Net zero technologies: environment impact summaries

Chief Scientist's Group report

May 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 This a fast-moving topic area and inevitably information is likely to go out of date, so these are a summary of information available at time of writing.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 and how the Environment Agency may need to regulate such impacts. 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. Batteries are considered hazardous waste due to containing heavy metals and corrosive solutions and the handling of their disposal must follow the UK's hazardous waste regulations [4]. Many mining and disposal facilities will require permitting under the Environmental Permitting Regulations (EPRs) and may fall under Control of Major Accident Hazards (COMAH) if, for example, thermal runaway occurs.

Technology	Notes	Environmental Issues	Environment Agency Interest
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.	**EPR** battery disposal (metal contamination from landfill e.g., cobalt, nickel, manganese-dependent on ion type). **EPR** air quality and soil contamination impacts from mining. **EIA** needed to assess impacts on local biodiversity due to mining. **COMAH** chemical fires in shipping, landfills and disposal sites [14]. Lithium is a combustible metal and requires class D fire extinguishing solution (sodium chloride base).
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 **EPR**s and **EIA** for lithium-ion.
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 ore [7]. Nickel mining releases sulphur dioxide [10]. Likely offshoring of pollution.	See **EPR**s and **EIA** for lithium-ion.

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 **EPR** and **COMAH** for lithium-ion. Need for alkaline battery recycling to be more accessible.
Sodium-ion	Potential competitor for Li-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.	**EPR** air quality and soil contamination impacts from mining. **EIA** needed to assess impacts on local biodiversity due to mining if salt is sourced within the UK.
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 electrolyte solution (mostly sulphuric acid). Electrodes	Vanadium mining. Toxicity of sulphuric acid. Fossil fuel necessary for electrode oil-based polymer. Likely offshoring of pollution.	**COMAH** chemical fires in shipping, landfills and disposal sites (although sulphuric acid is not flammable itself, it is a strong oxidizing agent which can lead to the combustion of surrounding materials). See **EPR**s and **EIA** for lithium-ion.

	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 **EPR**s and **EIA** for lithium-ion.

Better science and regulation

Various electrochemical battery compositions are being evaluated under our Net Zero work. 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]. With natural resources, labour laws and environmental regulations varying between countries, the sourcing of battery materials outside of the UK leads to the discussion of offshoring pollution and ethical issues surrounding workers' rights. Regarding electrochemical battery regulations, the Environment Agency would be responsible for EPRs pertaining to any air, water or soil contamination associated with mining and battery disposal as well as COMAH for 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 affect the surrounding ecosystem. 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 piping installation, with potential for local biodiversity disturbance. Some facilities will require licensing (abstraction and transfer licences and Groundwater Investigation Consents) under the Water Resources Act and permitting under the Environmental Permitting Regulations (EPR) and may also fall under Control of Major Accident Hazards (COMAH) if, for example, there is a risk of chemical leakage. Major hazards would be jointly regulated with the Health and Safety Executive.

Technology	Notes	Environmental Issues	Environment Agency Interest
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.	**EPR** for water disposal (especially if contaminated). **EIA** for impacts of salt mining within aquatic ecosystems. **COMAH** if molten salt was accidentally released. **Water Resources Act, Groundwater Investigation Consents ((GICs) which are the pre-application stage) for** water abstraction licences and water resource licences for abstractions > 20 m3/day.
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.	**EIA**s if installing underground pipe system. Life cycle analysis for sand (e.g. from extraction through to use/disposal, or reuse from construction industry).
Phase Change Materials (PCM)	Directly integrated into building materials and infrastructure, most often to retain solar energy. Can be made	Paraffin wax PCM apparatus are derived from crude oil. Fatty acid PCM apparatuses can contain palm oil.	**EPR** standard rules permits with pollution prevention conditions have a potential role if using PCM batteries

