The SEIA continue to highlight the three main ways to harness solar energy;

- Photovoltaics – Generates electricity directly from sunlight via an electronic process and is used to power the user's requirements
- Solar Heating & Cooling – Uses the heat generated by the sun to provide space or water heating
- Concentrating Solar Power – Used to run traditional electricity-generating turbines

Solar energy is a rather flexible technology as it can be built as distributed generation which is near the point of use, such as street signs or battery storage facilities. Additionally, it can be as a central station such as a solar power plant.

The Building Research Establishment (BRE) completed a project running from July 2015 to 2018 that was owned and funded by the Department for Business, Energy, and Industrial Strategy (BEIS) into fire risk associated with solar panels. The project highlighted that 36% of the fire incidents associated with solar panels in the UK occur from inadequate installation. In total the project investigates 58 incidents of the timeline with Table 2 highlighting the breakdown on what was caused by PV;

Table 2

Severity of fires	PV involvement			
	Caused by PV	Involving PV but not caused by	Cause unknown	*Total*
Serious fires	17	10	1	*28*
Localised fires	16	0	5	*21*
Thermal events	9	0	0	*9*
Total	*42*	*10*	*6*	***58***

Table 2: Summary of severity of fire and PV involvement to January 2017

Fires are classed as *Serious* if they were difficult to extinguish and spread beyond the area of origin.

Building Research Establishment Ltd (2017)

The organisation Amazon, who have a significant volume of warehouse space which had their roof space utilised for solar panel installation has had a significant change in direction due to unresolved hazards with DC isolators. Palmer and Kolodny (2022) reports that Amazon have removed solar panels from the roof of their warehouses due to fires and/or electrical explosions occurring between April 2020 and June 2021. The panels had been taken offline until Amazon could confirm they were designed, installed, and maintained properly before re-energizing. Amazon spokesperson Erika Howard informed CNBC that;

"Out of an abundance of caution, following a small number of isolated incidents with onsite solar systems owned and operated by third parties, Amazon proactively powered off our onsite solar installations in North America, and took immediate steps to re-inspect each installation by a leading solar technical expert firm," the statement said.

This has potentially impacted Amazon's drive to operate on renewable energy by 2025. However, more than that we see a link from the UK and US on potentially incorrectly installed solar panels resulting in fire and explosion which can potentially impact the inventory of an organisation.

BRE (2017 – Investigations and evidence) have conducted site investigations in the UK and have advised that occurrences of PV fires start in early spring as we start to have more sun exposure and reduce in occurrences towards late autumn. This highlights that potentially an organisation should be setting up a suitable and efficient inspection and maintenance programme pre-early spring.

The project by BRE highlights that from 2010 – 2017 there were approximately 1 million solar PV installations with only 60 recorded incidents. It is assumed this figure is potentially higher as some incidents are unlikely to be reported due to suppressing fires before they have escalated to the point where fire services are required. With this information we can come to the conclusion that solar is a relatively safe way of generating renewable energy. However, depending on the location of the solar panels the severity is high, somewhat in line with process safety events.

Table 3 shows the main contributors to fires occurring;

PV Components	Probable	Possible further	*Total*
DC isolators	16	2	*18*
DC connectors	4	6	*10*
DC cables	1	3	*4*
Inverters	6	1	*7*
PV modules	1	2	*2*
Unidentified components	4		*4*
Total	*32*	*14*	***46***

Frequency with which PV components were recorded as the likely cause of fire

Building Research Establishment Ltd (2017)

Although table 3 above provides information on the component more likely to fail thus leading to an emergency situation, table 4 below highlights the root causes of the failures of components.

These learnings can be distilled into three main causes for the fires;

- System Design Error
- Faulty Product (Design or Quality Issue)
- Poor Installation Practice

Table 4

Root cause	Probable	Possible further	*Total*
System design fault	1	1	*2*
Faulty product	4	1	*5*
Poor installation	13	2	*15*
Unknown	27	-	*27*
N/A (fire not caused by PV)	9	-	*9*

These figures should be treated with caution until there is more data available to increase the granularity and confidence.

Building Research Establishment Ltd (2017)

Anomalies have been highlighted in Britain that the British regulations for wiring BS7671 only provide basic information for the wiring of PV systems and does not contain as much detail as the guidance document written for installing PV systems. The Microgeneration Certification Scheme (MCS) has produced more detailed guidance on installing PV systems, MCS 3002 is the installation standard which then refers you to MCS 012 – installation guide.

