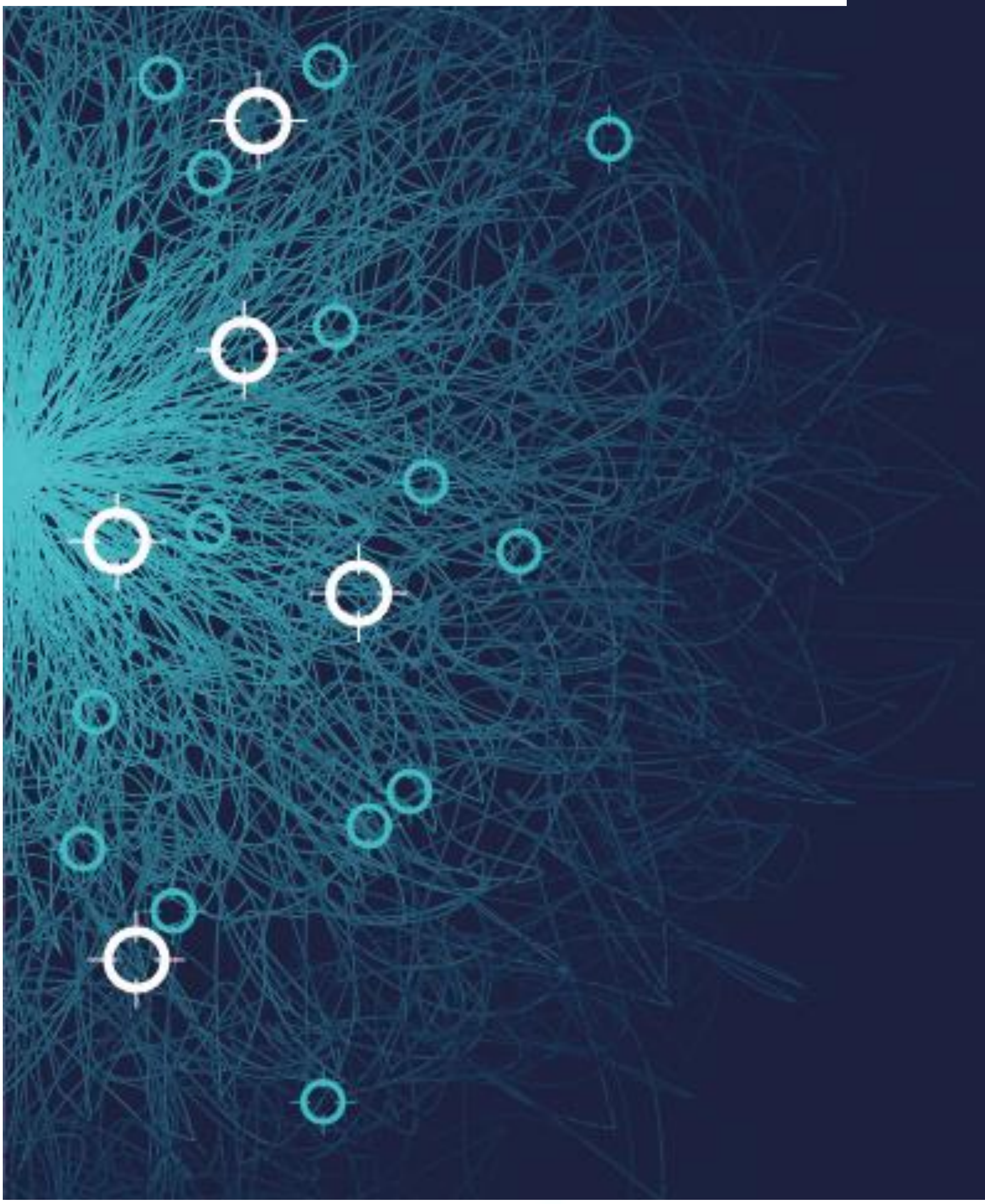
Technology Prioritisation

A NECCUS / OGTC report for the
Scottish Net Zero Roadmap



Technology Prioritisation & Phase #2 Plan

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Overview

This section of the report outlines and prioritises key technologies for the Scottish Net Zero Roadmap (SNZR) as determined from industry and stakeholder engagement activities; UKCS, European and Global publication; industrial insight and technology development and projections. In addition, the plan for Phase #2 is outlined, with key WP3 accountabilities and responsibilities.

Methodology

For deliverables T3.1, T3.2 & T3.3 shown below, OGTC developed an initial technology framing report, outlining technology focus areas, relevant to Scotland, across Hydrogen Generation, Carbon Capture Utilisation and Storage (CCUS), Decarbonisation (optimisation) and Renewables Integration. In addition to this, OGTC outlined an initial scale and cost analysis of technologies. Existing, at scale, technologies have been reviewed to demonstrate where there can be expected to be similar cost reduction pathways when scaling Net Zero technologies from First of a Kind (FOAK) to Nth of Kind (NOAK).

- T3.1 Identify/define potentially attractive technologies
- T3.2 Assessment of the relevance of key technologies to Scotland
- T3.3 Review potential scale and costs of key technologies

For this section, expanding on feedback from stakeholder engagement interviews and the workshop seminars, the OGTC have now compiled a full screening process for the 4 areas of focus; Electrification, CCUS, Hydrogen and Fuel Switching. These 4 areas have been expanded on to deliver a review of all technologies in each section outlining technologies, descriptions, Technology Readiness Level's (TRL's), advantages and disadvantages as well as cost reduction pathway estimations from FOAK to NOAK where applicable. For the full list of technologies please refer to Appendices.

For the benefit of this report and the stakeholders, the screening list has been analysed and summarised to show and highlight the key technologies for the SNZR moving forward outlining the challenges and technology that's required moving into phase #2.

Stakeholder Engagement

Stakeholder and industry engagement, conducted by Optimat during Phase 1 of this project , revealed some interesting insights into technology requirements moving forward and while much of the feedback gained from this engagement was generally high level and didn't specifically challenge technical pain points of the industry, it did corroborate the initial thoughts of the OGTC with regards to technology focus areas moving forward.

Through the engagement process 20 organisations were interviewed, with a total of 35 stakeholders across multiple organisations; manufacturing, oil & gas operators and supply chain, energy sector, infrastructure, technology providers, public agencies, research community & academia. Through this exercise, Optimat compiled a SWOT analysis that generated the following technological insights (see Figure 1):

Figure 1 - Technology SWOT Analysis

While much of the conversation centred around regulatory and fiscal policy change requirements, it was clear that CCUS and Hydrogen were areas of strategic importance from a technical standpoint. While there are no guidelines/policy/framework on the adoption of CCUS technologies in industry, coupled with a high price for existing technologies, there is a lack of incentive for industry to adopt such solutions and it is generally unclear what solutions there are. In addition, a key consideration was the market for CO_2 captured. Whilst the industry understands the importance of CO_2 storage through the likes of Acorn project, is there likely to be a market for the potential sale of CO_2 to other industries remains to be seen.

Further to CCUS, the engagement sessions highlighted the importance of fuel switching as a net zero-technique, i.e. the use of low/zero carbon fuels such as Hydrogen for direct replacement in Natural Gas burning processes. However, some points to consider include if the relevant technology exists already. And, if it doesn't, when is it likely to be available?

Technology Analysis

Screening Criteria

For the screening of technologies applicable to the 4 areas of focus, the OGTC have utilised Microsoft Excel as a simple tracking tool. The 4 focus categories were condensed to 3 given fuel switching and hydrogen are related; Electrification (including plant optimisation), Hydrogen & Carbon Capture Utilisation and Storage.

From here, each section was split into defining categories or subsections (for example Hydrogen Storage, Hydrogen production and Hydrogen usage). In turn, each sub section was also broken down into relevant technologies, some of which were highlighted in our conversations with industry and explored to determine feasibility to the roadmap.

As a next step, comprehensive technology lists were reviewed and explored to give an understanding and, in some cases, an estimation of current Technology Readiness Level (TRL) using publicly available case studies and publications, where applicable. In addition to TRLs, each technology showcases advantages and disadvantages. Where possible, cost estimations have also been included, continuing from work compiled in T3.3 'Review potential scale and costs of key technologies' although a comprehensive review including cost base, strengths and weaknesses, installation timelines and challenges will be expanded upon in Phase #2. The initial high-level screening of net zero technologies, coupled with deployment scale, cost analysis and interview feedback has led to an understanding of the critical technologies considered for Phase #2.

Electrification

The screening of electrification technologies (see Appendix A) was separated into; process/plant optimisation, connection to grid, renewables integration and storage.

Optimisation

Plant optimisation refers to the quick wins, process efficiency optimisation techniques and short-term measures that can be implemented in the immediate future to reduce emissions of assets. Aimed at the offshore upstream oil and gas industry, OGUK has recently outlined its new targets for net zero, that around 10% of emission reduction can be achieved by operating more efficiently. There are a number of processes to consider, from methane detection, flaring reduction, digitalisation, process heat recovery and unmanned operations. Many of these processes are site specific and cannot be wholly understood for this analysis. Industry collaboration can lead to the adoption and realisation of these small-scale reduction measures. In parallel, the OGTC has recently prepared a solutions document, aimed at the oil and gas industry, that outlines the technologies, categorised in short, medium- and long-term solutions that can help decarbonise assets. Repeated across the onshore and downstream sectors, this could unlock the path to reducing the first 10% reduction in emissions through quick wins.

