Net zero technologies: environment impact summaries

Chief Scientist’s Group report

Updated September 2024

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Dr Robert Bradburne
Chief Scientist

Foreword

The Net Zero research programme is a programme of work managed by the Environment Agency Chief Scientist's Group and funded by Defra. The aim is to use science and evidence to ensure that the environment is part of a sustainable and equitable transition to a low-carbon economy. Our strategic objective is to understand at different scales what different pathways to net zero mean for the environment, the sectors the Environment Agency regulates, and the communities in which we work. We are approaching this challenge from different directions, building a multidisciplinary picture to inform the organisation's strategic planning, underpin its regulatory decisions, and influence a wider discussion in government and society on the interactions between achieving net zero and other environmental and social objectives.

These short summaries were produced in 2023. This a fast-moving topic area and inevitably information is likely to go out of date, so these are a summary of information available at time of writing. The aim of the summaries is to provide an overview of the potential environmental impacts of different technologies, although it is noted that many of these challenges could be mitigated to varying degrees through effective management. They are intended to provide a broad overview, rather than specific detail, ideally aimed at those new to a subject or those wishing to gain additional knowledge in a quick and easy to use format.

Contents

1. Electrochemical batteries

Background

It is widely accepted that the transition to net zero will require increasing electrification of our energy system, with most electricity coming from intermittent renewable energy sources (e.g., wind, tidal and solar). As a result, there will be a need to store energy at times of high supply and low demand, to feed into the grid later when supply is low, and demand is high. Electrochemical batteries are well-suited to energy storage and release. Electrochemical batteries operate through oxidation-reduction reactions where an exchange of electrons takes place between chemical species, with cations being transferred from anode to cathode within varying electrolyte solutions. The type of electrolyte solution used, as well as the material the electrodes are made of, determines the battery's properties (e.g., energy density, voltage etc.), applications, demand, and environmental impacts. Primary batteries are single use, designed for small domestic functions like powering clocks and remotes (typically disposable alkaline batteries), secondary batteries are rechargeable and service items with long lifespans such as cars, phones, and laptops. Secondary batteries allow for electrical energy to be transformed back into chemical energy when supplied with an electric current.

Environmental and public health impacts

The greatest impacts of batteries on environmental and human health occur while initially mining for battery metals and at the end of life during the disposal process. Metal mining (e.g., lithium, cadmium and nickel) involves high water demand, land degradation and can release gases such as sulphur dioxide into the atmosphere, which in large concentrations causes acid rain and human/animal asphyxiation. Mining for battery metals such as lithium and cobalt primarily takes place in China, Australia, and South American countries [9], and nickel in Southeast Asian countries [3]. With this said, mining does occur within the UK (a lithium mine in Cornwall is projected to be ready for operation in 2024 [2]). Although ores are often of higher quality and extraction is cheaper when outsourced overseas, the ability to monitor and regulate social and environmental impacts is compromised. During battery disposal, metal leaching and subsequent soil and groundwater contamination are possible, as well as the likelihood of chemical fires if batteries are physically damaged/improperly disposed of. In many cases, batteries are considered hazardous waste due to containing heavy metals and corrosive solutions and the handling of their disposal must follow waste management regulations [4]. Many mining and disposal facilities will be managed through appropriate environmental legislation.