The theme of poor installation continues from the United States to the United Kingdom and onto Australia as O'Leary and Whaley inform us that 1 in 4 domestic properties have solar panels installed. In 2018 the Energy Minister Angus Taylor warned that lives are at risk from substandard installation practices as the regulator had inspected only 1.2% of installations and found there are potentially tens of thousands of systems poorly installed. In Australia, the data highlights that approximately 1 in 30 (3.1%) of the solar panels installed are deemed unsafe with a breakdown provided in *figure 8* and 17.9% are substandard. The main contributor is DC isolator switches, the same concern as the US and UK.

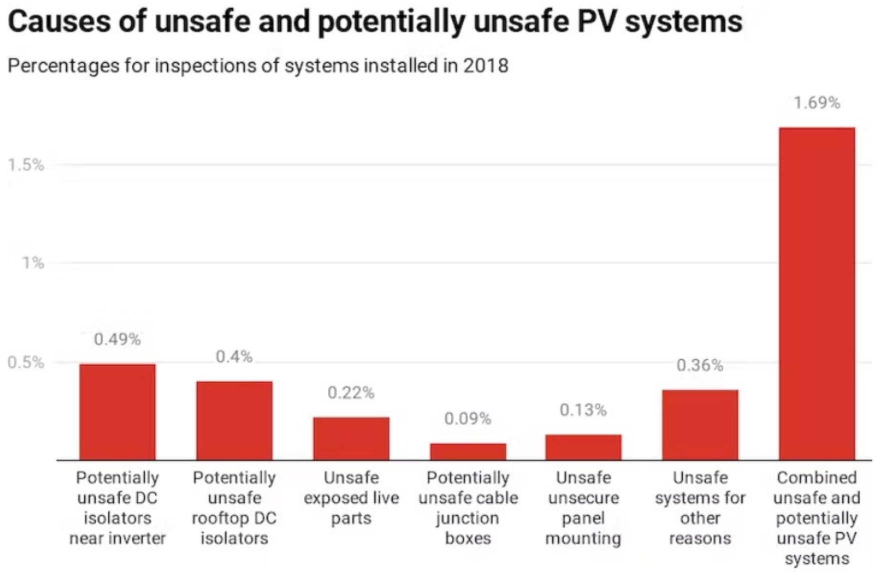


Figure 8 O'Leary & Whaley (2021)

Here we can see documentation for installation and maintenance could potentially be streamlined and we could take learnings from other industries. Approved code of practice documents by the Health and Safety Executive (HSE) provide more detail to legislation that is written. Such documents may be able to assist in supporting current British Standards or alternative international standards. Within your organisation it would be recommended to review local wiring and PV installation standards to ensure robust procedures can be created and put in place. Ensuring an effective management of change document captures the addition of PV systems to your buildings or sites may help capture they need for effective installation and maintenance plans.

Additional points to consider with regards to solar is when they are being installed on buildings it is imperative to ensure a structural report is completed so that an organisation can verify the building can support the additional weight of the solar panels. The insurance sector is continuing to monitor the development of solar panel use on the roof of buildings and the contents of said building should there be potential the solar system, building and inventory can become compromised due to an incident escalating.

Wind

Iberdrola (2023) informs us that wind is generated due to the pressure difference created from the temperature of the air. As solar radiation does not affect the earth's surface equally certain areas have warm air which weighs less and tends to rise creating low pressure areas while in colder areas the air descends and weighs more, creating high pressure areas. The difference in pressure causes the air to move and create wind, which can be so powerful it can be used to generate energy.

Wind energy is obtained from the force of the wind by a wind turbine. The energy is extracted with the rotor, which transforms the kinetic energy into mechanical energy. The generator transforms mechanical energy into electrical energy.