Grid Integration

Technically, the feasibility for electrification through connection to the Grid and renewables integration is understood. Grid integration of offshore and onshore wind assets have been in development for decades, with onshore wind being surpassed by offshore wind and the market for floating wind expected to do the same. Many solutions for Grid connection exist although not without challenges, the business case for electrification for a cluster (or) individual assets depends on a number of conditional factors such as existing infrastructure, location, age and condition of equipment and processes as well as the cost of changing to an all-electric based system.

As a result, generally speaking, new assets and locations will consider all electric solutions with the Brownfield (BF) market perhaps more inclined to adopt a partial electrification solution, especially since the solution may only be viable if the costs (or) financial incentives are balanced against the fuel saving/CO_2

emissions and production downtime as a result of modifications. Electrifying a cluster of companies or industries may significantly reduce capital costs whilst also allowing for use of a large source of available energy (i.e. renewable sources).

Renewables Integration

The integration of renewables, although comprising of technologies which are fully commercialised, presents new hurdles with regards to capital intensive costs of cabling, substation and BF modifications as outlined above. The reduction of costs in High Voltage Alternating Current (HVAC) cabling, for use over short distances, has allowed for the electrification of offshore assets in areas such as Norway. Given the development of offshore wind, both fixed and floating, it may be commercially feasible for a cluster development to invest in wind as a primary source of energy for electrification of the said cluster. This business concept gives rise to the possibility of owning (or) co-owning an energy generating system after the cluster has been decommissioned, allowing the sale of clean electricity to the grid. Furthermore, due to the fact that wind energy is intermittent, systems that require round-the-clock availability will need to consider a backup connection to the national grid (or) adopt battery storage as a back-up power source.

Storage

The screening of battery technologies (see Appendix A) has identified that several solutions are of a high TRL level, however, the caveat with embracing battery storage systems, is that generally the more developed solutions do not allow for the storage of power for a prolonged period of time. The use of Wind as a source of electricity would require batteries with capacity 10 MW-100 MW with shorter discharge durations (seconds to minutes) and energy storage in the minutes to hours (MWh to GWh) range[1]. Due to the rapid increase of use in areas such as electric car manufacturing, lithium-ion batteries have been a preferred option for battery storage, however new solutions are beginning to emerge such as iron phosphate (LFP), nickel manganese cobalt oxide (NMC) and flow batteries such as vanadium redox or zinc bromine. These alternatives, although in early TRL stages, could offer solutions to longer term and higher capacity storage (see Figure 2).

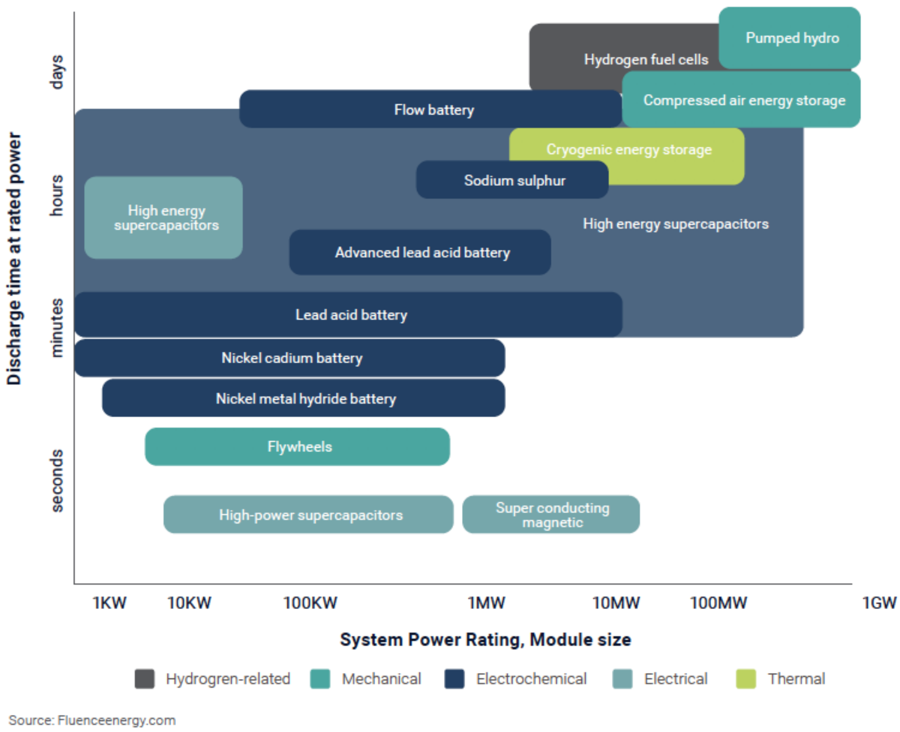

Figure 2 - Power Storage Technologies

[1] Wood Mackenzie, UKCS Net Zero Technology Landscaping, June 2020

Based on initial investigations and screening, it is recommended that sites first consider process and plant efficiency and optimisation projects to impact the first portion of emissions reduction measures. Given the capital investment requirements for backup energy storage requirements, partial or full electrification through grid connection transmission infrastructure (incl. HV stations) can be considered with long term focus on renewable integration when the price of battery storage and offshore floating wind reduced through largescale adoption in Scotland. In support of the Electrification of both onshore and offshore assets to meet net-zero targets, OGTC commissioned a consultancy firm to detail the short- term to long-term strategies that can be deployed, which have been detailed below (see Fig 3).

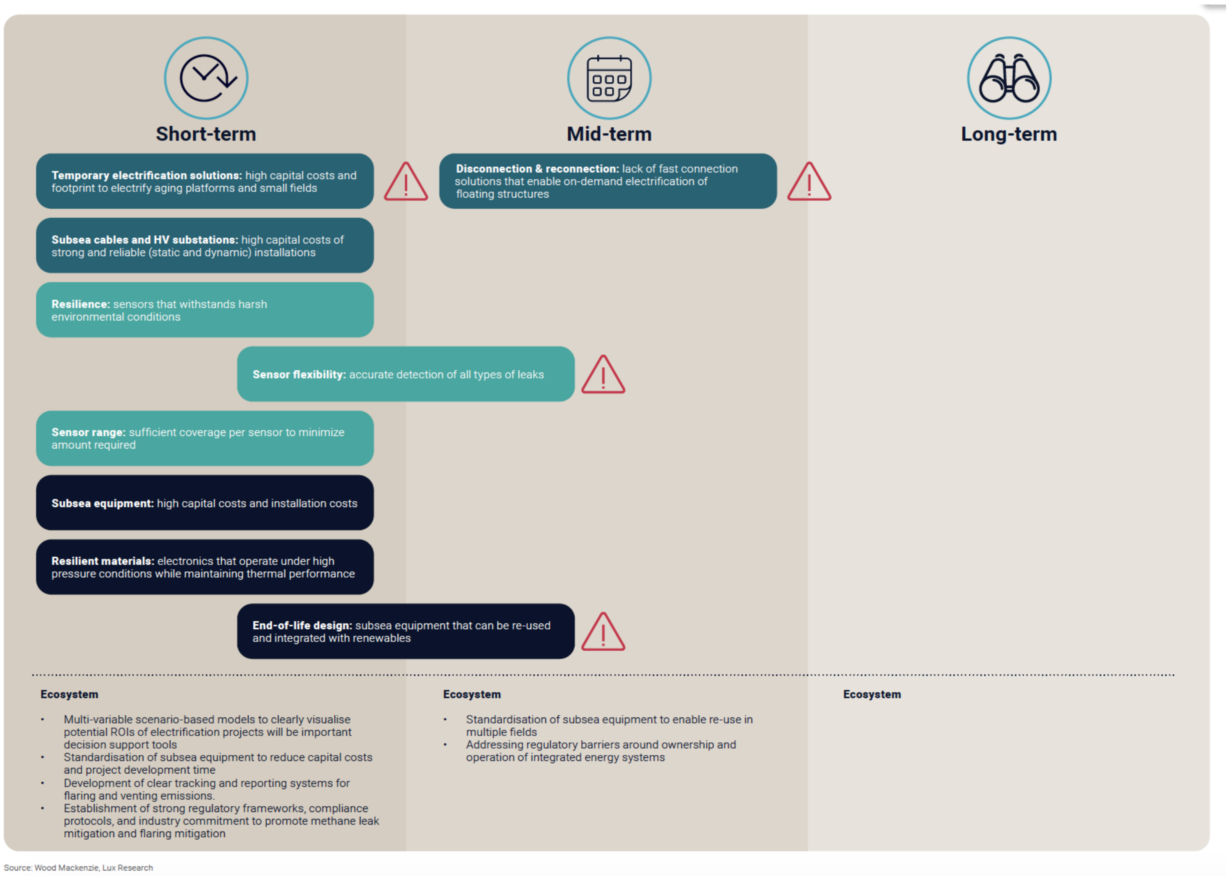

Figure 3 - Roadmap to 2050 – Electrification (source: WoodMac[1], Lux Research)

Hydrogen

The screening of Hydrogen technologies have been categorised into the following 3 subcategories; Hydrogen Generation, Hydrogen Storage and Hydrogen Use.

