

A survey of key technological
innovations for the low-carbon
economy

Lead Author: Tamaryn Napp

Contributing Authors: Thomas Hills, Salman
Masoudi Soltani, Jonathan Bosch, Christoph
Mazur

Contents

Executive Summary.....	4
Introduction	4
Technology Spotlight.....	6
Conclusion	8
Technology Discussions.....	9
1 Aviation	9
1.1 Biojet.....	9
1.2 Hydrogen Aircraft.....	11
2 The Industrial Sector	13
2.1 Carbon Capture and Storage (CCS)	13
2.2 Hydrogen in steelmaking.....	15
2.3 Iron ore electrolysis	15
3 Advanced biofuel supply.....	16
3.1 Artificial photosynthesis for biofuels production	16
3.2 Algae for bioethanol production	17
4 Built environment.....	19
4.1 Alternative building materials for steel and cement.....	19
5 Negative emissions technologies	20
5.1 Bioenergy with CCS.....	21
5.2 Bio-char	23
5.3 Ocean Liming (OL).....	24
5.4 Soda/Lime Process.....	25
6 Energy Storage	26
6.1 Thermal Cycle.....	26
6.2 Flywheels.....	27
6.3 Power-to-Gas	28
6.4 Lithium-Ion Battery	29
6.5 Redox Flow Battery.....	30
6.6 High Temperature, Sodium-based Batteries	31

References	31
Appendix: Full technology list	39

Disclaimer:

This paper was provided to the OECD in the context of the project “Growth, investment and the low carbon transition”. The content remains the sole responsibility of the authors and of the Grantham Institute – Climate Change and the Environment, Imperial College London”. The views expressed herein do not necessarily reflect the position of the OECD or its member countries.

Executive Summary

Introduction

This work summarises the main technological innovation priorities required to achieve deep decarbonisation consistent with meeting 2°C and below. The aim was to identify technologies which are crucial to achieving a low-carbon economy in the future but that are not yet at commercial scale and therefore still require significant R&D (Research and Development). In order to narrow the scope, technologies that are currently commercially deployed, even if they could benefit from further research to reduce costs or overcome non-technical barriers, were excluded from this report. The assumption being that there is likely to be sufficient momentum behind the technology for this to happen through learning and deployment. An exception to this was where there were no or very few alternatives to a technology (e.g. biofuels for aviation) or where a new application of an existing technology requires further R&D (e.g. lithium ion batteries for grid-scale storage).

A long-list of 52 mitigation options was drawn up by looking at existing innovation priority documents, mitigation pathways and by drawing on expert experience and opinion. A decision tree approach, as shown in Figure 1, was used to short-list these options and to identify key innovation priorities. The full list of the technologies considered as well as the justification for inclusion or exclusion is provided in the appendix. The concept of Technology Readiness Level (TRL) is a way of ranking technologies based on their level of the maturity. For simplification, we have grouped the TRLs into three levels: basic research at the lab-scale (TRL 1-3), technology development and small-scale demonstration (TRL 4-6) and large-scale operational demonstration and commercialisation of the full system (TRL 7-9). This was used to identify technologies that are not yet commercialised and thus still require support for R&D.

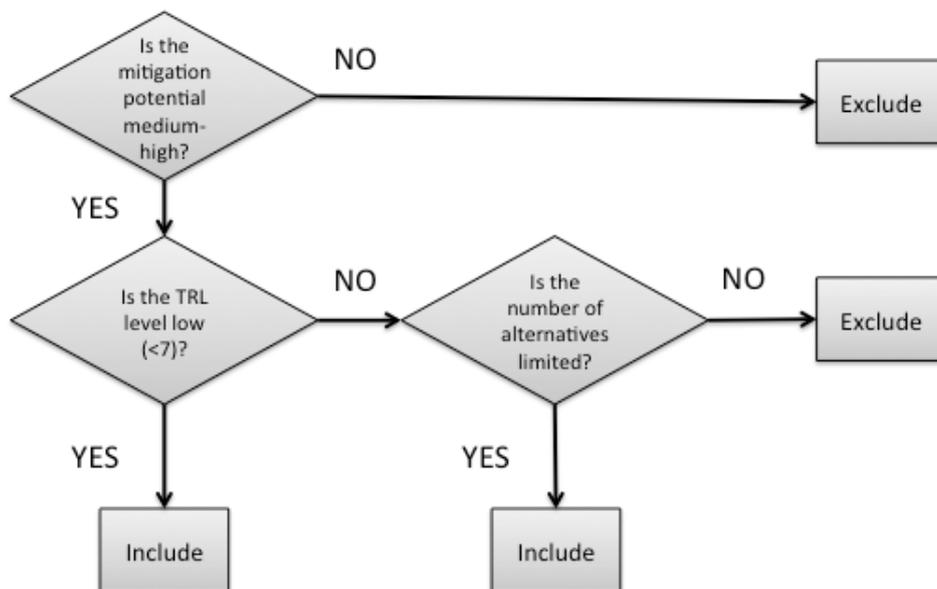


Figure 1: Diagram of the decision-tree approach used to select technologies. Note: TRL = Technology Readiness Level.

In total, 21 options were shortlisted. These can be categorised as follows: Carbon capture and storage (CCS), energy-intensive industry, aviation, biofuel supply, negative emissions, and energy storage. This finding is supported by energy systems modelling results (Figure 2) which show that by 2070, when emissions will need to be net zero if we are to have a chance of limiting global temperature change to 2°C, we will likely be heavily reliant on CCS and negative emissions technologies to achieve this, and in particular, to offset emissions from challenging sectors such as industry and aviation.

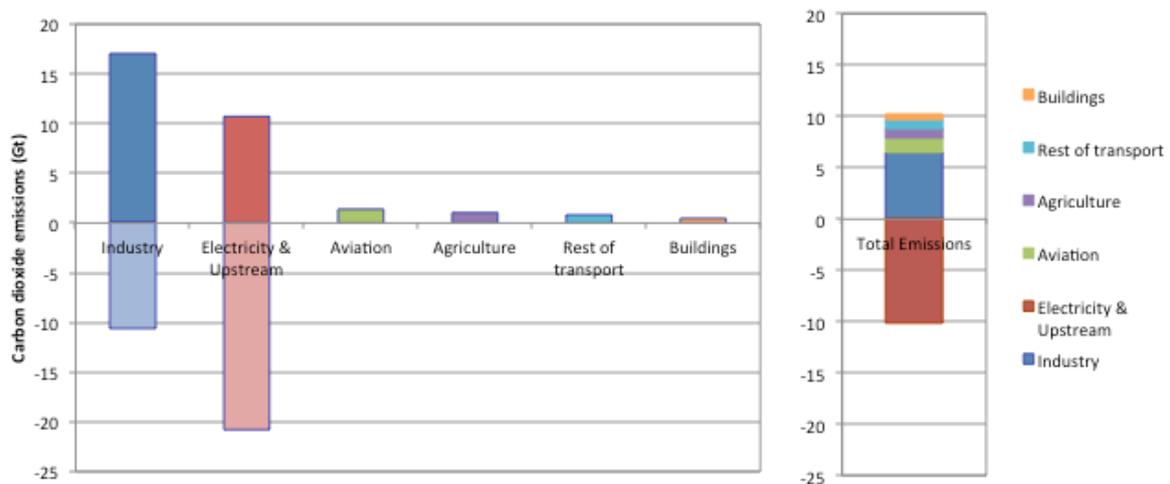


Figure 2: Breakdown of global CO₂ emissions by sector in 2070 for a scenario having a 50% probability of staying below 2°C. Based on results generated using the TIAM-Grantham energy systems model as part of the AVOID 2 project (AVOID 2, 2015, p. 2).