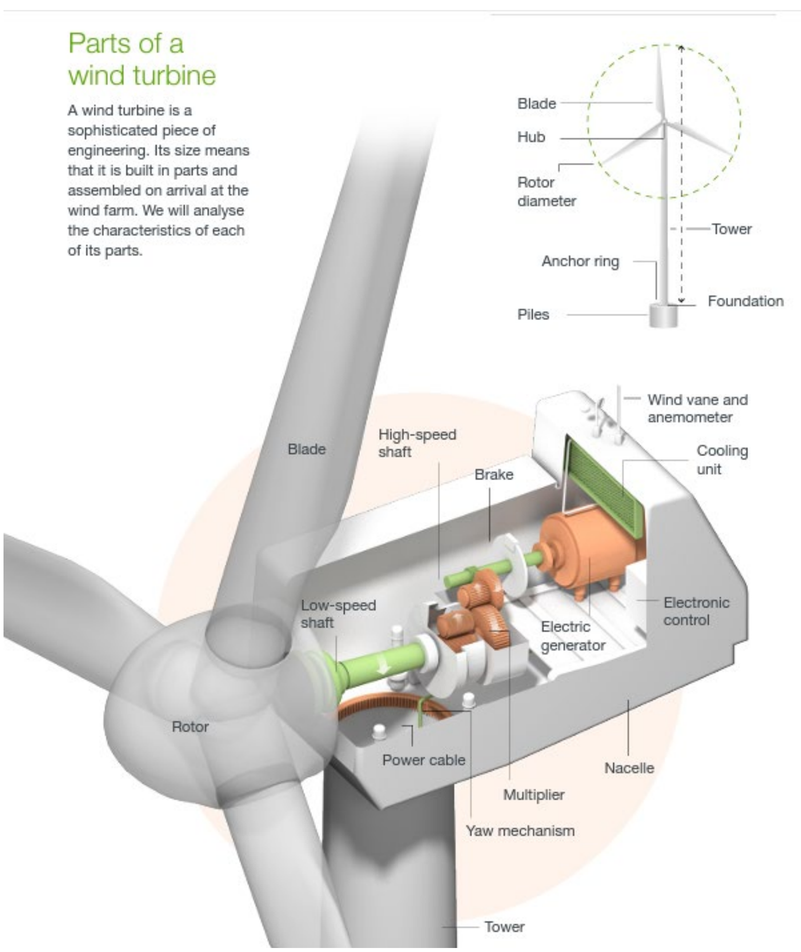


Figure 9 shows parts of a wind turbine Iberdrola (2023) What is wind energy, how is it converted into electricity and what are its advantages?

Wind turbines are erected in onshore wind farms or offshore either as floating units or fixed (secured to the seabed). The technology is constantly evolving and at the time of writing we are seeing a change coming through in the ability and construction of offshore winds farms where they will not only generate energy from wind but convert this energy directly into hydrogen offshore. This section will continue to provide information on the conventional route of renewable energy generation via wind.

G+ Global Offshore Wind Health & Safety Organisation (2021) (G+) provides some key facts and figures which state there were 780 reported incidents and injuries. 98 incidents during lifting operations, 74 during manual handling and 55 during access/egress.

Some of the hazards associated with the development of an offshore windfarm are;

- Falls from height
- Mechanical hazards such as contact with moving parts
- Blade Failures
- Ice throws
- Ship Collision
- Personnel Overboard which may occur during marine operation and/or transportation
- Electrical Hazards
- Fire or Explosion of turbine or vessel

One of the main risk factors to consider for organisations regarding wind power generation is the transition period for maintenance. Currently the industry requires personnel to be transported by boat to the ladders at the base of the construction tower.

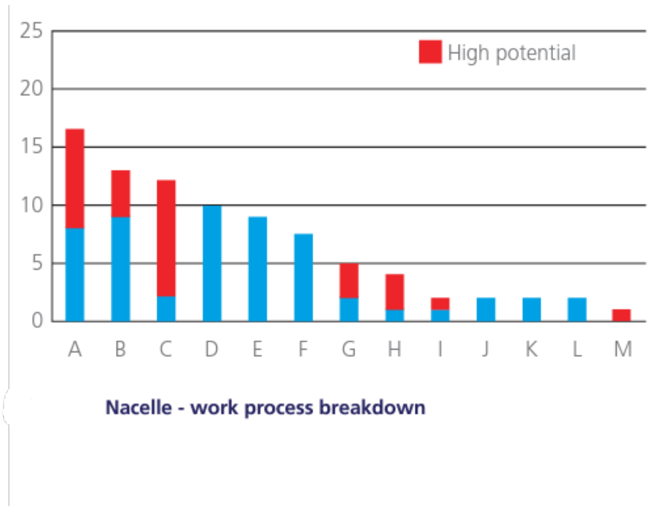
G+ (2021) have provided statistics on safety incidents from 2015 through to 2021 which are shown in table 5

Table 5

Safety statistics for 2021[9]

	2015	2016	2017	2018**	2019	2020	2021
Hours worked*	21,220,000	21,726,000	26,815,000	25,359,000	22,374,000	25,318,000	32,342,000
Fatalities	0	0	0	0	0	0	0
Lost work day injuries	41	43	49	39	62	43	50
Restricted work day injuries	32	35	30	34	23	30	22
Medical treatment injuries	53	42	78	45	38	22	34
Total	126	120	157	118	123	95	106
Total recordable injury rate (TRIR)	5.94	5.52	5.85	4.65	5.50	3.75	3.28
Lost time injury frequency (LTIF)	1.93	1.98	1.83	1.54	2.77	1.70	1.55

G+ highlights that the area that has the largest number of incidents is with the nacelle. The Wind Energy Technologies Office (2023) informs us that the nacelle sits atop the tower and contains the gearbox, low and high-speed shafts, generator, and brake. The nacelles vary in size with some being larger than houses and for a 1.5MW geared turbine the nacelle can weigh more than 4.5 tons. Given they are the most complex part of the system, it is no surprise the largest number of incidents in the whole system occur with the nacelle. In 2021 91 incidents occurred, with approximately 16 of these coming from lifting operations. *Figure 10* provides a breakdown of the incidents associated with the Nacelle.