Concerns raised earlier with regards to Grid integration and the upgrades required for the National Grid infrastructure in order to receive tie-ins for the ongoing development of offshore wind (both fixed and floating) raises opportunities for wind developers to consider new options for both offshore and onshore wind sites. A feasible option, and one being considered for sites included in ScotWind, is the use of offshore wind sites to generate green hydrogen at scale. Utilisation of a pipeline to shore as opposed to costly cable, substation and grid integration costs has led to the possibility of making previously unfeasible wind site, financially appealing (given that the demand is there for the sale of Hydrogen to the onshore market). Given the projects for wind capacity here in the UK are expected to reach 75GW by 2050, it is expected that hydrogen production through wind may equal up to 44TWh (for pure hydrogen generation not used for electricity) requiring up to 7GW on electrolyser capacity[2]

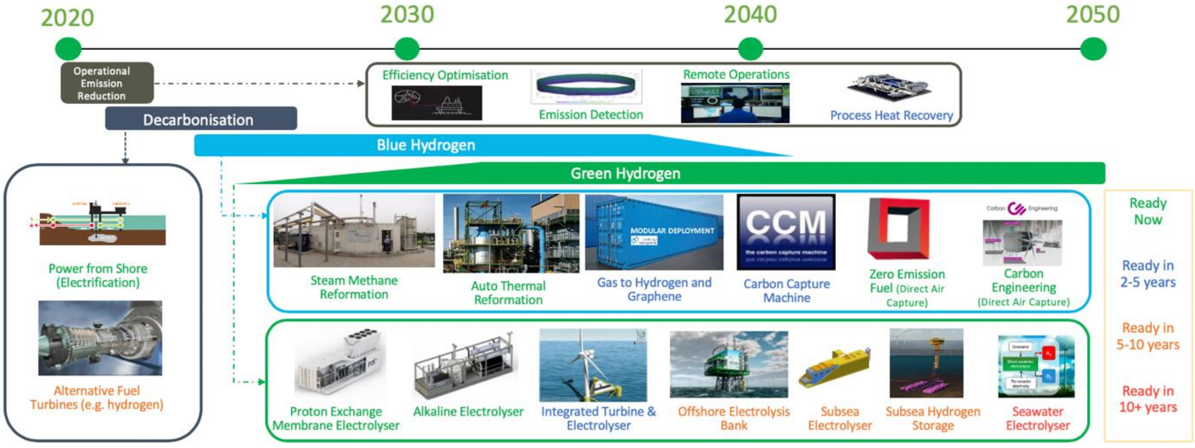

Figure 4 - OGTC Review of Hydrogen Technologies

Hydrogen Generation

As per figure 4 above, The OGTC has performed a preliminary review of hydrogen and electrification enabling technologies in the market towards 2050. It indicates the technologies ready now, in 2-5 years, 5-10 years and over 10 years. Even so, OGTC is working with developers of next generation technologies like the Seawater Electrolysers now, to rapidly develop this hydrogen generating solution that removes the requirement for desalination of seawater before use in an electrolyser. Technologies such as this will be deployable inside wind turbine towers removing the requirement for structures offshore.

The OGTC review of hydrogen technologies ties in with the technology roadmaps for the offshore industry towards 2050 too and the realisation that prior to largescale adoption of green hydrogen, will be the requirement for Blue Hydrogen deployment at scale utilising Steam methane Reformer (SMR) primarily as a source for Hydrogen generation. SMR is a commercialised solution to H_2 production, however, as is known, CCUS technology is still a high cost solution and is a critical requirement for blue Hydrogen through SMR. Appendix B reiterates the commercial readiness of alternatives to SMR.

Use

As described in Appendix B, hydrogen use has been separated into 4 areas; as a direct replacement in gas turbine generators for power, as described above where there are inherent risks with regards to metals becoming brittle due to exposure; blended hydrogen in power applications as well as in domestic gas systems, as is being trialled in a number of UK wide projects and finally in transportation applications such as hydrogen fuel cells in transportation and hydrogen shipping. It is important to ensure that while evaluating the approach for roll out of hydrogen-based technologies, as described in the 'methodology' section later, that the future demand and use of hydrogen is established. Hubs such as Grangemouth, Dundee and Aberdeen have the potential to become major distribution hubs for hydrogen used in the shipping industry which currently has its own roadmap in development. Although TRL levels are lower at the moment, it is expected that as technologies to enable hydrogen use in transportation, shipping and in domestic and industrial applications will establish Scotland as a potential hub for distribution.

Storage

For Hydrogen storage as can be seen in Figure 2, hydrogen storage has the potential to store significant portions of energy over a longer period of time. Our analysis of hydrogen storage technologies includes both physical (as a cryogenic liquid or gas) and material storage (where the Hydrogen is absorbed as

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[2] CCC Further Ambition Scenario - https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-Technical-report-CCC.pdf

ammonia or as a hydride). Figure 5 outlines critical technologies in development and outlines the TRLs of each. Of physical storage, generally required for transportation at scale, High Pressure Gaseous H_2 is a preferred option although transported as a gas means that a much higher volume unit is required (if considering shipping for instance). Cryogenic Liquid Hydrogen is an alternative although it is not without challenge given the processing requirements and the energy required to do so. Carbon Nanotubes is a concept in early development and offers a comparable much safer route to storage and transportation of H_2.

Material storage refers to the use of a carrier to store/transport and utilise Hydrogen with a number of technologies ready or in development. Ammonia is presently the most established technology in this field and can be utilised in shipping as fuel and also for combustion in power plants, however concerns over HSE risks with ammonia are developing the technologies to make ammonia usage safer to use. It is important to consider that ammonia production results in energy conversion losses and transportation costs are comparable to liquid hydrogen.

Physical	High pressure gaseous H2	Compressed gaseous hydrogen is currently the main stream for on-board storage. Maximum storage pressure varies from 35 to 70 MPa. Tanks of (aluminium liner and polymer liner made of carbon fibre- reinforced resin are in use due to their weight.	9	Simple, mature method. Cost-effective	Low volumetric density, humidification required
	Cryogenic liquid	Cryogenic hydrogen has a density nearly twice that of compressed hydrogen at 70 MPa. Liquid hydrogen is stored in specially insulated cryogenic tanks under pressure, which have provisions for cooling, heating, and venting.	8	Low pressure, high density	Complex compression double-step, high cost
	Adsorbed (Carbon nanotubes)	Single-walled carbon nanotubes are essentially a one-atom-thick layer of carbon rolled into a tube. All the carbon atoms are on the surface, allowing easy access for bonding. The carbon nanotubes offer safe storage because the hydrogen atoms are bonded to other atoms, rather than freely floating as a potentially explosive gas.	6	Moderate pressure and temperatures, material cost, high H2 capacity per weight %	Cryogenic temperatures and extremely high surface areas needed, not available commercially
Material	Absorbed (hydrides)	Materials suitable for hydrogen storage in solid-state have to meet specific requirements in order to be used for the development of hydrogen based technologies, in particular storage. The material has to retain its performances in terms of kinetics and total hydrogen capacity, even after cycling.	6	NTP conditions, yields high purity H2, moderate cost material.	Low gravimetric density, lifetime proportional to purity of stored H2
	Ammonia (NH3 as carrier)	Ammonia—one nitrogen atom bonded to three hydrogen atoms. Ammonia is of interest as a hydrogen storage and transport medium because it enables liquid-phase hydrogen storage under mild conditions.	9	Taps into existing supply chain, Can be used as shipping fuel or combusted in power plants. Approx. twice the energy density of other carriers in anhydrous form	Anhydrous ammonia is corrosive and forms lethal gas clouds if released. Cracking to release hydrogen is immature and trace ammonia can damage fuel cells
	Liquid Organic Hydrogen Carriers	Unsaturated organic compounds can store huge amounts of hydrogen. These Liquid Organic Hydrogen Carriers (LOHC) are hydrogenated for storage and dehydrogenated again when the energy/hydrogen is needed.	8	Can be stored and transported in existing liquid bulk assets. Safe to handle at room temperature	Requires large conversion plants at supply and demand locations. Dehydrogenation step is energy and time consuming. Depleted carrier must be shipped back to hydrogen production site
	Absorbed (complex hydrides)	Complex hydrides are inorganic materials that are best described as salts, which are built from complex anions containing hydrogen as terminal ligand, such as the BH4– (tetrahydroborate or borohydride) or AlH4– (alanate) anions and counteractions from many different groups in the periodic table	5	Moderate pressure and temperatures, high volumetric density, low safety issues.	Thermal management, hydride recycling

Figure 5 - Physical & Material Hydrogen transportation/ storage

In addition to the above applications, is the ability to store hydrogen, at scale, in underground natural structures (salt caverns) or depleted oil and gas reservoirs, as is being adopted in CCUS projects, globally. Like CCUS in the UK, there is extensive infrastructure both onshore and offshore that could accommodate hydrogen transportation and storage. The UKCS offshore oil and gas industry has the expertise in topside modification, subsea control systems, well access and injection system capability in addition to vast analysis and screening of offshore sites for CO_2 storage that could be reused for Hydrogen applications. Hydrogen storage in the UK, however, has not yet been realised and it is not wholly known if depleted reservoirs offshore have the capacity for hydrogen storage given the concerns of seepage of H_2 through porous rock formations that would otherwise keep natural gas contained.