Technology	Notes	Environmental Issues	Management challenges
Lithium-ion	500-2000 charge cycles. Lithium is light and has a high energy density. It is increasing in demand globally and is mined for predominantly in Australia, China and South America [9]. This is the favoured type of battery for electric vehicles.	Lithium mining (lithium is a finite resource, its extraction threatens biodiversity in mining locations, causes land degradation, air pollution and water contamination). Water intensive [1]. When accidently placed in lead-acid battery recycling can lead to explosion. Likely offshoring of pollution.	Mining locations and activities leading to possible losses of amenity and local biodiversity Contaminant emissions from mining of raw materials such as dust and rock, as well as key trace elements such as cadmium, copper, lead, lithium, manganese and nickel. Long-term disposal of end-of-life articles and potential emissions such as landfill leachates Potential for incidents during storage, use, and disposal including fires as a result of combustible materials such as lithium [14].
Lead-acid	300-500 charge cycles. Low energy density and short lifecycle. Less of a fire hazard than lithium-ion.	Extraction and processing of lead and polypropylene (lead mining occurs in the UK as does the manufacturing of polypropylene, derived from hydrocarbon fuels). Impacts of lead-acid battery production per kg of battery are: GHGs - 0.9 kg $CO2_{eq}$ and fossil fuel - 0.3 kg oil_{eq} [10].	See lithium-ion above.
Nickel-cadmium	2000-2500 charge cycles. Useful for uninterruptible power supply [4]. Large memory effect.	Cadmium is a toxic heavy metal and nickel oxides are carcinogenic upon inhalation [6]. Cadmium is produced mainly as a biproduct mining other metals that have a higher concentration in the	See lithium-ion above.

		ore [7]. Nickel mining releases sulphur dioxide [10]. Likely offshoring of pollution.	
Alkaline batteries	Normally single use batteries. The electrolyte (normally potassium hydroxide) has a pH of >7.	Not often accepted at recycling plants. Single use.	See lithium-ion above. Alkaline batteries may be more likely found in mixed municipal wastes.
Sodium-ion	Potential competitor for lithium-ion batteries. Sodium is heavier and has a lower energy density. Requires a less concentrated electrolyte solution. Good thermal sustainability - higher safety ratings. Sodium is more readily available than lithium. CATL (largest lithium-ion battery company in world, Chinese) manufactures sodium-ion batteries with lithium-ion factory equipment (no need for new infrastructure).	Salt mining (habitat destruction, biodiversity loss, groundwater contamination). Salt mining occurs worldwide, including the UK (Cheshire). Likely offshoring of pollution.	See lithium-ion above.
Redox Flow	15,000 – 20,000 charge cycles. Can discharge fully. No memory effect. Made of vanadium (scarce and expensive metal) and a highly toxic	Vanadium mining. Toxicity of sulphuric acid. Fossil fuel necessary for electrode oil-based polymer. Likely offshoring of pollution.	See lithium-ion above. Note that sulphuric acid is a strong oxidizing agent which can lead to the combustion of surrounding materials.

	electrolyte solution (mostly sulphuric acid). Electrodes made of an oil-based polymer.		
Organic Redox Flow	Similar qualities to regular redox flow battery but not currently technologically ready. Made of iron sulphate (cheap and plentiful waste product from mining) and anthraquinone disulfonic acid (carbon-based material) [11], [12]. Less than half the cost of regular redox flow. Completely recyclable. Doped-quinone organic redox battery in infancy [8].	Although iron-sulphate is a bi-product of other mining efforts, it is still associated with mining's environmental impacts.	See lithium-ion above.

Future science needs

Lithium-ion batteries currently dominate the market for large-scale energy storage but are projected to be overtaken by sodium-ion batteries due to the growing cost and dwindling availability of lithium [1]. Organic redox flow batteries are projected to increase in use, inferred from large investments being made in their technology globally, although still far away from mainstream availability [15]. For electrochemical batteries, any air, water or soil contamination associated with emissions from mining and battery waste treatment and disposal would need to be managed to protect health and the environment, along with the fire hazards associated with battery transportation, storage and disposal.

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2. Thermal energy storage

Background

Throughout the net zero transition, it is accepted that the UK's energy systems will become increasingly reliant on electricity produced by intermittent renewable energy sources like solar, wind and tidal. Daily and interseasonal fluctuations in supply and demand will need to be managed within the energy system through energy storage. Thermal energy storage is a mechanism of conserving excess energy from the grid within high energy density media that retain heat, contained in an insulated vessel or reservoir. It is particularly useful in managing fluctuations in supply and demand with intermittent renewable energy sources like solar, wind and tidal, which can occur both daily and interseasonally. Two main thermal energy storage mechanisms exist: sensible and latent. Sensible thermal energy storage methods use batteries made of materials such as sand, water, molten silicon, and molten salt to retain heat, remaining in one phase as heat accumulates and dispels, and temperature fluctuates. Latent energy storage utilises phase change materials (e.g., organic paraffins and fatty acids) where latent heat accumulates in the material without a change in temperature until sufficient energy is contributed for a phase change to occur (e.g., solid to liquid) [4].