The technologies excluded using the above approach are all either fully commercialised (Technology Readiness Level higher than 7) or are not expected to play significant mitigation role. It was found that several important sectors do not require extensive technical R&D to be decarbonised as the technologies and processes to do so are already available. These sectors include: transport (excluding aviation), buildings and electricity generation. For road transport, fuel cells, batteries and biofuels are the major options and these technologies have been deployed successfully and are continuing to see cost reductions. Similarly, for the electricity sector, the major low-carbon electricity generation options (solar, wind, nuclear, geothermal etc.) are already commercially viable. Solar photovoltaics (PV) in particular has seen rapid uptake in recent years. Many sectors lie in between the two extremes. The built environment has several options, which simply require deployment – fuel switching to low-carbon alternatives is a good example, but equally developing lower-carbon materials which can be readily substituted for steel and Portland cement could greatly accelerate decarbonisation of the construction phase.

Technology Spotlight

A summary of the key technologies identified is given below, including a brief description of (1) the potential mitigation role and why it is important, (2) the current development status and (3) the R&D priorities and the potential for innovation.

Current scenario projections rely heavily on **Carbon Capture and Storage (CCS)** to meet emission targets. In the Energy Technology Perspectives 2DS scenario, CCS contributes to 14% (6 Gt/yr) of emissions reductions by 2050 (IEA, 2016). Of this, ~ 30% is from industrial emissions. CCS provides one of the few options for heavy industrial processes such as steel, cement and chemicals to achieve low or even zero carbon processes. Furthermore, negative emissions technologies such as Bioenergy with CCS (BECCS) would benefit from the advancement of conventional CCS. The components of carbon capture, transport, injection and storage have been demonstrated individually at commercial scale (Florin and Fennell, 2010). However, large-scale demonstration of CCS is an urgent priority to overcome the challenges of whole systems integration across the CCS chain (LCICG, 2014). The main research priorities for CCS identified (IEA, 2012; UKCCSRC, 2015) are (1) development of advanced adsorption and membrane processes; (2) research into advanced CCS processes such as Ca-looping and (3) improved modelling of carbon dioxide (CO₂) storage including optimal injection scenarios and expected leakage. The cost of CCS for power generation is estimated at around USD 43-80/tCO₂ (IEA, 2012). CCS applied to industrial processes is less well developed and is generally more challenging, but has the potential to be cheaper than CCS for power generation. Each process and even each site is unique and will likely require bespoke equipment and plant design. Current cost estimates range from USD 15-138/tCO₂ for cement and USD 51-64/tCO₂ for steel (Fennell et al., 2012). Research priorities for industrial CCS include (1) improved heat and flow integration, (2) testing the impact of impurities on the capture process and (3) development of novel sorbents which are optimised for industrial operating conditions.

Currently, the **industrial sector** accounts for around 30% of global GHG emissions. Of this, steel, cement and chemicals together make up over 70% of these emissions (IEA, 2010). Energy efficiency improvements will only be able to reduce industrial emissions by around 27% by 2050, but will not be enough to offset growth in demand (IEA, 2016). The options for achieving low (or zero) emissions from industrial processes can be broadly categorised into switching from fossil fuels to biomass or hydrogen, electrification, and CCS. Decarbonisation of the industrial sector is particularly challenging at the moment owing to competitiveness issues and its inherent heterogeneity. With the exception of biomass usage in certain applications, currently all of these options are still in the concept phase (TRL < 3) and there is an urgent need for the development of breakthrough processes (e.g. steel production based on hydrogen or electrolysis), which can result in a step-change in emissions reductions. Development of alternative building materials to steel and cement is also an important research priority, which can reduce emissions from both industry and the built environment. Alternative cement chemistries (i.e. not based on limestone) could provide a low-carbon solution for cement; however, extensive testing is required to provide the construction industry with the necessary confidence for wide-scale acceptance.

CO₂ emissions from the **aviation sector** amounted to 700 MtCO₂ in 2013, equivalent to around 2% of global CO₂ emissions (Elgowainy et al., 2012). With demand for aviation expected to rise by around 5% per annum, emissions could be as high as 3100 Mt by 2050 (ATAG, 2014). In the medium

term, radical new aircraft designs (e.g. the 'blended wing' concept) could improve fuel efficiency by 25% compared to the most efficient planes today (DfT, 2007). Currently, the options for low (or zero) carbon airplanes are extremely limited. Biofuels present the most viable alternative. Biofuel-powered planes have been proven to be technically feasible and blending of up to 50% is now allowed for commercial use (Epstein, 2014). At present, biofuels for aviation are limited to those that meet industry standards and are interchangeable with conventional fuels. New engine designs that can cope with the low aromatics composition of biofuels from Fischer Tropsch could open the aviation sector up to cheaper biofuels supply options. Hydrogen powered planes should not be ruled out. In 2016, the first 4-seater hydrogen fuel-cell powered plane took flight (Pultarova, 2016). This is promising; however, significant technical challenges will need to be overcome for commercial scale hydrogen powered planes to become a reality. In particular, the low energy density of hydrogen means a large storage volume, which will require major design modification. Hydrogen aviation has the advantage that fuelling infrastructure is more centralised compared to that required for cars. A starting point for hydrogen in aviation may be for use on the ground during taxiing. EasyJet is currently exploring this idea (Carrington, n.d.).

These alternative fuels for aviation, as well as other sectors, will rely on cost-effective and scaled-up supply chains. Researching and designing new plant strains optimised for **biofuel production** would increase crop yield and reduce the cost of biofuels supply. Other promising avenues for investigation include cellulosic biomass, algae, and halophytes (Epstein, 2014). **Hydrogen supply** from electrolysis, which requires lots of electricity, could be superseded by new technologies such as photocatalytic water splitting (Hisatomi et al., 2014; Moniz et al., 2015) or microbial processes (Magnuson et al., 2009), reducing the amount of electricity required per unit of hydrogen produced.