CCUS

For technologies relating to CCUS, for our screening, we have categorised commercialised and emerging technologies into 4 areas of focus; Capture Technology, Transportation, Use & Storage.

While the initial stakeholder consultations, as well as the concluding workshop session, indicated a requirement to review CCUS topics in general, it didn't however distinguish highlighted gaps in technology or a particular focus area. Therefore, as is shown in Appendix C, our review of CCUS technologies covers all types of capture available technologies including, post combustion capture (the most widely adopted at present), Post-conversion Capture, pre-conversion capture, BECCS and a further 8 technologies (please note that more may exist and will be elaborated on into Phase #2).

Capture

In our initial screening delivered in T3.1, we outlined that 'In addition to flue gas capture, both Pre-combustion capture (Solid or liquid fuels are first reformed or gasified, yielding a combination of hydrogen and CO2) and Oxy-combustion capture (Solid or liquid fuel is combusted using a pure oxygen stream instead of air, yielding a near-pure stream of CO2 and water which can easily be separated) have also been trialled for capturing CO2'. For our screening process leading to Phase #2, we have expanded on this to deliver a range of different techniques seen across the industry which include:

Technology	Technology Definition
Post-conversion Capture	Low-pressure flue gases undergo sorbent treatment for CO_2 selective removal.
Pre-conversion Capture	CO_2 can be removed from syngas (mix of H_2, CO and CO_2) from fossil fuels and biomass. Syngas can be shifted to H_2 while converting CO to CO_2.
Oxy-fuel Combustion	Pure O_2 used in combustion processes to yield flue gas with high CO2 concentration (O_2 separation from air is an energy intensive process)
Post Combustion Ionic Liquids	Ionic liquids (ILs) and "reversible" ionic liquids (RevILs) have been touted as alternatives to aqueous amine solutions for post-combustion CO_2 capture.
BECCS Power	BECCS is the process of extracting energy from biomass and capturing and storing the carbon using any mentioned CCUS technology. Biomass is processed through combustion, fermentation, pyrolysis, etc. and given that CO_2 is captured, it is a carbon negative process
Membranes - Dense Inorganic	Dense inorganic membranes are referred to those membranes made of a polycrystalline ceramic or metal, which allows certain gas species to permeate through its crystal lattice
Membranes - Polymeric	Porous and polymeric membranes have a thin layer of semi-permeable material that is used for solute separation as transmembrane pressure is applied across the membrane.
Post Combustion Biphasic Solvents	Biphasic absorption process with multiple stages of liquid–liquid phase separation for post-combustion carbon dioxide (CO_2) capture.
Chemical Looping combustion (CLC)	Chemical looping combustion (CLC) is a two-step combustion technology for power and heat generation with inherent CO_2 capture, using either gaseous fuels or solid and liquid fuels
Calcium carbonate looping (CaL)	Calcium looping (CaL), or the regenerative calcium cycle (RCC), is a second-generation carbon capture technology. It is the most developed form of carbonate looping, where a metal (M) is reversibly reacted between its carbonate form (MCO_3) and its oxide form (MO) to separate carbon dioxide from other gases
Cryogenic Capture	CCC uses phase change to separate CO_2 and other pollutants from exhaust or process gases. In CCC the CO_2 is cooled to such a low temperature (about -140 °C) that it changes from a gas to a solid. The solid CO_2 is separated from the remaining gas, pressurized, melted, and delivered at pipeline pressure.

As we move into Phase #2, the screening will develop to include financial data and potential timelines for when solutions are likely to reach full commercialisation and are likely to reduce the potential cost of CO2 capture towards 2050.

Direct Air Capture

As iterated in deliverable T3.1, for initial technology scanning, Direct Air Capture is the main competitor to exhaust gas-based point source emission capture technologies as mentioned above. Direct air capture offering many advantages over point source capture solutions although generally more expensive that CO2 capture as is traditionally adopted on smaller applications.

DAC is gaining momentum, with proposals in place for deployment in multiple states. Within the USA, DAC technology is eligible under California's LCFS framework and amounts to nearly $200 per tonne of CO_2 captured which makes its case for deployment in the shorter term. With both incentives to invest in CO_2 and a growing CO_2 injection market in the Gulf of Mexico, the USA market for DAC is growing. With similar incentives in the UK required for full-scale commercialisation.

Figure 6 outlines the growing market of alternative CO_2 capture techniques and DAC technology, some of which are actively progressing opportunity in the UK.

Technology Providers	CO_2 Capture	CO_2 Transport	CO_2 Storage	How it works - in brief
CCM Carbon Capture Machine	From the tail pipe / smoke stack	Via solid materials	In solid materials	CCM (UK) Ltd is a spin out from University of Aberdeen who developed a technology that profitably converts CO_2 from any source to carbonate ions. The carbonate solution is then reacted to yield Precipitated Calcium Carbonate, PCC and Precipitated Magnesium Carbonate, PMC. Both materials have application across several industries. CCM's technology represents a reliable, integrated carbon 'CAPture' and 'CONversion' (CAPCON) technology with low capital investment needs and able to use off-the-shelf components.
Global Thermostat	Direct Air Capture from air, Tail pipe/ smoke stack	To storage as CO_2, or to distribution if Air to Fuel	Underground, or reuse as fuel if Air to Fuel option	GT uses custom equipment and proprietary (dry) amine-based chemical "sorbents" that are bonded to porous, honeycomb ceramic "monoliths" which act together as carbon sponges. The captured CO2 is then stripped off and collected using low-temperature steam (85-100° C), ideally sourced from residual/process heat at little or no-cost. The output results in 98% pure CO2 at standard temperature and pressure. Plants are completely modular – from a single 50,000 tonne/yr. Module to a 40-Module, 2MM tonne/yr. Plant, and. GT Plants also have a small footprint – capturing from 20-500 tonnes of CO_2/yr./m2 or more, depending on the embodiment used.
ZEF Zero Emissions Fuels	Direct Air Capture from air, solar powered	As Methanol	No storage. Reuse as fuel.	ZEF is developing solar methanol farms by connecting a micro-plant add-on to a conventional solar panel. CO_2 and water are collected through direct air capture and alkaline electrolysis is applied to split water into hydrogen and oxygen. These are then used to synthesize methanol, CH_4. The synthesis process works but must reach ¼ of the current production costs to be competitive. A 12MW solar-methanol farm consists of 40.000 solar panel + micro-plant systems. The modularity of the system enables scaling up to any size, and the system size enables discontinuous operation by fast heating/cooling.
Carbon Engineering 	Direct Air Capture from air, electricity powered	To storage as CO_2, or to distribution if Air to Fuel	Underground, or reuse as fuel if Air to Fuel option	C.E. produces and licences plants to capture CO_2 straight from the air, with two possible applications: CCS, removing the need to transport the CO_2 from the production site to the storage site. An emissions market would enable a plant to keep producing and emitting, and be carbon neutral or even negative by capturing more CO_2 from the air straight above the storing location. Fuel production: combining the CO_2 with Hydrogen from electrolysis produced from excessive capacity, it can generate jet fuel, gasoline or diesel that is carbon neutral, as the emissions from the engine exhaust are compensated by the CO_2 captured from the air, so it's a possible way to decarbonise transport.
	Direct Air Capture from air, electricity powered	To Storage, as CO_2, piped	Underground	Climeworks is a spin off from ETH (University of Zurich, Switzerland) commercializing a highly efficient technology for CO_2 capture from ambient air. The plants capture atmospheric carbon with a filter which chemically bounds the CO_2. Once the filter is saturated, it is heated to around 100 °C. The CO_2 is then released and collected as concentrated CO_2 gas to supply to customers or for negative emissions technologies. CO_2-free air is released back into the atmosphere. This continuous cycle is then ready to start again. The filter is reused many times and lasts for several thousand cycles.

Figure 6 – CO_2 capture alternatives & Direct Air Capture

Utilisation

At present, the storage of CO2 is still preferred over utilisation due to the current lack of largescale demand for CO2 in industry and whilst the challenge of developing commercially viable carbon utilisation options are considerable, the implications of turning what is currently considered a waste product (CO2) and recycling it into a revenue-generating commodity are well received.