Environmental and public health impacts

Negative environmental and health impacts associated with thermal energy storage are limited. Generally, the potential impacts are with heat loss if a reservoir is not properly insulated, which can potentially affect surrounding ecosystems. With specific technologies such as sand batteries, there is the strategic sourcing of recycled sand; with molten silicon, the necessary use of thermophotovoltaic cells and their potential to leach metals after disposal. For thermal energy storage strategies that use water or air such as sand batteries, maximum efficiency is retained if the thermal energy is preserved and not converted to electricity (e.g., directly supplying hot water or powering steam engines), which can require below ground pipe installation with the potential for local biodiversity disturbance. Some facilities will require water to operate, with the quality and quantity of water managed to protect the surrounding environment from over abstraction and chemical leakages.

Technology	Notes	Environmental Issues	Management challenges
Molten Salt	Eutectic salt mixtures (sodium nitrate, potassium nitrate). Excess energy from renewables heats salt within a tank, discharges molten salt to a boiler, boiler fuels a steam turbine. Approx. 70% efficient. 30-year lifecycle.	Salt mining in seabed and salt caverns in the UK (disturbance to aquatic ecosystems, altering salinity levels and habitat destruction). Salt mining in salt caverns (water intensive). The energy and emissions associated with the industrial synthesis of sodium nitrate and potassium nitrate.	Disposal of contaminated water. Impact of salt emissions such as from mining on ecosystems. Incident management following release of molten salts Water abstraction
Sand	Insulated steel silo filled with sand and heat transfer pipes. Long lifespan. Only worthwhile if used for direct heating and not energy conversion (district-scale infrastructure necessary, or onsite steam plant).	Sourcing and transporting sand (upcycled sand from construction industry). Disturbance to ecosystems if underground piping network installation is necessary.	Local environmental impacts associated with construction and demolition activities such as pipework, and the quarrying of sand.
Phase Change Materials (PCM) (Latent Heat Storage)	Directly integrated into building materials and infrastructure, most often to retain solar energy. Can be made of organics (paraffin, fatty acid), inorganics (salt hydrate, metal alloys), eutectics (organic/inorganic mixture) [4]. Low thermal conductivity of most effective PCMs	Paraffin wax PCM apparatus are derived from crude oil. Fatty acid PCM apparatuses can contain palm oil.	See molten salt above and electrochemical batteries in Section 1.

	limits thermal energy storage efficiency [5].		
Water in mines	Naturally between 10 and 25°C [1]. Makes use of flooded, abandoned mines. Water consistently warm from natural geothermal processes. ¼ UK homes and businesses sited on former coalfields [3]. Water is usually pumped back into reservoir after use or can be pumped into pond/well or surface water once treated in combination with mine water management system.	Potential source of methane (CH_4) and hydrogen sulphide (H_2S) emissions to air or dissolved in water. Potential instability in mine structure. Thermal pollution of surrounding aquifers. Potential contamination from mobilisation of heavy metals and other mining compounds into surrounding aquifers or surface water [7]. (if open loop system)	Potential emissions to air and water from mine workings including contaminants and heat. For example, releases of toxic gases such as methane and hydrogen sulphide as a result of changing ground conditions [6]. Potential discharges of contaminated water from pumps and ponds. Water abstraction Potential for localised surface water and groundwater flooding.
Molten Silicon	Thermophotovoltaic cells used to convert incandescent radiation from the molten silicon into electricity. Can create electricity efficiently. Reduced containment size due to high energy density compared to molten salts and water.	Potential metal leaching as thermophotovoltaic cell degrades (approx. 25 years)	Accidental releases of molten silicon. See also electrochemical batteries in Section 1.
Aquifer thermal energy storage (ATES) / Borehole thermal energy	ATES, (open loop) warm groundwater abstracted and used to warm buildings in winter and stored in aquifers in summer, cool groundwater used in summer and stored	Temperature changes in groundwater, possible impacts on geochemistry and groundwater ecology, and potential impacts on nearby wetlands, springs, surface water	Potential discharges of contaminated water from open loop systems including chemicals and heat. Water abstraction.