The longer that concerted global effort to mitigate climate change is delayed, the more it is becoming likely that GHG emissions will overshoot the 450 ppm target recommended by the IPCC to limit global warming to 2°C (Workman et al., 2011). The challenge has increased in light of the Paris agreements pledge to limit warming to 1.5 degrees. It is widely acknowledged that this would mean that emissions must be zero around 2070 and net negative beyond then (IPCC, 2014). Energy systems models (AVOID 2, 2015) indicate that to achieve this could require upwards of 10 Gt/yr of CO₂ removed from the atmosphere by 2070. There are five main **negative emissions technologies**: direct air capture, the lime-soda process, augmented ocean disposal, biochar and, the most well-known, bioenergy with carbon capture and storage (BECCS). Current cost estimates for negative emissions technologies range from USD 59-155/tCO₂e (Workman et al., 2011). With the exception of BECCS, all of the negative emissions technologies are currently in a very early level of technical development (~TRL 1-3). BECCS relies on a sustainable source of biomass and given competing pressures for bioenergy across different sectors, it is unlikely that BECCS technology alone will be adequate. The main research priorities are (Gurwick et al., 2013; Workman et al., 2011): (1) development of novel sorbents to reduce the energy input for direct air-capture technologies and the soda/lime process; (2) optimised design of pyrolysis plants for biochar production (3) integrated testing of CCS with 100% biomass-firing; (4) improved liquefaction processes for artificial trees and (5) systematic studies of biochar effectiveness focussing on repeatability and side-effects.

Electricity storage is a key enabler technology, which will be necessary to accommodate the high level of intermittent renewable generation technologies (i.e. wind and solar) required to decarbonise the electricity sector. Beyond 2050, future scenarios consistent with 2°C have a share of generation

from intermittent renewables upwards of 50%. A rule of thumb is that for every GW of intermittent renewables, 1 GWh of storage is required (Budischak et al., 2013). Electricity storage technologies will be needed to deal with rapid fluctuations in electricity supply. The research priorities for electrical batteries include new cell chemistries emerging from the lithium-ion family such as lithium-air (Grande et al., 2015), lithium-sulphur (Fotouhi et al., 2016) or other metals such as sodium and magnesium (Erickson et al., 2015). These could improve power and charge density (Zhang, 2013), decreasing cost per unit of energy stored. Improved manufacturing techniques and efficient management of battery packs can provide evolutionary cost & performance improvements. Capital costs of lithium-ion batteries packs of around USD 193-254/kWh of storage capacity are possible (Darling et al., 2014) and new cell chemistries could offer further reductions to reach the USD 150/kWh thought to be the threshold for commercialisation of battery technologies for Battery Electric Vehicles (Nykvist and Nilsson, 2015). Less mature electricity storage technologies, such as redox flow batteries, molten salt batteries, flywheels, and power-to-gas could also play an important role in balancing supply and demand over different timescales (from seconds to months), and different scales (distributed and centralised) (Brandon et al., 2016b).

Conclusion

This review has identified 21 technologies that are critical for achieving a low-carbon economy and still require substantial R&D investment before they will be commercially viable. The selected technologies are broadly grouped as follows: carbon capture and storage (CCS), energy-intensive industry, aviation, biofuel and hydrogen supply, negative emissions, and energy storage. Aviation and energy intensive industry are challenging sectors to decarbonise with limited options. Innovation in these sectors is needed to develop new solutions that can provide a step-change in emissions reductions. CCS, negative emissions, and alternative fuel supply technologies are capital intensive, high-risk projects with long payback periods. This means that, particularly in the early stages, private investors will not drive innovation. The timescale for commercialisation of these technologies is likely to be decades. There is an urgent need for investment in innovation now in order for these technologies to be ready for commercial deployment at scale later in the century. Furthermore, it should also be noted, that many of the technologies which were excluded from the short-list for this review still face challenges and barriers to reach the levels of deployment required for limiting global temperature change to 2°C. These technologies would benefit from research into policies and strategies to overcome these barriers.

Technology Discussions

1 Aviation

1.1 Biojet

Description of the technology

Aviation biofuels (usually referred to as biojet or renewable jet fuel (RJF)) are liquid fuels that can be produced from a wide range of biomass sources including vegetable oils, plant materials and animal waste. They describe jet fuels that are “drop-in” alternatives to conventional jet fuels, i.e. they can be used in place of fossil fuel-derived jet fuels with no modification to aircraft.

To ensure the required properties are achieved, biojet is currently blended with fossil fuel derived jet fuel. However, 100% unblended drop-in biojet fuels are in the early stages of development (Fuel Readiness Level¹ 1-3) (E4tech, 2009). A variety of feedstocks suit different process technologies depending on the physical and chemical structure of the biomass used. The aviation industry can currently use biojet fuel blends via the Fischer-Tropsch (FT) process, Hydroprocessed oils and fats (HEFA), and direct sugars to hydrocarbons (DSHC), as long as they are blended with fossil jet fuel up to a certain percentage to reach ASTM (American Society for Testing and Materials) certification standards. Other options include alcohol-to-jet fuel (ATJ) and Hydrogenated Pyrolysis Oils (HPO), both of which are not yet certified (CAAFI, 2011).

Mitigation potential

CO₂ emissions from the aviation sector amounted to 705 Mt in 2013, equivalent to around 2% of global CO₂ emissions (A. Elgowainy, 2012). With demand for aviation expected to rise by around 5% per annum, emissions could be as high as 3100 Mt by 2050 (ATAG, 2014).

Because plants sequester carbon from the atmosphere as they grow, over multiple cycles of growth, harvest, and re-growth, the net carbon emissions from using biojet fuel can be less than the emissions from burning fossil fuels. The carbon sequestered is offset by the energy used in fuel production and also in the CO₂ returned to the atmosphere after combustion in the jet engine. Nevertheless, depending on the feedstock source and fuel conversion technology, biojet fuel pathways can reduce life-cycle emissions by between 20-95% (E4tech, 2009). The carbon intensity of the feedstock is an influential factor; those derived from waste products (municipal wastes, forestry residues, etc.) have high emissions saving potential because the waste is generated even if it is not used as a feedstock. Conversely, conventional oil crops have a reduced savings potential because the embedded fossil fuel derived energy involved in the production phase (fertiliser, harvest, oil extraction, etc.) is relatively large. New energy crops such as *Jatropha* and *Camelina* could

¹ Fuel Readiness Level (FRL) is akin to Technology Readiness Level and provides a way to classify and track the progress in research, certification and demonstration of different fuels in the aviation industry (“CAAFI - Fuel Readiness Tools,” n.d.)

demonstrate increased yields and therefore better CO₂ savings. However, these benefits may be offset by indirect land use change (ILUC) impacts as they compete for land previously used for food production, especially when scaled up to the volumes required for jet fuel supply chains. Current land-use scenarios predict that an increase in the use of biofuels for all forms of transport could increase land requirements to 160 Mha by 2050 from a 2005 baseline of 20 Mha (IEA, 2010).