With numerous technologies being developed to produce products such as synthetic fuels, chemicals, high-strength material and fish food/protein, this area is rapidly developing, as curtailed renewables continue to rise. The growth of this market generates a potentially more attractive financial model versus the CO2 capture and storage option which requires significant infrastructure and transportation investment.

As can be seen in Appendix C, there is a significant market for growth in the utilisation of CO_2 yet still, the case doesn't yet match the scale required and can be satiated by the storage capacity in the UK. Forming part of Phase #2, we shall evaluate the utilisation markets specific to market in Scotland as we understand that some may be more useful internationally, such as CO_2 for greenhouses, which is a growing market in the Netherlands.

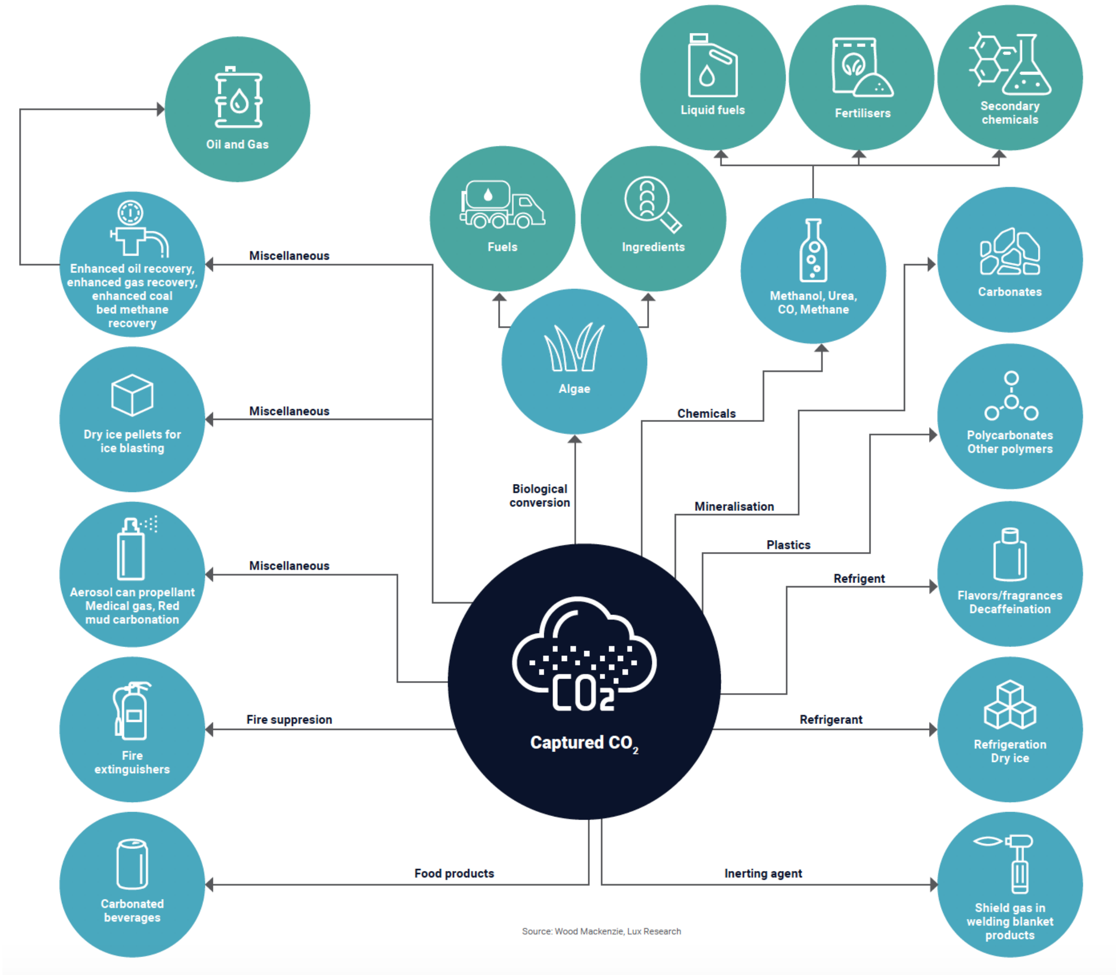

Figure 7 - Utilisation of CO_2

Transportation & Storage

Technologies considered for the transportation of CO_2 included pipelines, for which of course Feeder10 is being considered as well as offshore gas infrastructure in the North Sea (Goldeneye) for export to Acorn, trains/lorries and also shipping vessels. Transportation utilising both ships and trains/trucks is an established method of moving CO_2 yet generally small scale at the moment having been utilised in the food and drink industry for a number of years and not on the scale required for storage of CO_2 to meet 2050 targets. CO_2 tankers are comparable to commercial LNG shipping vessels however it needs to be fully understood how much a vessel such as this would need to be modified to accommodate CO_2. In Norway, for the Northern Lights project evaluating the largescale storage of CO_2 from multiple sites, are currently evaluating the viability of CO_2 shipping.

Pipelines are the primary opportunity for significant scale CO_2 transportation onshore in the UK and, indeed, Scotland with the potential reuse of Feeder10 being a critical enabler for the decarbonisation of the East Coast and Central clusters of Scotland. Currently, the challenges of CO_2 pipelines for transportation include corrosion (due to contamination in anthropogenic CO_2), asset integrity and pressure control to minimise losses. In onshore pipelines, over long distances it will be important to be able to actively monitor and assess pipeline conditions especially for the reuse of existing pipelines to mitigate crack propagation, pressure losses and corrosion.

The storage of CO_2 is not limited to depleted oil and gas reservoirs although the injection of CO_2 in the North Sea is currently only implemented in such. In the NCS, Equinor in the Sleipner project has been injecting CO_2 back into the reservoir for a number of years, enabled by the Oil and Gas infrastructure due to extensive mapping of subsurface structures and topside and subsea infrastructure. In addition to CO_2 EOR for existing fields and injection into depleted fields CO_2 can also be stored in Saline Aquifers, Coal Seams, Basalts and, on a smaller scale, Mineral and Ocean storage. Of these technologies, CO_2 EOR is the most established, particularly in the Gulf of Mexico, where due to government tax levies and incentives CO_2 capture is more financially viable and can be sold as an EOR enabler in the Gulf of Mexico. Depleted hydrocarbon fields and Saline aquifers make the UK a prime candidate for CO_2 storage given that is now a mature basin and has a potential 8Gt capacity (37 shortlisted areas from above) for storage.

A comprehensive analysis of CO_2 storage locations was released in 2016, outlining the volume and types of storage locations[3]. Figure 8 outlines these storage locations, categorised into storage type and total numbers.

Site Numbers	Unit Designation				
Storage Unit Type	**Saline Aquifer**	**Oil & Gas**	**Gas Condensate**	**Gas**	**Total**
Fully confined (closed box)	228	3	1	8	240
Open, with identified structural/ stratigraphic confinement	20	0	0	0	20
Open, no identified structural/ stratigraphic confinement	62	0	0	0	62
Structural/ Stratigraphic confinement	50	85	15	101	251
Uncategorised	1	0	0	0	1
Total	**361**	**88**	**16**	**109**	**574**

Figure 8 - UKCS Storage Locations

[3] ETI, 'Strategic UK CCS Storage Appraisal' [Online]. Available: https://www.eti.co.uk/programmes/carbon-capture-storage/strategic-uk-ccs-storage-appraisal

Appendix A – Electrification Screening[4]