(Latent Heat Storage)	of organics (paraffin, fatty acid), inorganics (salt hydrate, metal alloys), eutectics (organic/inorganic mixture) [4]. Low thermal conductivity of most effective PCMs limits thermal energy storage efficiency [5].		made with inorganic substances (e.g., salt hydrate and metal alloys) as salt and metal mining can be involved.
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)	**EIAs** for planning regime and **HRAs** for licensing and permitting regime (soil and water contamination) If open loop systems **Water Resources Act, Groundwater Investigation Consents ((GICs)** which are the pre-application stage) for water abstraction licences and water resource licences for abstractions > 20 m3/day. **EPR** – environmental permit for a water discharge activity or a groundwater activity, heat and chemical pollution. Flood risk activity permit. **COMAH** for H_2S leakage, toxic by inhalation. No environmental assessment levels for CH_4 or H_2S but hydrogen sulphide affects human health at as low as 2.8 mg/m^3 [6].

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)	**EPR** and **Integrated Environmental Permit** for battery disposal for thermophotovoltaic cell. **COMAH** if molten silicon was accidentally released.
Aquifer thermal energy storage (ATES) / Borehole thermal energy storage (BTES)	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 in aquifers in winter. BTES, closed loop (using heat transfer fluids) systems. Can use heat pumps to concentrate heat.	Temperature changes in groundwater, possible impacts on geochemistry and groundwater ecology, and potential impacts on nearby wetlands, springs, surface water 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.	**EIAs for planning regime and HRA**s for licensing and permitting regime (soil and water contamination) **EPR** – environmental permit for a water discharge activity or a groundwater activity (if open loop system), heat and chemical pollution, future closed loop regulation. **Water Resources Act, Groundwater Investigation Consents ((GICs) which are the pre-application stage) for** water abstraction licences and water resource licences for abstractions > 20 m3/day.

Better science and regulation

Alternative energy storage technologies are being considered under the Net Zero work in the Chief Scientist's Group. 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. The Environment Agency could have a role in understanding the impact of infrastructure such as underground pipe networks or the installation of silos as well as permitting releases to air, water or soil. COMAH assessments would apply to the use of any 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, see Environment Agency, 2022). 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. Standalone DACC plants are not classed as an ‘installation’ so would not be permitted under EPR. DACC facilities may fall under Control of Major Accident Hazards (COMAH) if, for example, chemical leakage occurs. Major accidents would be regulated in conjunction with the Health and Safety Executive.

Technology	Notes	Environmental Issues	Environment Agency Interest
Solvent-based (liquid DACC) (TRL = 6*)	Aqueous basic solution (e.g. potassium hydroxide). Releases CO2 through several units operating at high temperature (300-900°C).	High temperature requirement means it is difficult to power by 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.	Potential COMAH implications. Water abstraction and quality.
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.	Potential COMAH implications
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”. We do not have Environmental Assessment Levels for these. Land use.	Potential COMAH implications
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.	Potential COMAH implications

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	Potential COMAH implications

*TRL=Technological Readiness Level; these have been sourced from Gambhir & Tavoni (2019), IEA (2022a) and IEA (2022b)

Better science and regulation

DACCS technologies are being considered under the Net Zero work within the Chief Scientist’s Group. We aim to consider the environmental impacts associated with different DACCS technologies, as well as the cumulative impact of Net Zero technologies (including DACCS) which may be clustered in particular areas. As DACCS is currently at a relatively low technological readiness level (compared to other carbon capture and storage techniques), current work will improve foresight of potential future environmental impacts, increase understanding of any future regulatory requirements and encourage externally conducted research and development of the technologies to consider the environment earlier in project design. It will provide insight for permitting teams to aid permit applications as and when those applications start to be submitted.

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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 (MacLean, 2021; MacLean et al., 2021). It is expected that the government will release a policy on longer duration energy storage by the end of 2024. 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 we have used lithium-ion batteries for some time and have procedures in place for leaks, fires and safe disposal, the scale-up of BESS facilities and the overall prevalence of batteries is likely to change the importance and nature of environmental risks associated with these technologies. An overview of energy storage technologies, their potential environmental impact and the Environment Agency's role is 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. Some storage facilities will require permitting under the Environmental Permitting Regulations (EPRs) and may fall under Control of Major Accident Hazards (COMAH) if, for example, chemical leakage occurs. However, this will depend on the nature and characteristics of a particular facility and will likely only apply if a substance is being transferred from the environment to the facility or discharged from the facility into the environment.