Current status of development

Biofuel-powered planes have been proven to be technically feasible and blending of up to 50% is now allowed for commercial use (Epstein, 2014). ASTM standards mean that before introduction into jet fuel supply chains, new biojet fuels have to meet a number of performance benchmarks concerning operational and safety requirements for existing jet engines. These include properties such as energy content, freeze point, lubricity and so on. There are currently five certified fuel blends for synthetic and biojet fuels (FRL 7-9), but not all are at full scale commercial production levels. A further sixteen fuel pathways are being reviewed by ASTM (FRL 5-7). Based on industry experience, new biofuel pathways can expect to advance by one FRL every 3-5 years (E4tech, 2009), so assuming a similar rate of progression, new fuels can expect to have advanced by 1-2 levels by 2020. Several international airlines have been involved in pilot schemes with biofuels. Over 2500 flights have been completed by 22 airlines up until mid-2016 (ICAO, 2016). However, currently only two international airports have biojet fuel mixes available for regular airline flights (ICAO, 2016).

Challenges and innovation needs

Biojet fuels are currently uniformly more expensive than conventional jet fuel (Jong, Hoefnagels, Faaij, Slade, Mawhood, & Junginger, 2015). Furthermore, jet fuel constitutes a large proportion of the operating costs of commercial airlines, so at current biojet prices, incentives are not strong enough for airlines to make purchases that are not wholly voluntary. However, airlines may still view investments as an opportunity to decouple their fuel supply from crude oil markets, since its volatility can significantly affect medium term business projections.

Biojet fuel pathways with high feedstock costs will prevent some biojet products from becoming price competitive because the feedstock cost may already exceed the current petroleum-derived jet fuel price. Achieving a competitive minimum fuel selling price (MFSP) therefore requires efficiency gains in the production process, while feedstock costs must be cheap and predictable. Economies of scale, in addition to innovative co-production strategies, present further cost reduction opportunities, but the large investment commitments may necessitate additional policy incentives that focus specifically on biofuels.

Biomass gasification and FT (i.e. BTL) pathways produce fuels with a desirable composition for road transport (Rebecca Mawhood, 2014), increasing the likelihood that they will command a price premium, particularly in jurisdictions with strict road fuel standards such as the US and EU (James I. Hileman, 2009). New engine designs that can cope with the low aromatics composition of biofuels in the FT pathway could open the aviation sector up to cheaper biofuels supply options. However the absence of aromatics reduces the energy density of these fuels, and there is currently little dedication to these pathways by equipment manufacturers.

The current global fleet is approximately 23,000 aircraft with an average age of 10 years and average retirement age of around 25 years (Forsberg, 2014). The current fleet represents a past investment of hundreds of billions of dollars and this significant tied investment and long fleet life-cycle mean that airlines are reluctant to consider new fuels that are not “drop-in” alternatives to current petroleum-derived jet fuel.

1.2 Hydrogen Aircraft

Description of the technology

Hydrogen fuelled aircraft use liquid hydrogen (LH₂) at cryogenic temperatures, and can operate via two different propulsion technologies. The first type functions in a similar way to conventional aircraft, as the fuel is combusted in turbine engines with few modifications. The second is via a hydrogen fuel cell, which converts the chemical energy of a reaction into electricity to power a propeller or ducted fan. The advantage of fuel cells is that the reaction is at a lower temperature, thus eliminating the production of NO_x emissions; H₂O is the only emission when using pure hydrogen. Secondly, the fuel efficiency can be higher because heat is not produced as a by-product, limiting the efficiency of conventional turbine engines. This efficiency may however be negated by the electricity-to-thrust conversion to turn the fan.

In hydrogen aircraft, new materials for tanks, insulation, pipes and pumps, and safety systems are required because of the cryogenic temperatures. New aircraft designs may include those similar to current large passenger aircraft with additional large tanks running above the fuselage, since the liquid hydrogen occupies 4 times the volume of conventional kerosene, although it is 2.6 times lighter for the same energy content. This allows potential new aircraft to be lighter, but more radical designs that optimise air flow while increasing fuel storage capacity, will be needed. Examples include the blended-wing-body (BWB) configuration of NASA’s concept B aircraft (Gynn, Freeh, & Olson, 2004), used for its aerodynamic efficiency and the noise shielding it provides for the top mounted fans, in addition to noise mitigation from the airframe.

Mitigation potential

Hydrogen can be produced by electrolysis from carbon-neutral energy sources, such as solar PV, hydro, and wind, as well as fossil fuel sources with CO₂ capture and storage, or by gasification of biomass. The use of hydrogen could consequently completely eliminate greenhouse gas emissions from the aviation sector. Hydrogen fuelling of aircraft is done from centralised infrastructure (i.e. airports), which means the costs and efficiencies of reduced transport infrastructure can further improve full lifecycle emissions of aircraft.

The primary product of combustion from H₂ is water, with the only secondary emissions of significance being oxides of nitrogen (NO_x). Burning H₂ produces 2.6 times the amount of water vapour than that produced from burning a mass of kerosene with equivalent energy content, which is significant because of water vapour’s greenhouse gas potency at high altitudes (Bob Saynor, 20103). There remains some debate about critical altitudes, with some studies showing that flying above 10 km could make significant contributions to GHG levels (Hans W. Pohl, 1997). Consequently, it is thought that flight altitudes should be reduced for hydrogen aircraft, which would also mean optimising aero designs.

For turbine combustion technology, engines would have to be modified from current forms, in particular to keep NO_x emissions within acceptable levels. Low NO_x emissions are possible with particular modifications to suit H₂ burning properties (A. Contreras, 1997). Fuel cells operate at lower temperatures and produce only H₂O as exhaust emissions.

Current status of development

In 2016, the first 4-seater hydrogen fuel-cell powered plane, with a range of 1,500 km, was successfully flight tested (Pultarova, 2016). This is a promising development for fuel cell technology, but significant technical challenges will need to be overcome for commercial scale hydrogen powered aircraft to become a reality.

Hydrogen is still in the early stages of testing in commercial aircraft; namely, only for use on the ground during taxiing and for powering auxiliary systems during flight. EasyJet is currently developing a hybrid system that captures brake energy to power a fuel cell for taxiing after landing (Carrington, 2016). Airbus has flight tested “Multifunctional Fuel Cells” as a replacement for conventional auxiliary power units that currently use gas turbine power. These include systems for autonomous taxiing and for replacing the aircraft’s back-up hydraulic circuit, potentially providing 100 kW of electricity (Airbus, 2011).