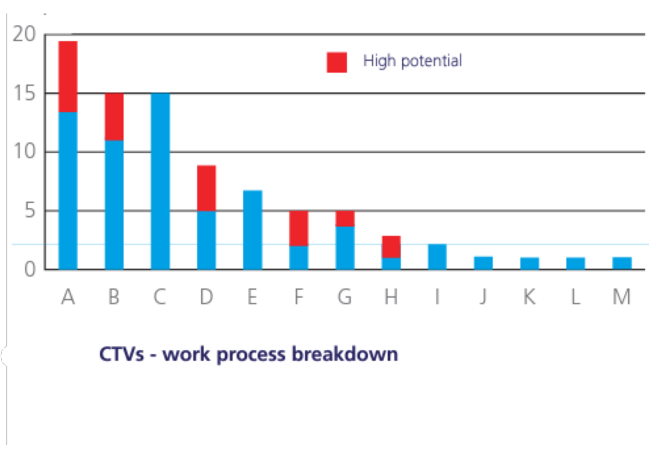


Key	
A	Lifting operations
B	Routine maintenance
C	Electrical systems (working with)
D	Manual handling
E	Hand tools/power tools (working with)
F	Walking from A to B
G	Mechanical systems (working with)
H	Access/egress
I	Operating plant and machinery
J	Catering/cleaning
K	Confined spaces (working in)
L	Replacing major components
M	Chemicals and hazardous substances (working with)

Figure 10 G+ Global Offshore Wind Health & Safety Organisation. 2021 incident data report. Energy Institute

Closely following on from Nacelle incidents are crew transfer vessels (CTVs) incidents with 85 in 2021.

Figure 11 provides the breakdown of incidents in offshore wind CTVs although more insight is required to understand if other factors have contributed to these incidents such as weather.



Key	
A	Transit by vessel
B	Vessel operation (including jack-ups and barges)
C	Transfer from/to vessel
D	Lifting operations
E	Manual handling
F	Access/egress
G	Walking from A to B
H	Routine maintenance
I	Catering/cleaning
J	Commuting
K	Davit crane operations
L	Operating plant and machinery
M	Painting/blasting

Figure 11 G+ Global Offshore Wind Health & Safety Organisation. 2021 incident data report. Energy Institute

An example of emerging hazards is that since writing this document is that the HSE (2023) has issued a safety notice on the 15th of August 2023 to highlight an emerging hazard associated with the wind turbine generator service lift. The HSE investigation of an incident at a WTG found that the design of landing gates and guarding did not eliminate or reduce access to dangerous moving parts of the lift car as it operated with external one touch controls. It was possible to reach the lift car and become crushed or sheared against the gates. The report highlights that the service lifts tend to be retrofitted, which is a key contributor to the issue. This has led to a new British Standard, BS EN 81-44 'Safety rules for the construction and installation of lifts. Special lifts for the transport of people and goods. Part 44 Lifting appliances in wind turbines', which is referred to as setting the benchmark for the safe design of service lifts and associated safeguards.

Battery Storage

Battery storage is a technology that enables the power generated to be stored for later use. This generation is typically from renewable sources such as solar or wind. The National Grid A (2023) advises that Battery Energy Storage Systems (BESS) are devices that enable energy from renewables to be stored and then released when customers need power most.

The dominant storage technology is Lithium-Ion batteries for large scale plants to help electricity grids harness the renewable energy generated and provide a reliable supply of this energy.

The Lithium-Ion battery was developed by a British scientist in the 1970s and was first used commercially by Sony in 1991 for their handheld video recorder. The Clean Energy Institute University of Washington (2020) advises that lithium ions are a key component of the lithium-ion battery electrochemistry. During a discharge cycle, lithium atoms in the anode are ionized and separated from their electrons. The lithium ions move from the anode and pass through the electrolyte until they reach the cathode, where they recombine with their electrons and electrically neutralise. The lithium ions are small enough to be able to move through a micro-permeable separator between the anode and cathode shown in *figure 12*. Lithium-ion batteries are capable of having a very high voltage and charge storage per unit mass and unit volume due to lithium's small molecular size, third only to hydrogen and helium.