Technology	Notes	Environmental Issues	Environment Agency Interest

CAES	Converts electricity into mechanical energy (pressure), which can then be converted back to electricity by powering a turbine. Compressed air is often stored underground in a salt cavern.	Capturing and storing waste heat can improve their efficiency (circular economy). Reservoir instability. Water consumed 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 the reservoir. Air quality and pollutant emissions from burning natural gas to power the turbine (CH_4, SO_2, NO_x, particulates, CO).	COMAH- explosion risk. EPRs for emissions (e.g. air quality monitoring), waste disposal (brine) and water abstraction. Water abstraction licence (Water Resources Act 1991) for cavern creation.
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.	Potential MCerts (standards) or EPR to monitor chemical emissions to groundwater. Potential COMAH impacts.
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).	MCerts (standards) to monitor chemicals/ pollutants moving into the environment.

BESS	Lithium-ion is currently the most developed composition and is widely used. Other battery compositions are likely to proliferate in the near future.	Impact depends on composition. Impact from mining raw materials, through to battery use (chemical/metal leaching, issues associated with fire fighting foams) to re-use and recycling (link to circular economy). Water-based batteries may pose less environmental risk.	Water abstraction licence (Water Resources Act 1991). Waste permits. EPR/MCerts to monitor chemicals/ pollutants moving into the environment.

Better science and regulation

The potential environmental impacts of the differing energy storage technologies are being considered under our Net Zero work within the Chief Scientist's Group. We will work closely with RI and permitting colleagues to develop the underpinning evidence to assess and manage new energy storage facilities. We will also encourage researchers to consider environmental implications at an earlier stage of the technology development. Finally, we will work closely with other relevant bodies, such as the Coal Authority and the Health and Safety Executive to regulate these storage facilities.

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5. Hydrogen production

Background

Hydrogen can be burned as a fuel for transport (vehicles, shipping and aviation), for industrial processes such as refining, for operation of hydrogen boilers and for electricity production. The process primarily produces water and few particulates compared to fossil fuels, although small quantities of 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" (BEIS, 2022). Hydrogen can also be reacted with oxygen in a fuel cell to produce electricity. While the Environment Agency has already permitted over 20 hydrogen production plants, there are almost double this in the pre-application stage and with expected permit applications, 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 with little notice, such as when renewable energy production falls. Hydrogen transportation and storage is covered in Section 6 below.

Environmental and public health impacts

There are a number of different types of hydrogen, which are 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, just not currently considered cost-effective (green hydrogen costs are at least double that of blue hydrogen at present; Milani et al., 2020). Pink and turquoise hydrogen are at earlier stages of development. An overview of their environmental impact and the Environment Agency interest is outlined below. Many hydrogen production facilities will require permitting under the Environmental Permitting Regulations (EPRs) and may fall under Control of Major Accident Hazards (COMAH) if, for example, leakage occurs. Major accidents would be regulated in conjunction with the Health and Safety Executive. Leakage of hydrogen throughout its lifecycle (from production through to use) is of concern due to its explosive nature but also its ability to indirectly extend the atmospheric lifetime of methane. There are several other methods of hydrogen production in development, many of which would contribute to a circular economy. These include hydrogen production from photo-pyrolysis of organic waste (Limb, 2022) and hydrogen-rich gas from urine (Atchison, 2022). The wider environmental impacts of the most developed clean hydrogen production methods are summarised below. We have excluded grey and brown hydrogen, which are not low carbon.

Technology	Notes	Environmental Issues	Environment Agency Interest
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 (Buist et al., 2015; Mazari et al., 2019). Water requirements (up to 24L/kg of hydrogen, Ajanovic et al., 2022).	Water resources for CCS, thermal pollution. Development of EALs for amine-based compounds. EPR for new facilities.
Green hydrogen	Electrolysis 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.	Water resources-abstraction requirements, water discharge, thermal pollution. EPR for new facilities.
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	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.	Understanding of where existing nuclear regulations can be applied. Water resources-abstraction and thermal pollution.

	advanced nuclear 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).	Waste permitting for black carbon.