Challenges and innovation needs

Hydrogen aircraft have been the subject of much research in Europe, the USA, Russia and elsewhere since the 1950s. Its limited progress since then has been blamed on the scarcity of carbon-neutral energy sources, which would help mitigate emissions impacts of producing hydrogen via electrolysis, as well as innovations in fuel cell technology for that pathway.

Hydrogen supply from electrolysis, which is energy intensive, could also be superseded by new technologies such as photocatalytic water splitting (Takashi Hisatomi, 2014), (Moniz, Shevlin, Martin, Guo, & Tang, 2015) or microbial processes (Ann Magnuson, 2009). These would reduce the amount of electricity required per unit of hydrogen produced, but are long-term options. Hydrogen supply is currently very low, although recent commitments and increases to renewable energy capacity across the world could make hydrogen production economically viable by utilising excess renewable generation.

The necessary technology to store and deliver hydrogen fuel can be done at a small scale using technologies developed for road vehicles. In a fully developed system, hydrogen could be delivered in gaseous form via pipelines, or produced on site by electrolysis and stored at the airport to be stored in tanks. Storage options for hydrogen are as compressed gas or cryogenic liquid. Equipment for compressed storage is similar to that for natural gas, while large-scale storage of liquid hydrogen will require further development (Heinz G. Klug, 2001).

While fossil fuels, and potentially “drop-in” biofuels will cover the needs of aviation in the next decades, a changeover to more sustainable technologies is desired, and liquid hydrogen, generated from carbon-neutral sources is the only alternative.

2 The Industrial Sector

2.1 Carbon Capture and Storage (CCS)

Description of the technology

There are currently a number of different steel production routes that can be combined with Carbon Capture and Storage (CCS) in different ways. In an integrated steel works or 'BF-BOF' (Blast-furnace to Basic Oxygen Furnace) process, top-gas from the blast furnace can be recycled as a reducing agent reducing the amount of coke required. When this process is operated with pure oxygen, a high concentration stream of CO₂ is produced which can be captured using Vacuum Pressure Swing Adsorption (VPSA). This process is known as BF-TGR-CCS (Blast furnace top gas recovery with CCS) and was developed as part of the ULCOS (Ultra-low CO₂ steel) programme (Abdul Quader et al., 2016). CCS can also be applied to the direct reduced iron (DRI) process with natural gas, coal or even biomass as a fuel. In this process, known as ULCORED, the fuel is partially oxidised to produce a gaseous fuel rich in hydrogen and carbon monoxide, which is used as a reducing agent in the DRI reactor. CO₂ from the partial oxidation stage combined with CO₂ produced in the reactor is removed using VPSA (Knop et al., 2008). A novel process, which was also developed by ULCOS, is the HIsarna process. This is based on the smelt reduction process and operates with pure oxygen resulting in a high concentration of CO₂ in the flue gas which suitable for storage with minimal post-processing (Abdul Quader et al., 2016).

In cement production, CO₂ is generated and released via two sources: combustion of fossil fuels (e.g. coal) and decomposition of CaCO₃ to CaO (main component of cement) and CO₂. Cement CCS refers to a broad spectrum of technologies that can be coupled with a typical cement plant to capture the generated CO₂. In the cement process, the release of CO₂ takes place through four sources: combustion of fossil fuels (40%), raw material transportation and electricity generation for electrical motors and facilities (10%) and about 50% during the decomposition (calcination) of CaCO₃ and MgCO₃ to CaO and MgO, respectively (Benhelal, Zahedi, Shamsaei, & Bahadori, 2013). According to the IEA, of the available CO₂ capture technologies *i.e.* pre-, post- and oxy-fuel combustion capture, the latter two are the most suitable for cement industry. Pre-combustion being least favourable as it does not capture the CO₂ arising from the calcination process.

Mitigation potential

The mitigation potential of CCS applied to industrial processes is high. Carbon Capture and Storage offers one of the few options for truly low carbon production of key basic materials such as steel, cement and certain chemicals. The IEA estimates that by 2050, around 30% of the CO₂ emissions captured through CCS will come from industrial processes (IEA, 2016).

Current status of development

There are some industrial processes in which the production or separation of CO₂ is inherent to the process (e.g. natural gas processes, bio-ethanol production, ammonia/fertiliser production). These processes typically combined with enhanced oil recovery (EOR) have been the sites of some of the early demonstrations of CCS and thus are relatively mature and have been proven at scale. Examples of these include: the Sleipner CO₂ project in Norway which captures CO₂ from a natural

gas stream and was the world's first demonstration of deep saline aquifer storage; the Enid and Coffeyville projects which capture CO₂ from fertiliser production processes and use it for EOR (Global CCS Institute, 2016a).

As part of the ULCOS project, ArcelorMittal was involved in plans to retrofit a post-combustion capture plant to an idled blast furnace in Florange, France (ZeroCO₂, 2015). The demonstration project was expected to capture around 0.5 MtCO₂ per year for storage in a saline aquifer but has since been cancelled due to withdrawal of funding. In November 2016, the Global CCS Institute announced the start of the world's first commercial-scale CCS steel project - the Al Reyadah project in Abu Dhabi. Located in the Mussafah industrial area, the project captures CO₂ from an Emirates Steel plant and injects the CO₂ for Enhanced Oil Recovery. The CO₂ is captured from a gas-fired direct reduced iron furnace using a post combustion amine-based absorption process (Global CCS Institute, 2016b).

Cement CCS has shown a good opportunity for CO₂ capture. There have been some reports on trials carried out for CO₂ capture from cement plants e.g. post-combustion capture with amine scrubbing was analysed based on a cement plant in the Guangdong Province of China (Xu, Yi, & Fan, 2016). However, due to several preventative barriers, as of today, there is no large-scale cement CCS project at any stage of development listed by the Global CCS Institute.

Challenges and innovation needs

The components of carbon capture, transport, injection and storage have been demonstrated individually at commercial scale (Florin and Fennell, 2010). However, large-scale demonstration of CCS is an urgent priority to overcome the challenges of whole systems integration across the CCS chain (LCICG, 2014). The main research priorities for CCS, in general, have been identified (IEA, 2012; UKCCSRC, 2015) as (1) development of advanced adsorption and membrane processes; (2) research into advanced CCS processes such as Ca-looping and (3) improved modelling of CO₂ storage including optimal injection scenarios and expected leakage. The cost of CCS for power generation is estimated at around USD 43-80/tCO₂ (IEA, 2012).