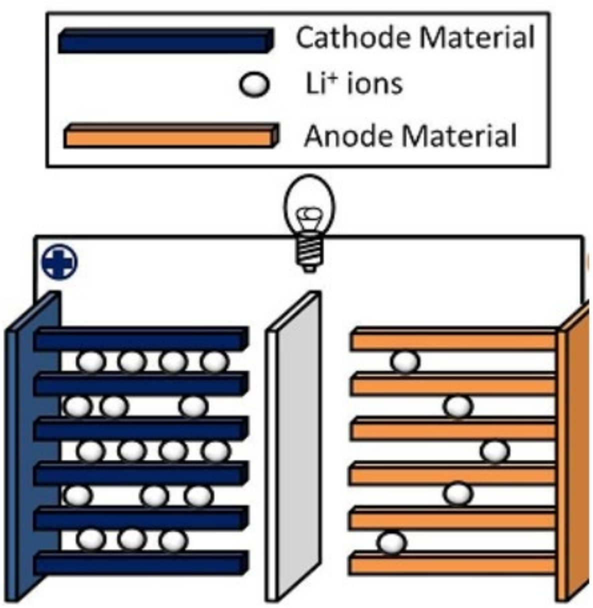


Figure 12 Clean Energy Institute University of Washington (2020) What is a Lithium-Ion Battery and How Does it Work?

Lithium-ion batteries can use various different materials as electrodes. The most common combination is lithium cobalt oxide (cathode) and graphite (anode), which is most commonly found in portable electronic devices such as mobile phones, laptops, and portable power units. Other cathode materials include lithium manganese oxide which is used in hybrid/electric vehicles and lithium iron phosphate.

While Lithium-Ion batteries are currently the most economically viable energy storage solution there are a number of other technologies currently being developed such as (National Grid A, 2023);

- Compressed Air Energy Storage – with these systems, generally located in large chambers, surplus power is used to compress air and then store it. When energy is needed, the compressed air is released and passes through an air turbine to generate electricity
- Mechanical Gravity Energy Storage – one example of this type of system is when energy is used to lift a concrete block up a tower. When energy is needed, the block is lowered which in turn generates electricity using the pull of gravity. Another example is a pumped hydroelectric system, where excess electricity is used to pump water to the input dam for release not the penstocks as required
- Flow Batteries – Garg (2012) describes a flow battery as a fully rechargeable electrical energy storage device where fluids containing the active materials are pumped through a cell, resulting in reduction/oxidation on both sides of an ion-exchange membrane, resulting in an electrical potential. In a battery without bulk flow of the electrolyte, the electro-active material is stored internally in the electrodes. However, for flow batteries, the energy component is dissolved in the electrolyte itself. The electrolyte is stored in external tanks, usually one corresponding to the negative electrode and one to the positive electrode. The convention we will use is that the negative electrode is the anode, and the positive electrode is the cathode when discharging. Further to this flow batteries, particularly those with reaction involving only valence changes of ions, are especially robust in their cycle lifetime, power loading and charging rate. The electrolyte has an essentially indefinite lifetime and can be charged to full capacity and discharged completely with no adverse effects. *Figure 13* shows a typical flow battery arrangement;

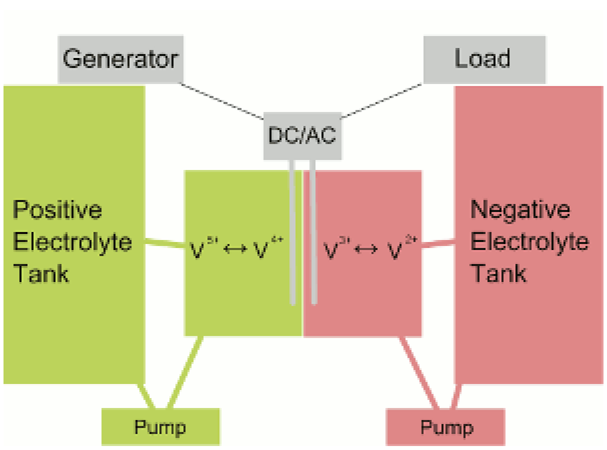


Figure 13 Garg, M (2012) Introduction to Flow Batteries: Theory and Applications

There are organisations currently developing technologies to allow battery storage systems to service industrial, commercial, and residential buildings, which will require further research as this technology develops. The National Grid A (2023) advise that intelligent battery software uses algorithms to coordinate energy production and computerised control systems are used to decide when to store energy or to release it to the grid. Energy is released from the battery storage systems which is likely one of the three methods above, during peak demand which can support in keeping costs down and electricity flowing. Battery storage brings many challenges to the energy transition. Vast volumes are required to store the volume of energy required to meet energy demands. Some challenges with battery storage facilities can be their locations, too warm a climate and we can see the systems overheat, too cold a climate and we can see underperformance. Additional precautions are also the emergency response systems put in place. Additional challenges are the increase in lithium-ion thermal runaway battery fires.