Core Technology		Route	Technology	Technology Definition	Readiness	Advantages	Challenges
Electrification	Optimisation	Methane Detection	Methane Detection	Direct measurement: Rare on offshore sites. Requires monitoring system (Monitoring Certification Scheme (MCERTS) provides standards). Doesn't appear to be clear guidelines on what system to use/how systems are verified. Emissions can also be measured remotely from ships/aircraft to estimated large source emissions (e.g. entire installation) Indirect measurement: Emissions calculated using activity data (e.g. Fuel consumption) and emission factor specific to source (e.g. Valve leak). Most common method for national inventories			
		Flaring Reduction	Flaring Reduction	Technology utilised to reduce the requirement of flaring of natural resources. Smart metering, performance optimisation			
		Connected Workforce	Connected Workforce	Supports continuous improvement and operational efficiency through real-time insight and by supporting a connected workforce working from centralized data			
		Unmanning	Unmanning	Reduction of personnel and therefore carbon footprint. Increased safety factors and removes people from dangerous situation to therefore add value to other areas of focus			
		Asset Integrity	Asset Integrity	Asset integrity, or asset integrity management systems (AIMS) is the term for an asset's capacity to run effectively and accurately. A digitial solution to find and locate inefficiencied and solve them			
		Electrifying heat	Electrifying heat	Replacing process heat input with an electrical equivalent			
	Connection to Grid	Physical	HVAC Cabling	High Voltage Alternating Current cabling. Traditional in oil and gas an short distance step out applications. Over around 100km, HVDC cabling becomes more cost competitive due to lower relative loses over the distance	9	Over short distances HVAC is cheaper	Increased losses over distance (electrical losses and heat losses)
			HVDC Cabling	High Voltage Direct Current cabling. Traditionally used in applications with step out distances of over 100km. Requires expensive HDVC to AC conversion at destination substation	9	DC lines are cheaper than the AC lines, but the cost of DC terminal equipment is very high as compared to AC terminal cables. HVDC lines increase the efficiency of transmission lines due to which power is rapidly transferred. ease of controlling active power	less reliability and lower availability. Increased equipment for conversion at both ends
			HVAC Substations	HVAC Collector Substations provide a centralised collection point for the inter-array cables and will transform the voltage of the electricity generated at the WTG to a higher voltage for distribution to shore	9	Lower cost than HVDC systems with reduction in weight	Increased losses over distance (electrical losses and heat losses)
			HVDC Substations	HVDC are larger, heavier and cost more than their HVAC counterparts due to the technology required to convert DC voltages to AC before integration into the UK National Grid	9	A lesser number of conductors and insulators are required thereby reducing the cost of the overall system.	Size and weight concerns and higher CAPEX than HVAC systems
	Renewables Integration	Material	Onshore Wind	Fixed onshore Wind. Generally for largescale applications Horizontal Axis Wind turbines are utilised (HAWT) with vertical axis wind turbines (VAWT) usually used in smaller scale applications.	9	Mature market, costs are much lower now and can be utilised incentive free in some cases. Size of turbines are increasing onshore after previously slowing.	Lots of envirnomnetal and regional concerns over adoption - Issues in concenting and the effect on the landscape and local bird population
			Wave power buoys	Power buoys are electricity generation units that utilise the waves to create power through powerful electromagnets. Systems can be used to balance power for remote operations and have been used to power small scale loads such as well monitoring equipment in the offshore oil and gas industry	9	Devloping into larger capcity units, can be used in conjunction with other industries and technologies. Abundant resources	Still a developing market, with small scale power generation limiting it to niche markets
			Tidal	Tidal array with battery storage providing an alternative to grid upgrade – Challenging, grid upgrade cheaper than batteries.	9	Abundance of resource, can be used in conjunction with other technologies for specific applications.	Still a developing market, with small scale power generation limiting it to niche markets
			Offshore Wind - Fixed	Fixed offshore wind - monopile or jacket design with arrays connected to shore (traditionally, offshore fixed solutions are applicable in water depths up to 50m but some are increasing)	9	Mature market, costs are much lower now and can be utilised incentive free in some cases. Size of turbines are increasing 12MW+, expanding into deeper waters	Dgredation of jackets, jackets and monopiles have to be designed for the seabed that theu are installed on, limited to shallower waters. Ease of maintenance and decomissioning
			Offshore Wind - Floating	Floating offshore wind (spar technology/semi-submersible/TLBs) is a solution that allows for offshore wind to be moored in deeper waters and also can be standardised in terms of design (with fixed being specific to the location of installation)	9	Ease of maintenance, manufacturability at scale since floater is a standardised unit, turbine agnostic, use in deeper water, leasing availability,	Current high CAPEX due to emerging technology
	Storage	Rechargeable	Lithium ion (Li-ion) batteries	Buoyed by massive scale-up and cost reductions in the last few years because of the increase of electric vehicles, Lithium ion (Li-ion) batteries are currently the preferred energy storage option. Li-ion batteries primarily differ by cathode chemistry, and each has its own benefits and drawbacks.	8	High energy density - potential for yet higher capacities. Does not need prolonged priming when new. Relatively low self-discharge. Low Maintenance	Requires protection circuit to maintain voltage and current within safe limits. Subject to aging, even if not in use. Transportation restrictions - shipment of larger quantities may be subject to regulatory control. Expensive to manufacture. Not fully mature
			Na-ion		6	Lower material costs (sodium carbonate is less than 10% of the cost of the equivalent lithium salt), cheaper collectors and the use of existing lithium ion manufacturing lines	Low life (300 cycles), prototype stage
			Li-sulphur		6	higher gravimetric energy density, in theory five times that of lithium-ion batteries at the cell level	Poor rate capacity (i.e. low power), high self-discharge and safety issues with electrolyte stability and Li metal anode. Low cycling capability. Li-S cells operate at low nominal voltages
			Metal-air		4	high potential to increase gravimetric energy density. Some metals, like with Zinc-air batteries are much cheaper than lithium-ion veriants	Poor cycle life, poor rate capability, low efficiency and safety issues with electrolyte stability and Li metal anode (for Li-air)
			Solid electrolytes		4	safety, as they lack volatile or flammable liquid components.	Lower conductivity, volume interphase issues, fabrication methods
			Magnesium anode		3	Over litium-ion, increased energy dentisy and increased safety	Slow reaction kinetics, imply a low discharge power/C-rate
			Supercapacitors		4	speed of charge. In some cases, they're nearly 1,000x faster than the charge time for a similar-capacity battery.	Complementary to battery, would provide extra capabilities. At current costs, not viable
		Mechanical	Flow Batteries	A flow battery is a rechargeable fuel cell in which an electrolyte containing one or more dissolved electroactive elements flows through an electrochemical cell that reversibly converts chemical energy directly to electricity	7	the active material could be easily refilled at the station, instead of charging the battery	Low energy density
			Pumped hydroelectric storage	Gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost electric power is typically used to run the pumps. During periods of high electrical demand, the stored water is released through turbines to produce electric power. Commonly used renewable source of power in Norway	9	Balance of power, renewable power source (clean energy)	net consumer of electricity, due to hydraulic and electrical losses incurred in the cycle of pumping from lower to upper reservoirs
			Mechanical flywheels	Flywheel energy storage systems (FESS) employ kinetic energy stored in a rotating mass with very low frictional losses. Electric energy input accelerates the mass to speed via an integrated motor-generator. The energy is discharged by drawing down the kinetic energy using the same motor-generator.	8	No carbon emissions, faster response times and ability to buy power at off-peak hours	low energy density and the high cost of ensuring the system's safety

Figure 9 - Electrification Review

[4] Battery TRLs
https://www.energy.gov/sites/prod/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf

https://es.catapult.org.uk/wp-content/uploads/2019/11/CVEI-Battery-Cost-and-Performance-and-Battery-Management-System-Capability-Report-and-Battery-Database.pdf

Appendix B – Hydrogen Screening[1, 5]