Although there are strong synergies between CCS applied to industrial processes and CCS applied to the power sector, and there will be considerable opportunity for knowledge transfer, there is an urgent need for large-scale demonstration of industrial-specific capture in order to address the process-specific challenges. Each process and even each site is unique and will likely require bespoke equipment and plant design. CCS applied to industrial processes has the potential to be cheaper than CCS for power generation. Current cost estimates range from USD 15-138/tCO₂ for cement and USD 51-64/tCO₂ for steel (Fennell et al., 2012). Research priorities for industrial CCS include (1) improved heat and flow integration, (2) testing the impact of impurities on the capture process and (3) development of novel sorbents which are optimised for industrial operating conditions. In the cement sector, the European Cement Research Academy (ECRA)'s goals is to look at the technical issues and the feasibility of cement CCS (Schneider, Romer, Tschudin, & Bolio, 2011). One of the areas that can be further explored is the techno-economic assessment of the oxy-fuel combustion capture in cement industry and its consequent impact on the clinker production process.

The key challenge ahead of a wide-spread industrial CCS is the lack of comprehensive climate change policies and carbon price in order to encourage CCS in general. Furthermore, a governmentally-backed initiative is essentially required to develop CO₂ transportation pipelines and the subsequent storage facilities.

2.2 Hydrogen in steelmaking

Description of the technology

The use of hydrogen for steel making would provide a breakthrough process for producing steel. Hydrogen steel making could take on a number of different forms. Direct-reduction of solid iron ore with hydrogen rich gas is a relatively straightforward option that is not significantly different from the MIDREX DRI process today. An alternative is to use ionised or atomic hydrogen to reduce molten iron ore. Ionised hydrogen occurs at very high temperatures in the presence of an electric or plasma arc. This process is known as Hydrogen Plasma Smelting Reduction (HPSR) (Hiebler and Plaul, 2004).

Mitigation potential

Hydrogen-steel making has the potential to reduce emissions from steel by more than 80% (Abdul Quader et al., 2016). However, this level of mitigation is contingent on the availability of hydrogen produced from a low-carbon source.

Current status of development

The concept of hydrogen steel making is not a new one, however the technology is still in the early research phase (TRL 1-3). Hiebler and Plaul (2004) have demonstrated the HPSR process at a lab scale with promising results. A number of modelling activities (Ranzani et al., 2013) have been carried out to investigate using hydrogen as a reductant under different conditions.

Challenges and innovation needs

Hiebler and Plaul (2004) list the main research priorities for the HPSR process as to address: (1) continuous pre-heating of the ore fines and transport into the HPSR reactor, (2) design of the reactor and control of the high-energy concentration, (3) control of the necessary large volumes of gas and (4) refractory lining and cooling of the reactor.

2.3 Iron ore electrolysis

Description of the technology

Electrolysis of iron ore is a completely new way of producing iron, which could transform the industry. Two electrolysis options exist: the electrowinning process and Molten Oxide Electrolysis (MOE). Both of these were investigated as part of the ULCOS (Ultra-low carbon dioxide steelmaking) programme and were named, ULCOWIN and ULCOLYSIS, respectively. With electrowinning, iron ore is dissolved in an alkaline electrolyte at just above 100°C. In the ULCOLYSIS process, a molten oxide is used as an electrolyte. Iron ore is dissolved in the electrolyte at 1600°C. Despite the high operating temperature, ULCOLYSIS could theoretically have much lower energy requirements

compared to the electrowinning process as reduction of iron ore occurs more easily at these higher temperatures.

Mitigation potential

Assuming that the electricity for the electrolysis process can be supplied by a carbon neutral source, this technology has the potential to provide a carbon neutral method of producing iron.

Current status of development

Electrolysis of iron ore is still in the laboratory phase but proof of concept has been demonstrated as part of the ULCOS programme.

Challenges and innovation needs

A significant amount of basic research is still required to advance this process. Given that this is currently the only option for zero-carbon steel production without the need for CCS, there is a strong argument for continued research into this nascent technology. The main priority for research is the development of inert anode materials for the MOE process that 'resist depletion but can sustain oxygen evolution' (Allanore et al., 2013). Promising results have been observed with Chromium-based alloys (Allanore et al., 2013) and ferrosinell-based ceramics (Ferreira et al., 2016), but further research is required.

3 Advanced biofuel supply

3.1 Artificial photosynthesis for biofuels production

Description of the technology

Artificial photosynthesis (AP) is the attempt to replicate the ability of organisms to convert carbon dioxide and water to hydrocarbons and oxygen using sunlight. These processes are sometimes referred to as artificial leaves.

Plants produce their own solar fuels through photosynthesis, turning carbon dioxide and water into sugars (made of hydrogen, oxygen and carbon) and oxygen with a solar efficiency of around 0.1–2%. There are two main parts: the splitting of water into hydrogen ions (H⁺) and oxygen (O₂) using light as a source of energy; and the reduction of carbon dioxide (CO₂). Both, or either, of these biological processes can be altered or replaced by an artificial alternative. A completely abiotic system, with photocatalytic nanowires on two sides of an electrically conductive barrier, can convert CO₂ and water to a range of chemicals. A hybrid system of abiotic photocatalysts coupled genetically-modified bacteria to achieve a similar outcome (Liu et al., 2015; Sakimoto et al., 2016).

Mitigation potential

AP could enable the replacement of liquid fossil fuels with renewable, low-carbon alternatives more efficiently than growing biomass and processing it, or than using solar electricity to convert CO₂ conventionally. Due to the eventual emission of CO₂ from their combustion, use of fuels from AP

should be prioritised in sectors where other fuels/chemicals such as hydrogen or electricity cannot replace fossil hydrocarbons, e.g. long-distance air and marine transport (1.4 Gt CO₂ in 2010 (IPCC, 2014)) and chemical manufacture. AP biofuels would also be more suitable for long-term (e.g. inter-seasonal) energy storage than hydrogen.

Current status of development

Non-biological light harvesting to produce electrons is more efficient than natural photosynthesis (see photocatalytic water splitting), but organisms are still more efficient at using those electrons to reduce CO₂ to other chemicals. The US DOE target is a system-wide solar-to-fuel efficiency of 5–10% [REF]. A proof-of-concept nanowire device had a solar-to-fuel efficiency of around 0.12%, roughly the same as natural photosynthesis (Liu et al., 2014).

Challenges and innovation needs

The rates at which catalysts or organisms produce fuels are generally not yet fast enough for commercial application. Separating the electrons from the holes is critical for preventing their recombination and subsequent loss in efficiency, especially because the reduction of CO₂ is so slow in current systems. Development of co-catalysts and organisms that perform charge separation and CO₂ reduction better and faster is critical for the success of the overall concept. Computer simulation of the materials and organisms could provide a more efficient method of identifying promising candidates. Although this is a growing field it is relatively immature and significant investment is required to produce the desired results.

Many current designs use precious or rare elements in their cells. Systems based around more common materials like iron and tungsten could improve both financial viability and scale-up prospects. Finding the optimal balance between harnessing a larger fraction of incident light (low band gap) and providing an over-potential to speed up the kinetics of the process (high band gap) is also important for each system developed.