Better science and regulation

The potential environmental impacts of switching to a hydrogen economy are being considered as part of our Net Zero work. Each colour of hydrogen will have different environmental impacts, and therefore different regulatory requirements, which will need to be identified in advance of permit applications. We will work with permitting colleagues and regulated industry to ensure that potential environmental issues are understood and that installations consider all aspects of the environment, particularly in industrial clusters where there is greater potential for cumulative impacts.

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6. Hydrogen storage

Background

Hydrogen for fuel and industry (e.g. for fertiliser production or drink carbonation) has been stored underground in salt caverns for decades, including in Teesside since the 1970s. Hydrogen storage is currently regulated by the Environment Agency through Environmental Permitting Regulations and COMAH. However, the anticipated scale-up of hydrogen production (10 GW by 2030, with at least half of this coming from 'green' hydrogen; BEIS, 2022a, compared to 10-27 Twh produced at present, mostly from 'grey' hydrogen for use in the petrochemical sector; BEIS, 2021) means that the cumulative environmental risk posed by such storage facilities could increase. The scale and pace of change is a key issue. 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 is outlined in the table. Many facilities will require permitting under the Environmental Permitting Regulations (EPRs) and may fall under Control of Major Accident Hazards (COMAH) if, for example, leakage occurs. An emerging issue is hydrogen leakage from production through to use (see Warwick et al. 2022). Fugitive hydrogen could indirectly extend the lifetime of methane in the atmosphere (BEIS, 2022b), negating some of the "clean" benefits of hydrogen. Additional atmospheric methane will contribute to more frequent episodes of photochemical pollution, with subsequent impacts on human and ecosystem health (e.g. Sher, 1998).

Technology	Notes	Environmental Issues	Environment Agency Interest
Transport to storage site (e.g. tankers, pipelines)	Pipelines considered most feasible, but questions remain regarding pipe embrittlement due to the corrosive nature of hydrogen. Transport may take place close to existing or new infrastructure.	Potential for accidental ignition/explosion. Fugitive emissions. Accidents could lead to H_2 releases. Human health/ societal impacts caused by odours (hydrogen suphide emissions), toxicity, ignition/ explosions. Habitat/biodiversity disturbance due to construction of storage sites or pipelines.	COMAH and Pipeline Safety Regulations
Aboveground storage	Short-term storage in new or existing gas	Liquefaction has high energy requirements.	COMAH. EPR monitoring

	infrastructure. This could include pipelines and storage tanks. Could be stored as compressed gaseous hydrogen or cryogenic liquid hydrogen. Also includes hydrogen fuel cells.	Storage tanks would likely be heavy/large to ensure supply, which could affect biodiversity and demand for land.	requirements (e.g. waste licensing for 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, pumping into/out of the storage facility or at the point of use. Reservoir instability. Water consumed 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 suphide gas. Dust/particulates from cavern creation/drilling.	EPRs apply to waste (e.g. brine) and emissions (incl. warmed water). Water abstraction licence (Water Resources Act 1991). Hydrogen leakage falls under COMAH.
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. Methane is another storage medium.	Impact of nitrogen on habitats and biodiversity loss, if leaked. Human health impacts. Ammonia gas can mix with other gases to form particulate matter.	EPRs apply to emissions. MCerts to monitor ammonia in the environment.
Solid hydrogen	Could involve adsorbents, metal hydrides or chemicals,	Sourcing of raw materials (e.g. manganese, magnesium) and	EPR for waste disposal (depends

storage systems	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.	associated environmental impacts (water use, leaching). Potential for dense gas risk to local areas.	on material used and lifetime).

Better science and regulation

The potential environmental impacts of switching to a hydrogen economy are being considered as part of our Net Zero research work. There will be evidence requirements with regards to transport and storage of hydrogen, particularly in terms of hydrogen leakage (locations, magnitudes and monitoring techniques). We will work with permitting colleagues and regulated industry to ensure that potential environmental issues are understood and that installations consider all aspects of the environment, particularly in industrial clusters where there is greater potential for cumulative impacts.

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