Dragonfly Energy (2023) refers to thermal runaway as a chain reaction within a battery cell that can be very difficult to stop once it has started. It occurs when the temperature inside a battery reaches the point that causes a chemical reaction to occur inside the battery. This chemical reaction produces even more heat, which drives the temperature higher, causing further chemical reactions that create more heat. In thermal runaway, the battery cell temperature rises incredibly fast (milliseconds). The energy stored in that battery is released very suddenly. This chain reaction creates extremely high temperatures (around 752 degrees Fahrenheit / 400 degrees Celsius). These temperatures can cause gassing of the battery and a fire that is so hot it can be nearly impossible to extinguish.

Colthorpe (2021) highlights how an incident occurred in phase 1 of the largest battery storage facility in the world. The incident was reported as overheating of batteries which Colthorpe (2022) reported occurred again in February 2022 in phase 2 of the facility. The investigation found that the phase 1 incident was due to smoke coming from an air handling unit due to a bearing failure which then activated the sprinkler system. The sprinklers themselves then caused the batteries to overheat. Phase 2 is reported to be due to leaking hoses.

This shows that when implementing emergency response procedures, there is potential to create more incidents. A solution for Phase 1 was to seal each individual floor so that water leakage could not occur from one level to another, reviewing the programme in place for Very Early Smoke Detection Apparatus (VESDA) and testing all heat suppression equipment, thus isolating potential incidents. In Phase 2 we see the challenges associated with the routing of emergency response equipment. Chen *et al* (2021) discuss how the environment which can control the temperature, voltage and electrochemical reactions is the leading cause of disturbances in batteries. This makes environmental considerations key to ensuring battery safety.

Within battery storage facilities lithium-ion batteries are a popular choice because of how much power they can provide given their size and weight. However, the lithium-ion battery has some challenges and safety concerns such as thermal runaway. The Research Institute (2021) identify that in a lithium-ion cell, the cathode and anode electrodes are physically separated by a component called the separator.

Defects in the cell that comprise the separator's integrity can cause an internal short circuit condition that can result in thermal runaway. This is especially likely in cells of poor quality. Organisations and individuals may ask why would lithium-ion batteries be chosen over the arguably safer lead acid battery? A standard lithium-ion battery may store around 150 watt-hours of electricity in 1 kilogramme of battery which compared to Nickel Metal Hydride (NiMH) battery pack is 100 watt-hours per kg or a lead acid battery which is 25 watt-hours per kg. To use lead acid batteries would require 6 times more volume than that of a lithium-ion battery and when storage and facility space is scare the lithium-ion battery is justified.

Chen et al (2021) discuss that battery safety is profoundly determined by the battery chemistry, its environments, and the abuse tolerance. *Figure 14* breaks down some of the findings into abuse categories and the likely impact areas of a battery following this.