Artificial photosynthesis has been developed on a small scale in the laboratory but working prototypes have not been designed and built (Liu et al., 2014). The processes tend to use pure CO₂ as a feedstock, but creating systems which can cope with impurities would lower the total cost of a capture-and-use system (Liu et al., 2015).

3.2 Algae for bioethanol production

Description of the technology

Investigation into third generation biofuels, which use algae as a feedstock is gaining interest. The process consists of a number of different stages including: algal cultivation, harvesting, pre-treatment and hydrolysis, fermentation and refining. During cultivation, vast quantities of algae are grown in vessels that ensure the right conditions are maintained for optimal growth, i.e. light, nutrients, water and CO₂. Cultivating methods can range from closed photobioreactors, open ponds or a hybrid system. Harvesting the algae, the next step, is challenging because of the size of microalgae (3-30 microns) and dilution (~1% algae). Various methods have been tested each with their own advantages and disadvantages: centrifugation, gravity sedimentation, filtration, flotation,

immobilization, ultrasonic aggregation, electrolytic method, chemical flocculation, bioflocculation and magnetic nanoparticle separation (Sirajunnisa and Surendhiran, 2016). Once harvested, the algae must be pre-treated to break down cell walls and release the lipids and carbohydrates followed by hydrolysis of the carbohydrates into simple sugars, a process known as 'saccharification'. This is also an energy intensive step and the different methods which are available include: physical pre-treatment using autoclave or ultrasonication, chemical pre-treatment using acids or alkalis and enzymatic pre-treatment. Of these, acid chemical treatment is currently the most widely used (Sirajunnisa and Surendhiran, 2016). Lastly, bioethanol is produced through fermentation typically by yeast or bacteria.

Mitigation potential

Algae are a potential feedstock for biofuel production that are particularly attractive for a number of reasons: They (1) do not compete with food supply for arable land or result in the serious deforestation associated with first and second generation bioethanol production, (2) contain energy rich lipids and carbohydrates, (3) are fast growing and (4) can be cultivated in different environmental types, (5) consume less water than other crops and, lastly (6) can produce commercially valuable co-products. The mitigation potential for algal-based biofuels is largely dependent on its ability to scale up to large-scale production and to compete with conventional fuels. There is a strong mitigation benefit though and it is estimated that 1.5 tonnes of CO₂ is saved for every 1 tonne of algal oil used in place of crude oil (Malik and Tamburic, n.d.).

Current status of development

Although commercial cultivation of algae for various purposes (including aquatic feeds and pharmaceuticals or supplements) has been done since the 1950s there are only a few companies who cultivate algae specifically for biofuel production. In general, large-scale cultivation of algae is achievable: Hutt Lagoon in Western Australia is the largest algae facility in the world and produces algae for food supplements in ponds covering 740 hectares (Campbell-Dollaghan, n.d.). Although there are a small number of commercial biofuel production companies, none of these can be considered 'large-scale'. Sapphire Energy is a demonstration plant funded by the US DoE and has the capacity to produce around 100 bpd [Bloomberg]. Algenol, based in Fort Myers, Florida, is another demonstration plant, which is expected to be completed in 2017 [ref].

Despite its potential, the biofuels market is a challenging one particularly when competing against current low oil prices. The US company 'Solazyme', who won a contract in 2008 to supply algae-based biofuels to the US Navy (Algae Biomass Organization, 2017), has since dramatically scaled down this side of their business and turned to the market for algal oils in the food and cosmetics sector ("Solazyme Ditches Biofuels (& Name) in a World of Cheap Oil," n.d.). Similarly, ExxonMobil who initially in 2009 allocated \$600 million for R&D into algal biofuels, pulled out after four years citing that the technology was at least 25 years away from commercialisation [ref].

Challenges and innovation needs

Harvesting of microalgae is particularly challenging owing to the very low concentration of microalgae in the suspension medium (typically < 1%). This stage of the process contributes 20-40% of the of the total cost of biomass production (Ođadjare et al., 2017). Research into advanced

and innovative solutions for harvesting such as magnetic separation using nanoparticles (Xu et al., 2011) could offer significant energy and cost savings. Nanoparticles can also be used to improve the yield of enzymatic pre-treatment by immobilising the enzymes (Sirajunnisa and Surendhiran, 2016). One novel option for cultivation, which has been proposed is 'non-suspended microalgae cultivation' (Liu et al., 2013) where algae is grown on surfaces and water is only supplied to keep the surface wet. This process has the advantage of reduced water consumption and ease of harvesting. There is considerable opportunity to improve production yields by enhancing the carbohydrate and or lipid content of algae. This can be done through optimisation of growing conditions (i.e. light, nutrients, temperature); however, this seems to be very specific to the particular strain of algae and thus is an area requiring further research and learning-by-doing. Alternatively, there is potential for the development of genetically engineered algae strains which can be optimised for biofuel production (George et al., 2014).

4 Built environment

4.1 Alternative building materials for steel and cement

Description of the technology

Steel and cement are critical construction materials but are responsible for around a third of the energy and half of the CO₂ emissions associated with building structures (Zabalza Bribián et al., 2011). Alternative building methods can drastically reduce emissions in certain circumstances (Robertson et al., 2012), but it is rare that cement and steel can be completely eliminated, especially in applications such as bridges, tunnels and building foundations. Materials that directly replace steel and Portland cement have been invented, but in many cases are underdeveloped.

Mitigation potential

Around half of all steel and virtually all cement is used in construction. Between them, the industries accounted for more than 4 Gt direct CO₂ emission in 2007 (Napp et al., 2014).

Current status of development

Cements which use only small amounts of clinker (the most carbon-intensive constituent), can be used in many situations but are limited by the availability of the replacements, such as blast furnace slag and coal fly ash. This is especially relevant for a low-carbon future where blast furnaces and coal-fired power plants are partially or fully replaced. Completely different compositions which reach IPCC CO₂ intensity requirements are available, such as geopolymers based on metakaolin, slag and sodium silicate, or magnesium silicate cements (Taylor, 2013). However, the former still relies on slag and the latter is only suitable for prefabricated concrete. Alternatives to steel reinforcement in concrete for construction include fibre-reinforced concrete (Afroughsabet et al., 2016). The fibres can be made from a range of materials. However, fibres cannot yet replace structural steel (e.g. steel beams). Replacement with other metals such as non-recycled aluminium could increase emissions (AAC, 2017; SETIS, 2011).

Challenges and innovation needs

For alternative cements, the discovery of low-carbon cementitious systems which do not use materials with likely constrained supply in the future (such as coal fly ash or blast furnace slag) is imperative. The use of widely-available natural materials such as metakaolin is particularly interesting but such mortars cannot yet reach typical Portland cement strengths (Vasconcelos et al., 2011). Wider use of fibre-reinforced concrete could reduce steel demand in construction, and research into renewable options such as bamboo offer hope of widespread low-carbon alternatives (Fairs, 2015; Javadian et al., 2016).