storage (BTES)	in aquifers in winter. BTES, closed loop (using heat transfer fluids) systems. Can use heat pumps to concentrate heat.	ecology and water sources. Possible mobilisation of contaminants in aquifer. Closed loop systems possible leakage of heat transfer fluids. Possible leakage of refrigerants into atmosphere from heat pumps. Sometimes noise disturbance.	

Future science needs

The potential environmental and human health impacts of thermal batteries are low relative to other energy storage technologies. It is important however to consider their respective longevities alongside the sourcing of their constituent materials through life cycle analyses to ensure that all environmental issues from battery creation to end of life are considered. There is a potential need to manage the impacts of these systems on the sub-surface environment as well as to control releases to air, water or soil. There may also be a need to understand incidents involving molten materials like silicon or salt.

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3. Direct air carbon capture technology

Background

Direct air carbon capture (DACC) technology is used to remove CO_2 directly from the atmosphere. As CO_2 concentrations are lower in ambient air than at point source emission locations, DACC requires more energy and is currently less efficient than standard carbon capture techniques (located at source, pre-/post-combustion). To ensure net negative emissions, DACC facilities must be powered by renewable energy. When combined with permanent storage of the CO_2 in either a geological feature or durable product, this allows near-permanent withdrawal of CO_2 from the atmosphere, known as direct air capture and storage (DACCS). DACCS can be used to move towards permanent offsetting of difficult-to-decarbonise industries, such as shipping and aviation. Currently, most DACCS facilities are on a relatively small-scale, and all but two plants globally use the captured CO_2 (e.g. for drink carbonation). Key concerns at present are that some techniques require high temperatures to operate, the technology has not been proven at scale and research has not been undertaken to assess which climates are suitable for DACCS (e.g. dry air, humid air, polluted air). There is also the risk that CO_2 storage sites are not currently being developed at scale which, given design and permitting timescales, could become a pinch point for CO_2 storage requirements.

Environmental and public health impacts

There are currently two main DACC methods: solvent-based (liquid DACC) and sorbent-based (solid DACC), each of which have different environmental implications. The main implications are (1) land use, (2) energy use, (3) water use and (4) chemicals use. Ongoing research is focusing on new solvent and sorbents, but there are also emerging techniques based on different methods, such as electro-swing adsorption, membrane-based DACC and liquid-solid phase separation. The different DACC technologies and associated potential environmental impacts are summarised in the table below.

Technology	Notes	Environmental Issues	Management challenges
Solvent-based (liquid DACC)	Aqueous basic solution (e.g. potassium	High temperature requirement means it is difficult to power by	Chemical releases to air and water.

(TRL = 6*)	hydroxide). Releases CO2 through several units operating at high temperature (300-900°C).	renewables (but potential for power by green hydrogen). Improvement of large-scale electric calcination technology (heating under low oxygen levels; currently TRL 3*) needed. 1-7 tonnes water required per tonne of CO2 captured, and more in dry, hot environments. Solvent disposal/ regeneration. Release of solvent aerosols. Land use.	Waste management Water abstraction.
Sorbent-based (solid DACC) (TRL = 7*)	Solid adsorbent. Operates at ambient/low pressure (under vacuum) and medium temperature (80-120°C).	Potential to be powered by low-grade waste heat. Water requirements depend on specific technology (vary from net water production to 1.6 tonnes water required per tonne of CO2 captured). Sorbent degradation products. Land use. Chemicals for sorbent manufacture. Disposal of sorbents.	See liquid-DACC above.
Electro-swing adsorption (TRL < 6*)	Electrochemical cell. Solid electrode adsorbs CO2 during negative charge and releases it when positively charged.	Impact of carrier molecules (quinones, 4,4’-bipyridine, thiolates) on environmental receptors and potential for “leakage”. Novel chemicals with limited knowledge of fate and hazard. Land use.	See liquid-DACC above.
Membrane-based DACC (TRL < 6*)	CO2 is separated from the air when permeated through specific membranes.	Requires expensive (energy-intensive) compression of lots of ambient air. Land use.	See liquid-DACC above.