Core Technology		Route	Technology	Technology Definition	Readiness	Advantages	Challenges
Hydrogen	Production	Thermal-chemical process	Steam Methane Reforming	Reformation of Natural Gas involves methane reacting with steam at 750-800°C to create a synthesis gas (syngas), a mixture primarily made up of hydrogen (H_2) and carbon monoxide (CO). The second step is known as a water gas shift reaction, where the carbon monoxide produced in the first step reacts with steam over a compound to form hydrogen and CO_2.	9	Most cost-effective, existing supply chain	Pollutant emission, unfavourable thermodynamic equilibrium
			Coal Gasification	Coal gasification is the process of producing syngas (mixture consisting of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), natural gas (CH_4), and water vapour (H_2O)) from coal and water, air and/or oxygen.	7	Abundant feedstock, cost effective	Pollutant emission
			Biomass Gasification	Gasification is a process that converts organic or fossil-based carbonaceous materials at high temperatures (>700°C), without combustion, with a controlled amount of oxygen and/or steam into carbon monoxide, hydrogen, and carbon dioxide. The carbon monoxide then reacts with water to form carbon dioxide and more hydrogen via a water-gas shift reaction. Adsorbers or special membranes can separate the hydrogen from this gas stream. [Source: Energy Department - Office of Energy Efficiency and Renewable Energy]	9	Abundant feedstock	Cost (feedstock and equipment)
			Thermochemical water splitting (Nuclear power)	Thermochemical water splitting processes use high-temperature heat (500°–2,000°C) to drive a series of chemical reactions that produce hydrogen. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen. [Source - Energy.gov]	3	Closed loop process (consumes water only), no emissions	Commercial viability (cycles and reactors)
			Alkaline (AE) Electrolyser	2 electrodes operating in a liquid alkaline electrolyte solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH). These electrodes are separated by a diaphragm, separating the product gases and transporting the hydroxide ions from one electrode to the other.	9	Lower costs – cheaper catalyst metals, Long performance history	Liquid electrolyte is hazardous, corrosive, and susceptible to leakage, Requires several minutes to ramp up and down
			Proton exchange membrane (PEM) Electrolyser	Electrolysis of water in a cell with a solid polymer electrolyte (SPE) that is responsible for the conduction of protons, separation of product gases, and electrical insulation of the electrodes. When voltage is applied between the two electrodes, negatively charged Oxygen in the water molecules give up their electron at the anode to make protons, electrons, and O_2 at the anode.	8	Rapid response time, better suited to pair with intermittent energy sources, Operates at high current density and wide load range	Higher CAPEX, Relatively unproven technology
			Solid oxide electrolysis cell (SOEC) Electrolyser	Electrolysis process using using a solid oxide, or ceramic, electrolyte to produce hydrogen gas (and/or carbon monoxide) and oxygen. Operating at high temperatures as apposed to lower levels with AE and PEM solutions	6	Operates at very high temperature (>700 °C) and efficiency	Moderate time to ramp up or down, Not suited for intermittent use because of need for high heat, Unproven in commercial use
			Electrolysis (General focus)	Green hydrogen is produced using one of several types of electrolysers, with a process that splits water molecules into hydrogen and oxygen, using renewable electricity. Electrolysers are predominately situated onshore; however, the offshore green hydrogen production market is growing with the technology to develop electrolysation from seawater underway. [SNZR Report]	7	No GHG emissions (depending on electricity source), possible synergy with renewable power generation.	Electrolyser unit cost, system balance, electricity - hydrogen conversion efficiency+L29
			Photo-electrochemical (Solar)	Utilises sunlight and specialized semiconductors called photoelectrochemical materials, which use light energy to directly dissociate water molecules into hydrogen and oxygen [energy.gov]	5	High conversion efficiency, low temperature, cost-effective materials	Efficiency (sunlight absorption and surface catalysis), durability
	Storage	Physical	High pressure gaseous H_2	Compressed gaseous hydrogen is currently the main stream for on-board storage. Maximum storage pressure varies from 35 to 70 MPa. Tanks of (aluminium liner and polymer liner made of carbon fibre- reinforced resin are in use due to their weight.	9	Simple, mature method. Cost-effective	Low volumetric density, humidification required
			Cryogenic liquid	Cryogenic hydrogen has a density nearly twice that of compressed hydrogen at 70 MPa. Liquid hydrogen is stored in specially insulated cryogenic tanks under pressure, which have provisions for cooling, heating, and venting.	8	Low pressure, high density	Complex compression double-step, high cost
			Adsorbed (Carbon nanotubes)	Single-walled carbon nanotubes are essentially a one-atom-thick layer of carbon rolled into a tube. All the carbon atoms are on the surface, allowing easy access for bonding. The carbon nanotubes offer safe storage because the hydrogen atoms are bonded to other atoms, rather than freely floating as a potentially explosive gas.	6	Moderate pressure and temperatures, material cost, high H_2 capacity per weight %	Cryogenic temperatures and extremely high surface areas needed, not available commercially
		Material	Absorbed (hydrides)	Materials suitable for hydrogen storage in solid-state have to meet specific requirements in order to be used for the development of hydrogen based technologies, in particular storage. The material has to retain its performances in terms of kinetics and total hydrogen capacity, even after cycling.	6	NTP conditions, yields high purity H_2, moderate cost material.	Low gravimetric density, lifetime proportional to purity of stored H_2
			Ammonia (NH_3 as carrier)	Ammonia—one nitrogen atom bonded to three hydrogen atoms. Ammonia is of interest as a hydrogen storage and transport medium because it enables liquid-phase hydrogen storage under mild conditions.	9	Taps into existing supply chain, Can be used as shipping fuel or combusted in power plants. Approx. twice the energy density of other carriers in anhydrous form	Anhydrous ammonia is corrosive and forms lethal gas clouds if released. Cracking to release hydrogen is immature and trace ammonia can damage fuel cells
			Liquid Organic Hydrogen Carriers	Unsaturated organic compounds can store huge amounts of hydrogen. These Liquid Organic Hydrogen Carriers (LOHC) are hydrogenated for storage and dehydrogenated again when the energy/hydrogen is needed.	8	Can be stored and transported in existing liquid bulk assets. Safe to handle at room temperature	Requires large conversion plants at supply and demand locations. Dehydrogenation step is energy and time consuming. Depleted carrier must be shipped back to hydrogen production site
			Absorbed (complex hydrides)	Complex hydrides are inorganic materials that are best described as salts, which are built from complex anions containing hydrogen as terminal ligand, such as the $BH_4^–$ (tetrahydroborate or borohydride) or $AlH_4^–$ (alanate) anions and counteractions from many different groups in the periodic table	5	Moderate pressure and temperatures, high volumetric density, low safety issues.	Thermal management, hydride recycling
	Use		Power	Direct use in Gas Turbine Generators etc.	6	zero emissions	Hydrogen's low volumetric density and potential embrittlement of some metals mean that changes to ducting, seals, and valves are required, as well as possible retrofits for turbine blades so that they can withstand higher flame temperatures
			Blended Heat	Blended, 100% H_2, Domestic/commercial, Combined Heat and Power (CHP)	6	lower emission (depending on blend %)	Appliance upgrade, Safety perception, network suitability
			100% H_2 Heat	Replace of natural gas for heating applications (domestic and industrial)	5	zero emissions	Appliance upgrade, Safety perception, network suitability
			Mobility (Fuel cells): Near zero carbon fuels	The power plants of such vehicles convert the chemical energy of hydrogen to mechanical energy either by burning hydrogen in an internal combustion engine, or, more commonly, by reacting hydrogen with oxygen in a fuel cell to run electric motors.	6	zero tailpipe emissions	fuel station network non existent

[5] Electrolysers TRL info: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5bd5eb58c&appId=PPGMS

Ammonia & Liquid Organic Hydrogen Carriers TRL info: https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

Appendix C – CCUS Screening[1, 6]