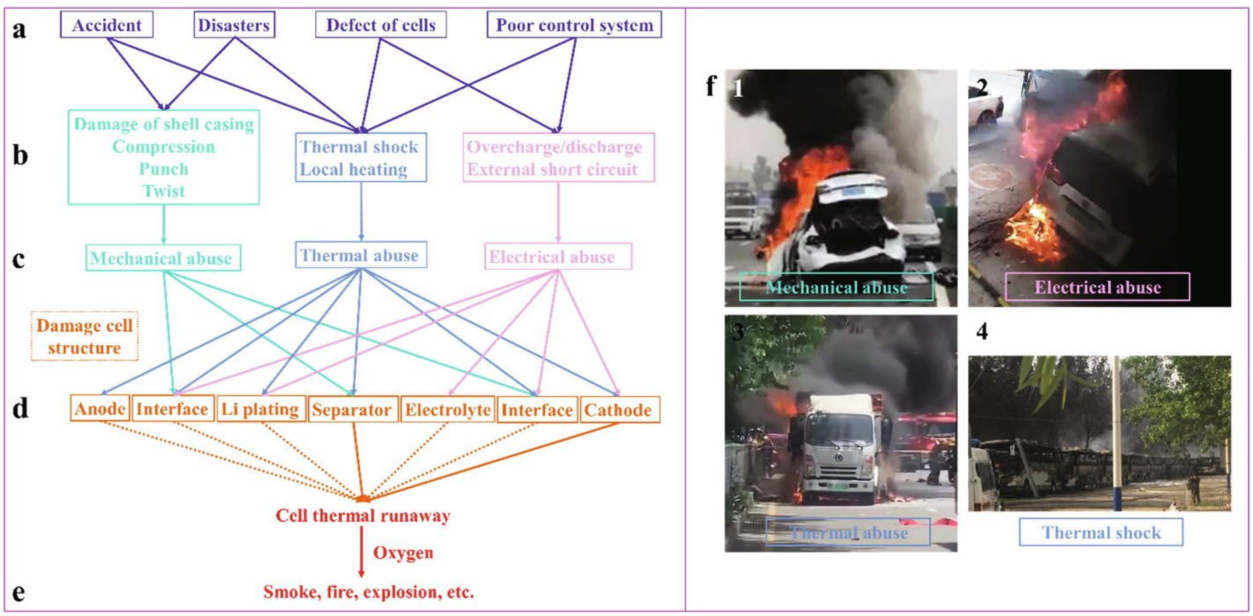


Figure 14 Chen, Y et al. (2021) A Review of Lithium-Ion Battery Safety Concerns: The Issues, Strategies and Testing Standards.

Advantages of Lithium-Ion batteries when compared with alternative options such as nickel-cadmium or nickel-metal-hydride are provided by Clean Energy Institute University of Washington (2020) as;

- One of the highest energy densities of any battery technology
- Can deliver up to 3 times higher volts
- Can deliver large amounts of current for high power applications
- Low maintenance – do not require scheduled cycling to maintain battery life
- No memory effect – battery will operate as its max capacity
- Low self-discharge rate of 1.5-2% per month

Figure 15 provide the volumetric density versus specific energy density of Lead acid, Nickel-Cadmium, Nickel-Metal-Hydride and Lithium-Ion batters to highlight the benefits of Li-Ion.

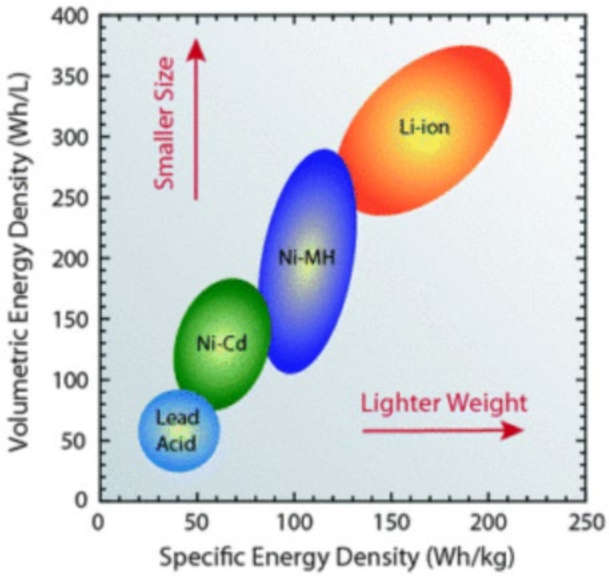


Figure 15 Clean Energy Institute University of Washington (2020) What is a Lithium-Ion Battery and How Does it Work?

Lithium-Ion batteries are not without their disadvantages however;

- Li-Ion batteries have a tendency to overheat and can be damaged at high voltages
- Thermal runaway and combustion can occur due to overheating
- Requires safety mechanisms to limit voltage and internal pressures
- Subjected to aging – can lose capacity and fail after several years
- Cost – approximately 40% high than alternative options
- Impact damage can result in overheating and fire

Some significant incidents where;

- Grounding of Boeing 787 fleet: after onboard battery fires were reported, resulting in some freight companies refusing to perform bulk shipments of batteries via plane
- June 2021: Illinois Warehouse Mishap which is one of the biggest lithium-ion incidents of modern times. Approximately 200,000 pounds of mostly lithium-ion batteries were stored at an abandoned warehouse with 50,000 being confirmed as damaged or defective. The lawsuit indicates a leaking roof resulted in water dripping onto defective batteries causing thermal runaway which the inexperienced firefighters then added further water too causing a significant incident that went on for the next 28 days.
- July 2021: Tesla Megapack fire in Australia – due to a coolant leak that went undetected during start-up tests two Tesla battery units ignited at an energy storage project. After initial testing a megapack was switched off which removed fault protection, a short circuit occurred, and the fault/fire went undetected and spread to the adjacent megapack compartment.

- February 2022: Felicity Ace cargo vessel caught fire and burned for over one week. Close to 4000 electric vehicles where onboard with an estimated valuation of $330m.
- August 2022: a blaze occurred in an East Harlem, New York apartment from a lithium-ion battery in an e-bike/scooter resulting in the death of a 5-year-old girl and 36-year-old woman along with three dogs.