Liquid-solid phase separation	Uses isophorone diamine, is twice as fast as most existing technology and 99% efficient.	Compound is reusable after reheating at 60°C. Land use	See liquid-DACC above.

*TRL=Technological Readiness Level; these have been sourced from [1], [2], and [3].

Future science needs

As DACCS is currently at a relatively low technological readiness level (compared to other carbon capture and storage techniques), work is needed to improve understanding of potential future environmental impacts and increase understanding of any future management requirements.

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4. Energy storage

Background

With the continued shift towards renewable energy production comes increased need for energy storage, to ensure supply during so-called *“dunkelflaute”* periods (when renewable energy production is low). The energy in stored when supply exceeds demand (e.g. at night/in summer), and is released when demand exceeds supply (e.g. during the day/in winter) A variety of technologies are available, depending on the type of energy being stored (e.g. gaseous *versus* electricity), the time for which the energy is expected to be stored and the location. These include: battery energy storage systems (BESS), compressed air energy storage (CAES) and thermal energy storage (TES). Energy can be stored over a range of timescales, with different technologies being most suited to particular timescales. For example, batteries (especially lithium-ion) would be more suitable for less than daily variability (balancing the system over 0-4 hours), while underground hydrogen storage could help balance seasonal and multi-year variability in energy supply and demand. Estimates anticipate a need for 3-4 TWh storage capacity to balance inter-day variability, 10s of TWh capacity for seasonal balancing and 100 TWh for multi-year balancing [1], [2]. For CAES and TES, research is currently focused on technological innovation, and understanding environmental impacts is less well covered.

Environmental and public health impacts

The scale and pace of change is a key issue. For example, while lithium-ion batteries have been used for some time and management procedures developed for dealing with leaks, fires and handling of wastes, the scale-up of BESS facilities and the overall prevalence of batteries is likely to increase the importance of managing the environmental risks associated with these technologies. An overview of energy storage technologies, their potential environmental impact and management challenges are outlined in the table below. The main areas of environmental impact are: (1) potential leakage from the system (and impacts on air, land and water quality, as well as biodiversity), (2) chemicals/heavy metals and (3) water use.

Technology	Notes	Environmental Issues	Management challenges
CAES	Converts electricity into mechanical energy (pressure), which can then be converted back to electricity by	Capturing and storing waste heat can improve their efficiency (circular economy). Reservoir instability. Water consumed	Large volumes of compressed air could represent an explosion risk.

	powering a turbine. Compressed air is often stored underground in a salt cavern.	for salt cavern creation. High salt content of brine produced during salt cavern creation-need clear guidance on disposal or, ideally, a use for the brine (circular economy). Explosion risk from rapid decompression of the reservoir. Air quality and pollutant emissions from burning natural gas to power the turbine (CH_4, SO_2, NO_x, particulates, CO).	Potential emissions to air and water from the salt cavern including discharges of brine during construction and maintenance. Water abstraction.
TES	Uses heat to warm a medium (e.g. rock, water, molten salts), which can then be reversed to release the stored energy. Energy can either be released as heat into heat networks or can be released as electricity.	Environmental impacts likely depend on chosen storage medium. Heat storage in water in former mines could have impacts on groundwater chemistry.	See Section 2.
Underground Pumped Storage Hydropower	Converts electricity into gravitational potential energy, which can then be converted back into electricity. Usually consists of two reservoirs: an upper and lower reservoir. Potential for use of old mine systems.	Land use change from reservoir construction and if upper reservoir dike fails-impact on habitats, biodiversity and hydrology. Reservoir instability. Groundwater-reservoir water exchange, and chemical/pollutant impacts (e.g. ferrihydrite, goethite, schwertmannite).	Chemical pollution of waters from storage locations and their movement between locations. Flood risk.
BESS	Lithium-ion is currently the most developed composition and is widely used. Other battery compositions	Impact depends on composition. Impact from mining raw materials, through to battery use (chemical/metal leaching, issues associated with fire	See Section 1.

	are likely to proliferate in the near future.	fighting foams) to re-use and recycling (link to circular economy). Water-based batteries may pose less environmental risk.	