Core Technology		Route	Technology	Technology Definition	Readiness	Advantages	Challenges
CCUS	Capture		Post-conversion Capture	Low-pressure flue gases undergo sorbent treatment for CO2 selective removal.	9	Applicable to most conventional power plants	Energy intensive, high CAPEX, BF mods required if multiple point sources exist in application
			Pre-conversion Capture	CO2 can be removed from syngas (mix of H2, CO and CO2) from fossil fuels and biomass. Syngas can be shifted to H2 while converting CO to CO2.	7	Simplified CO2 separation process prior to transport and storage	Cannot be retrofitted to pulverized coal plants.
			Oxy-fuel Combustion	Pure O2 used in combustion processes to yield flue gas with high CO2 concentration (O2 separation from air is an energy intensive process)	5	Free from nitrogen compounds	Only applicable to processes involving combustion
			Post Combustion Ionic Liquids	Ionic liquids (ILs) and "reversible" ionic liquids (RevILs) have been touted as alternatives to aqueous amine solutions for post-combustion CO2 capture.	1	igh physical and chemical CO2 solubility, with high stability and negligible vapour pressure	absorption capacity is likely to be much lower
			BECCS Power	BECCS is the process of extracting energy from biomass and capturing and storing the carbon using any mentioned CCUS technology. Biomass is processed through combustion, fermentation, pyrolysis, etc. and given that CO2 is captured, it is a carbon negative process	9	ability to result in negative emissions of CO2	Availability of feedstock of some processes - some requirring imports from other regions. efficiency of burning biomass. Cost of CO2 technology
			Membranes - Dense Inorganic	Dense inorganic membranes are referred to those membranes made of a polycrystalline ceramic or metal, which allows certain gas species to permeate through its crystal lattice	6	Inorganic membranes have the advantage of resisting harsh chemical cleaning, high temperature and wear resistance, high chemical stability, long lifetime,	More expensive that organic solutions and more brittle
			Membranes - Polymeric	Porous and polymeric membranes have a thin layer of semi-permeable material that is used for solute separation as transmembrane pressure is applied across the membrane.	6	minimize pretreatment needs and avoid large processing modules	Still in early stages of commerical development
			Post Combustion Biphasic Solvents	Biphasic absorption process with multiple stages of liquid–liquid phase separation for post-combustion carbon dioxide (CO2) capture.	4		
			Chemical Looping combustion (CLC)	Chemical looping combustion (CLC) is a two-step combustion technology for power and heat generation with inherent CO2 capture, using either gaseous fuels or solid and liquid fuels	7		
			Calcium carbonate looping (CaL)	Calcium looping (CaL), or the regenerative calcium cycle (RCC), is a second-generation carbon capture technology. It is the most developed form of carbonate looping, where a metal (M) is reversibly reacted between its carbonate form (MCO3) and its oxide form (MO) to separate carbon dioxide from other gases	7	sorbent derived from cheap, abundant and environmentally benign limestone and dolomite, relatively small efficiency penalty that it imposes on the power / industrial process	
			Cryogenic Capture	CCC uses phase change to separate CO2 and other pollutants from exhaust or process gases. In CCC the CO2 is cooled to such a low temperature (about -140 °C) that it desublimates, or changes from a gas to a solid. The solid CO2 is separated from the remaining gas, pressurized, melted, and delivered at pipeline pressure.	4	In addition to capturing 95–99% of carbon, CCC also captures other pollutants such as NOX, SOX, and mercury (Hg).	High CAPEX
			Direct Air Capture	In its simplest form, DAC, exploits the same process adopted by plants to extract CO2 during photosynthesis. The technology draws in atmospheric air, then through a chemical process, the CO2 is extracted, processed and compressed for utilisation and storage.	8	Doesn't require extensive BF mods, can be adopted by a cluster of companies, can be used for industry offsetting of CO2. Can be positioned anywhere (doesn't need to be onsite and can therfore be placed near storage site). Multiple technology solutions exist. Can be used long after source of emissions has been decomissioned	Expensive, requires commercial and regulatory insentive to become feasible. Requires separate transportation and storage networks and infrastructure
	Transport		Offshore pipelines	6000km in US, Snohvit in Norway. Technical standards DNV 2010. Scale up: International pipeline network	7	Infrastructure already in place in North Sea	Different corrosion impact of CO2 Vs gas
			Trucks/Train	Specialised freight containers for transportation of CO2 at pressure (small scale)	9	Established method	Small scale
			Ships	Specialised freight containers for transportation of CO2 at pressure	9	Established method	Small scale (~1,000 tonnes)
	Utilisation applications	Chemicals	Formic acid	Electrochemical reduction of CO2 (ERC) combines captured CO2 and water to produce formic acid (HCOOH) and O2. The formic acid can be used in conventional applications (e.g. food preservative or antibacertial agent) or as a H2 carrier in fuel cells	7	Use as a carrier for Hydrogen	
			Other (non-fuel) chemical synthesis	applications include: acrylic acid from ethylene and acetone fermentation; aliphatic aldehydes from alkanes.	3		
			Polymer processing	Use of CO2 in combination with traditional feedstocks to synthesise polymers. This technology allows the use of waste CO2 and transforms it into polycarbonates. The polymers that can be created with this technology are polypropylene carbonate (PPC) and polyethylene carbonate (PEC).	8		
			Sodium bicarbonate	Soda ash is a chemical used in a wide range of production applications, principally glass making, as well as domestic cleaners.	9		
		CO2 mineralisation	Bauxite residue carbonation	The extraction of alumina from bauxite ore results in a highly alkaline residue slurry (known as 'red mud'). Concentrated CO2 is used as a means of treating the highly alkaline by-product	9		
			Carbonate mineralisation (Carbonation)	Carbon mineralisation is the conversion of CO2 to solid inorganic carbonates using chemical reactions.	8		
			Concrete curing	Use of CO2 to enhance the cure of precast concrete products. It is purported to enhance the concrete strength.	7	Enhancement of strength of Concrete	Potential for CO2 to secrete from the concrete over time
		CO2 to fuels carrier	Algae cultivation	CO2 is utilised to accelerate biomass production rates/yield	5		
			Hydrocarbon excreting microorganisms (Helioculture)		5		
			Nanomaterial catalysts	Conversion of CO2 and steam into methane and other hydrocarbons.	3		
			Photocatalytic reduction of CO2 (CR5)	High temperature solar concentrator provides heat for chemical splitting (decomposition) of CO2 and H2O into CO, H2 and O2 using catalysis. The CO and H2 together provide a syngas that can be transformed into multiple hydrocarbon products	5		Release of CO2 when utilised
			Synthetic methane	In an exothermic reaction between H2 and CO2, CH4 and H2O are produced. The reaction is usually carried out with a catalyst	8		
			Synthetic methanol	The electrolysis of water produces H2 which is combined with CO2, compressed and reacted over a metal/metal oxide catalyst to produce methanol and water.	8		
		Enhanced commodity production	Enhanced geothermal systems with CO2		5		
			Methanol yield boosting	The yield of methanol from conventional methanol synthesis can be increased by the injection of additional CO2	9		
			Supercritical CO2 power cycles	The use of supercritical CO2 in closed loop power cycles as a replacement for steam (e.g. in fossil fuel-fired or nuclear power plants).	7	increased electricity conversion efficiency, less thermal fatigue and corrosion.	
			Urea yield boosting	used for the production of fertilisers (urea granules and other fertiliser derivatives)	9		Release of CO2 when utilised
			Enhanced Fuel Recovery	Produced gas or CO2 separated from natural gas at a later stage of the process, is separated and re-injected back into oil and gas fields acting as an Enhanced Oil Recovery method (similar to water injection). When the full capacity of the field is expolited the CO2 remains as a storage basin	9	Concept proven in industry. Circular economy, strong indutsry experience and solutions to implement. EOR and delay of COP. Reduction in EU ETS requirements?	Direct separation from produced gas requires high CO2 concentrations as well as significant infrastructure and BF mods on topsides. Requires market of CO2 separation and delivery to oil and gas assets. Only appliacble to certain structures
		Food & Drink	Beverage carbonation	CO2 may be utilised directly in (soft drink or alcoholic) beverage carbonation	9		
			Food freezing, chilling and packaging	CO2 may be utilised directly in food-related applications, such as freezing food using dry ice. In packaging applications, CO2 is used in modified atmosphere packaging	9		
			Horticulture (glasshouses)	Growth rates of several plant species increase with elevated CO2 levels as long as all other nutrients, water and sunlight are available	9		
		Other - Industrial applications	Electronics	Some Printed circuit board manufacture uses small quantities of CO2	9	Carbon dioxide is essential in several steps of the key lithographic technique in semiconductor manufacturing and also enhances wafer cleaning processes	
			Metal working (including casting, moulding and welding)	The mould for CO2 casting is made of a mixture of sand and liquid silicate binder which is hardened by passing CO2 gas over the mould. CO2 is also used in welding as a shrouding gas to prevent oxidation of the weld metal	9	delivers great accuracy in production methods	
			Refrigerant gas	CO2 is used as the working fluid in refrigeration plant, particularly for larger industrial air conditioning and refrigeration systems	9	Very good heat transfer coefficient Relatively insensitive to pressure losses Very low viscosity	Market already has sources of CO2 so additional resource not required currently. Small scale
			Supercritical CO2	Coffee decaffeination, Extraction of aromas or flavours and plant substances, Pharmaceutical processes and as a solvent in dry cleaning	9	Benefits of using CO2 compared to other chemicals used are that it is inert and non- toxic. Due to its low critical temperature and moderate pressure requirements, natural substances can be treated particularly gently.	
			Water treatment and pH control	CO2 is used for re-mineralisation of water following reverse osmosis and for pH control	9	Does not overshoot pH, even with excess acid addition Reduces risk of equipment corrosion Eliminates the need for storage and handling of hazardous mineral acids Cost-competitive with mineral acid	
			Fire suppressant	While some suppression agents reduce the heat of the fire, a CO2 fire suppression system eliminates the oxygen to suppress the fire	9	CO2 is a colorless, odorless, and electrically non-conductive gas that leaves no residue behind	
			Miscellaneous Items	Injected into metal castings, raspiratory stimulant, aerosol can propellant, dry ice pellets, red mud carbonisation	9	Circular economy, industry rejuvenation Integration with renewables	Limited impact (carbon storage is also needed) Hard to reach economic competitiveness (CCU fuels 2-3 times as expensive as fossil fuels)
	Storage (Locations)		Saline aquifers	Saline aquifers are geological formations consisting of water permeable rocks that are saturated with salt water, called brine. Super-critical carbon dioxide (CO2), CO2 that has been pressurized to a phase between gas and liquid, may be injected into a saline aquifer where it may either dissolve in the brine, react with the dissolved minerals or the surrounding rock, or become trapped in the pore space of the aquifer due to its attraction to the walls of the aquifer	5	Safe long term storage with large capacity in unused geological formations	Not well understood
			Ocean Storage	Carbon dioxide is naturally stored in the ocean through chemical processes, either as a dissolved gas or, over a longer time scale, as carbonate sediments on the seafloor. In fact, more than 70 percent of current CO2 emissions will eventually wind-up in the ocean. [maritime executive]	1	vast quantities of CO2 could be isolated in the deep sea, driving down atmospheric and ocean surface concentrations in the short term. Technical expertise in oil and gas industry exists to implement	Serious implications to ecosystems and environment. Unproven concept - Theoretically possible but not likely to be adopted
			Mineral Storage	The process involves reacting carbon dioxide with abundantly available metal oxides–either magnesium oxide (MgO) or calcium oxide (CaO)–to form stable carbonates. [WIKI]	3	the permanence of CO2 storage in a stable solid form results in no CO2 release from the storage site	The IPCC estimates that a power plant equipped with CCS using mineral storage will need 60–180% more energy than a power plant without CCS.
			Depleted O&G fields	Different to saline acuifers, depleted reservoirs that also contain cap rock (formations that prevent the seevage of hydrocarbons out of the reservoir) can be reused for CO2 sequestration. Significant study work and modelling required to ensure correct conditions.	6	Extensive geological and hydrodynamic assessments available	Limited capacity
			Oil fields (CO2-flood EOR potential)	Direct CO2 injection or CO2 disolved into produced water and reinjected for EOR activity	5	Rejuvenate oil production in maturing fields, extend production by decades	Highly dependent on site-specific characteristics
			Coal seams (unmineable, ECBM recovery potential)	Enhanced Coal-Bed Methane recovery	4	Potential methane recovery	Limited capacity in methane rich sites
			Basalts	Under investigation	3	Under investigation	High investment and operational costs, no financial compensation
			EGR, GHR	Under investigation, Enhanced Ras Recovery; Geothermal Heat Recovery.	2		

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CO_2 Mineral storage: https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter7-1.pdf

CO2 Utilisation: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/799293/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2__1_.pdf

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CO2 Capture (Other TRLs) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/800680/Literature_Review_Report_Rev_2A__1_.pdf