The battery storage industry is constantly evolving and as the demand for transporting lithium-ion batteries is increasing we are seeing different hazards emerging such as tunnel fires via rail or driving through tunnels.

Although the risk assessment methods are deemed adequate, they should be revisited for gap's in identifying hazards as battery technology evolves. Gap may become evident as we obtain more data in how thermal runaway occurs through site locations, impacts or even weather.

Carbon Capture Utilisation and Storage

The European Commission (2023) refers to Carbon Capture Utilisation and Storage (CCUS) as a set of technologies aimed at capturing, transporting and permanently storing carbon dioxide (CO_2) that would otherwise be emitted into the atmosphere.

CCUS has a part to play in the energy transition away from fossil fuels to a more environmentally friendly renewable energy option. As we cannot immediately halt fossil fuels extraction and production CCUS helps tackle climate change. The National Grid B (2023) provides information that the Intergovernmental Panel on Climate Change (IPCC) highlighted that to achieve the ambitions of the Paris Agreement and limit future temperature increases to 1.5°C (2.7°F) we must do more than just increase efforts to reduce emissions, we need to deploy technologies to remove carbon from the atmosphere. The London School of Economics and Political Science (2023) advise that CCUS can play a strategic role in global decarbonisation effort in a number of ways;

1. Reducing emissions in 'hard-to-abate' industries, those that are particularly difficult to decarbonise. CCUS is virtually the only known technological option for achieving deep emission cuts in cement production which is an industry contributing almost 7% of the worlds emissions.
2. Producing Low-carbon electricity and hydrogen, which can be used to decarbonise various activities.
3. Removing existing $CO_2$from the atmosphere.

The National Grid B (2023) advises that Carbon Capture and storage works by;

1. Capturing the Carbon Dioxide for Storage – The $CO_2$is separated from other gases produced in industrial processes, such as coal and natural gas fired power generation plants or steel/cement factories.
   The London School of Economics and Political Science (2023) advise that the main methods of capturing $CO_2$are;
   Post-Combustion, Pre-Combustion and Oxy-Fuel Combustion. Post-combustion technology separates $CO_2$from the flue gas by using a chemical solvent, after the fuel is burnt. Pre-combustion methods involve converting the fuel into a gas mixture consisting of hydrogen and CO2 before it is burnt. Once the CO_2 is separated, the remaining hydrogen rich mixture can be used as fuel. Oxy-fuel technology involves burning a fuel with almost pure oxygen to produce $CO_2$and steam with the release CO_2 subsequently captured.

2. Transport – Once the CO_2 is captured it is compressed and transported via pipeline, road transport or ships to a site for storage.

3. Storage – CO_2 is then injected into deep geological formations usually 1km or more into depleted oil and gas reservoirs, coalbeds or deep saline aquifers where the geology is suitable.

Prior to storing the carbon there is another option to use it in an industrial setting by converting it into plastics, concrete or biofuels as highlighted by The National Grid B (2023) while also being used in the agricultural industry for fertilisation requirements. Usage (or Utilisation) refers to using the captured CO_2 to produce commercially marketable products or services. The London School of Economics and Political Sciences (2023) advises that CO_2 usage does not necessarily reduce emission nor deliver a net climate benefit, once indirect and other effect have been accounted for. An example is enhanced oil recovery (EOR), which injects CO_2 into oil and gas reservoirs to increase extraction, this is one of the well-known methods of CO_2 usage. As CCUS is increasingly looked to for its decarbonisation potential most projects are now looking at storage rather than usage.

Key concerns around CCUS are the high costs as CCUS facilities are capital intensive to develop and energy intensive to operate, making them particularly expensive when energy costs are high. Risk and uncertainties around the technological performance of CCUS operations bring in other costly factors. As the CCUS market begins to expand and the demand for the technology grows there is potential that the costs involved will decrease however wide economic benefits should be considered and rather than do nothing, industries such as cement and fossil fuels may look to deploy the cost of CCUS technologies. The sites for CCUS also need to be managed effectively to ensure there is no leakage and accidental release of CO_2 into the atmosphere.

Incidents relating to CCUS are;

- Potential CO_2 release to atmosphere
- Asphyxiation risk from a release due to odourless nature and heavier than air – especially as pipelines run through populated areas
- Catastrophic failure of a high-pressure pipeline causing damage

The project found that the current level of risk assessment methodologies in place are adequate to meet the demands of renewable technologies. However, it is noted that this should be revisited periodically as the technologies advance and grow. CCUS is continuing to evolve as it was initially focused on using the product rather than storage. Now we see significant uptake in storage projects which may require adaptive consequence modelling and relevant software to match.

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