Future science needs

There is a wide range of potential environment impacts that should be considered as these new technologies are developed.

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5. Hydrogen production

Background

Hydrogen can be burned as a fuel for transport (vehicles, shipping and aviation), used in industrial processes such as refining and power generation (heat and electricity). The process primarily produces water and fewer particulates compared to fossil fuels, although as with combustion of other fuels, nitrogen oxides are also produced, with subsequent impacts on air quality. This has led to the assertion that hydrogen is “one of the greenest forms of energy that we have” [3]. Hydrogen can also be reacted with oxygen in a fuel cell to produce electricity. In the UK, over 20 commercial hydrogen production plants have been proposed, most of which will be located within the industrial clusters (Teesside, Humberside and Merseyside). In addition to having the advantage of being a “clean” fuel, hydrogen is also valued due to its potential to decarbonise industrial processes and other areas such as shipping and aviation (which are seen as difficult to decarbonise). Production or output can also be increased or decreased with little notice, such as to compensate for fluctuations in the supply of renewable energy. Hydrogen transportation and storage is covered in Section 6 below.

Environmental and public health impacts

There are a number of different types of hydrogen production techniques, which are typically categorised by colour based on their production method. Blue hydrogen (produced from steam methane reforming of natural gas with CCS) is the most mature low carbon technology, although green hydrogen (from splitting of water using electrolysis powered by renewable electricity) is also well-developed. However, green hydrogen costs are at least double that of blue hydrogen at present [7]. Pink and turquoise hydrogen production methods are at earlier stages of development. An overview of their environmental impact and the potential management challenges for the different methods are outlined below. Leakage of hydrogen throughout its lifecycle (from production through to use) is of concern not only due to its high flammability, but also because it indirectly extends the atmospheric lifetime of methane, a greenhouse gas. There are several other methods of hydrogen production in development, many of which could contribute to a circular economy. These include hydrogen production from photo-pyrolysis of organic waste and hydrogen-rich gas from urine [2], [5].

Technology	Notes	Environmental Issues	Management challenges
Blue hydrogen	From natural gas with CCS via. steam methane reforming. Expected to bridge the gap to green hydrogen.	Nitramines and nitrosamines breakdown products-these are potentially carcinogenic, mutagenic and toxic [4], [6]. Water requirements (up to 24L/kg of hydrogen; [1]).	Chemical emissions to air and water Water abstraction
Green hydrogen	Electrolysis of water – ‘green’ when powered by renewable electricity. Uses solid oxide electolysers (large-scale) and alkaline electrolysers/polymer electrolyte membrane electrolysers (small-scale).	Water abstraction and water resources (cumulative impact of need for high purity deionised water; up to 30 L/kg of hydrogen). Potential to link with circular economy (e.g. use of industrial effluent). Land use change for renewable energy.	Chemical and heat emissions to water Water abstraction
Pink hydrogen	Electrolysis: Uses advanced nuclear reactors and large-scale hydrogen fuel cells to split water molecules and extract the hydrogen using electrolysis. Use of waste heat is being explored to increase the efficiency of solid oxide electrolysers. Thermochemical: requires high operational temperatures (e.g. > 500 °C) that can only be achieved using advanced nuclear	Impact of uranium mining (in other countries). Water abstraction, temperature of water discharges. Use of waste heat from nuclear plant to increase electrolysis temperature can increase efficiency.	Environmental management of nuclear-powered processes including emissions, wastes, and cooling. Water abstraction.

	technologies (e.g. high temperature gas reactors, molten salt fast reactors). This method is not available with current nuclear power plants.		
Turquoise hydrogen	Thermal decomposition of natural gas. For example, methane pyrolysis or cracking to produce black carbon, from which the carbon can be sequestered.	Safe disposal of black carbon. Alternatively, black carbon can be sold (circular economy).	Management of black carbon residues.

Future science needs

The production method for hydrogen is likely to have different environmental impacts and require different management processes, which will need to be identified and considered as new plants are commissioned. There is also a potential for cumulative impacts where installations are likely to be co-located.

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6. Hydrogen storage

Background

Hydrogen for fuel and industry has been stored underground in salt caverns for decades, including in Teesside since the 1970s. However, the anticipated scale-up of hydrogen production (10 GW by 2030, with at least half of this coming from ‘green’ hydrogen; [2], compared to 10-27 TWh produced at present, mostly from ‘grey’ hydrogen for use in the petrochemical sector; [1]) means that the numbers of such storage facilities could increase. The scale and pace of storage developments is a key management consideration. Research is currently focused on improving the safety and cost-effectiveness of various storage methods, rather than on environmental impacts.

Environmental and public health impacts

An overview of the potential environmental impact of different storage technologies and the challenges in their management are outlined in the table. An emerging issue is hydrogen leakage from production through to use [6]. Fugitive hydrogen could indirectly extend the lifetime of methane in the atmosphere [3], negating some of the “clean” benefits of hydrogen.

Technology	Notes	Environmental Issues	Environment Agency Interest
Transport to storage site (e.g. tankers, pipelines)	Pipelines considered most feasible. Studies are ongoing to understand effect of hydrogen on existing pipework systems. Transport may take place close to existing or new infrastructure.	Potential for accidents resulting in ignition/explosion. Fugitive emissions of hydrogen. Habitat/biodiversity disturbance due to construction of storage sites or pipelines.	Fire and explosion resulting from major site incidents. Emissions to air including hydrogen leakage.
Aboveground storage	Short-term storage in new or existing gas infrastructure. This could include pipelines and storage tanks. Could be stored as compressed gaseous hydrogen or cryogenic liquid hydrogen. Also includes hydrogen fuel cells.	Liquefaction has high energy requirements. New developments including storage would likely be large facilities to ensure supply. Such developments may impact local biodiversity and reduce available land.	See hydrogen transport above. Wastes generated by fuel cells.

Underground hydrogen storage	Salt caverns can store hydrogen over short-to-medium timescales (interseasonally; Heinemann et al., 2018). Space created by pumping water through salt, which produces brine. Porous formations such as former onshore oil and gas wells (depleted hydrocarbon reservoirs) may also be used.	Leakage in production, transport, during transfer into/out of the storage facility. Potential for impact on groundwater needs to be addressed during cavern/storage design. Reservoir instability. High water demand for cavern creation (~14m^3 per m^3 cavern; typical cavern = 300,000 m^3). High salt content of brine produced during cavern creation- need clear guidance on brine disposal or use (circular economy). Interactions with microorganisms or host rock and subsequent effects on nutrient cycles. Production of methane and hydrogen sulphide gas. Dust/particulates from cavern creation/drilling.	See hydrogen transport above and also CAES in Section 4.
Ammonia	Ammonia can be used as a hydrogen storage medium but is also an energy source itself. Easier and cheaper to transport/store than pure hydrogen.	Impact of nitrogen on habitats and biodiversity loss, if leaked. Human health impacts. Ammonia gas can mix with other gases to form particulate matter.	Emissions to air and water of ammonia and other chemicals.
Solid hydrogen storage systems	Could involve adsorbents, metal hydrides or chemicals, all of which would have different energy requirements for converting to and from a solid. Current work is on absorption using metal hydrides and adsorption using metal organic frameworks.	Sourcing of raw materials (e.g. manganese, magnesium) and associated environmental impacts (water use, leaching).	Management of wastes produced

Future science needs

Transport and storage of hydrogen presents new challenges, particularly in terms of hydrogen leakage (locations, magnitudes and monitoring techniques). There is also a potential for cumulative impacts where installations are likely to be co-located.

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