Developing alternatives to structural steel bars and beams is a larger challenge than replacing steel reinforcement in concrete. Manufacture from renewable feedstocks rather than, say, petrochemicals would be a major benefit. In the absence of alternatives, new techniques which increase the fraction of steel from demolished construction sites that can be reclaimed and recycled could reduce the amount of virgin (and therefore high CO₂-intensity) steel that must be produced (Giesekam et al., 2014).

Long-term tests of any replacement to traditional building materials are necessary to increase confidence in their performance. The construction industry is known for its conservative nature, so widespread substitution is likely to be a success only if the new materials are superior to existing ones.

5 Negative emissions technologies

Description of the technology

As the name suggests, direct air capture (DAC) involves direct removal of CO₂ from the ambient air, a concept first introduced for climate change mitigation in 1999 (Sanz-Pérez, Murdock, Didas, & Jones, 2016). DAC has a TRL value of 2-4 (Mclaren, 2011). DAC does not compete with large-scale CCS technology; instead, it provides an atmospheric source of CO₂ (Carbon Engineering, 2017). In this process, CO₂ is directly removed, either physically or chemically, from air and is subsequently used as raw feedstock material in other chemical processes such as polymer synthesis and fuels.

Mitigation potential

DAC technology can eliminate the costly infrastructure required to transport and sequester the captured CO₂. This can be done by utilising the captured CO₂ on site to produce value-added chemicals. In other words, the prominent advantage of DAC is the fact that it has the potential to address emissions from distributed as well as point sources of emissions. Although carbon dioxide utilisation is growing year on year, global consumption of CO₂ compared to the total CO₂ emission is still very low. Therefore, although the use of captured CO₂ can be a short-term option allowing the emerging DAC technologies to mature, it is not a long-term option as a means of CO₂ disposal unless CO₂ can be economically converted to fuels.

Current status of development

The last five years have seen a rapid expansion of reports using various chemi-sorbents for CO₂ capture from ultra-dilute gas streams such as ambient air. At present, DAC systems typically employ solid supported amine-based adsorbents, wherein amine functional groups are bound to the surface of cellulose, porous polymer networks and porous silica materials (Sanz-Pérez, Murdock, Didas, & Jones, 2016). Uncertainty surrounding the effectiveness of direct air capture has produced cost estimates that range between \$100 and \$1000 per tCO₂ (Wilcox & Herzog, 2011).

On a commercial scale, there are a few companies that have started to develop commercial models for DAC. Some of these include: Carbon Engineering, a Canadian start-up, funded in part by Bill Gates, who use a capture solution; Global Thermostat who have designed modular systems capable of capturing up to 40,000 tonnes of CO₂ per year with pilot & commercial demo plants operating since 2010 at SRI International in Menlo Park and; Climeworks who employ filter modules (based on a cyclic chemical adsorption/desorption process on a novel sorbent material) with a capacity of 35 kg/h up to several tons per hour (>99.9% purity) allowing the production of carbon-neutral renewable fuels plus viable storage of renewable energies. Their process utilised low-temperature heat to meet 90% of its energy demand.

Challenges and innovation needs

The key challenge in DAC is the relatively low concentration of CO₂ in the atmosphere (~0.0004 atm vs ~0.15 atm in coal-fired post-combustion capture). In chemical absorption of CO₂ in DAC, the key challenge is the high energy required in regeneration process. The major challenge in the case of physi-sorption, is the competition of CO₂ with other gases and vapours such as N₂ and H₂O (Madden, et al., 2016). DAC is far more challenging to physi-sorbents than post-combustion CO₂ capture. However, DAC could become practical if an adsorbent offered optimum uptake, a good CO₂ selectivity over N₂ and H₂O and an ease of recyclability. Among current technologies, DAC using physi-sorbent materials has been much less studied, presumably due to the lack of feasible materials. Advanced sorbents which capture CO₂ via highly selective physi-sorption routes are potentially-promising materials as they require much less energy for recycling. There exist opportunities for the development of new materials that can capture CO₂ from ultra-dilute gas streams and also, operate under a wide degree range of humidity. It is equally important to develop highly-efficient contacting processes when dealing with ultra-dilute streams. Therefore, there is a significant need to comprehensively study the techno-economic analysis of DAC (Madden, et al., 2016).

5.1 Bioenergy with CCS

Description of the technology

The concept of BECCS was first introduced in the mid-1990s (Mac Dowell & Fajardy, 2016). This process involves the direct combustion of biomass (or its co-combustion with other fuels) in power plants fitted with carbon capture and storage (BECCS). In this process, plants are grown during which they absorb CO₂ from the atmosphere. These plants are then harvested, processed and turned either into pellets or chips. This fuel is then transported to power stations and is burned.

Therefore, with a CO₂ capture unit, BECCS can lead to a negative emission scenario. It currently has a TRL value of 3-7 (Kemper, 2016).

Mitigation potential

BECCS presents a global CO₂ mitigation potential of about 10 Gt_{CO2}/year (Smolker & Ernsting, 2012). However, in the context of CO₂ reduction, a scaled-up BECCS should be more focused on the “occasional selling of electricity” as opposed to a solution to a baseload electricity demand. In other words, the main goal of a BECCS can be to remove CO₂ from the atmosphere while occasionally providing some electricity to the power market. This needs to be seen as a compliment to intermittent renewable power sources and an ancillary to the existing grids (Mac Dowell & Fajardy, 2016).

Current status of development

At present, BECCS is the most widely studied and feasible technology compared to other negative emissions technologies. BECCS is associated with a cost estimate of USD 60-250/t_{CO2}. One of the key requirements of BECCS is land for biomass production. Approximately 500 Mha of land is required to produce around, corresponding to one-third of global crop land (Tokimatsu, Yasuoka, & Nishio, 2017). It has been estimated that by 2050, an annual supply of biomass of 125 EJ will be required if full technical potentials drawn by IEAGHG is deployed (Smolker & Ernsting, 2012). This estimates the importance of the availability of crop and land as a function of time. There has been little research into the large-scale commercial deployment of BECCS. Currently, there are approximately 15 pilot-scale BECCS around the world under construction (Gough & Vaughan, 2015). One of the largest of these, is a corn-to-ethanol plant in Decatur, Illinois, USA with an anticipated capture start date in early 2017. The plant has a capture capacity of 1 mt_{CO2}/year. One of the key pilot-scale research and demonstration projects is the sophisticated Pilot Scale Advanced Capture Technology (PACT) in Sheffield, UK, home to a 250 kW air- and oxy-fired biomass and coal boiler with amine-scrubbers for CO₂ capture. Although there exists several co-firing biomass pilot and commercial plants with coal, there are few equipped with a capture unit.

Challenges and innovation needs

BECCS will require appropriate policy support and integration with general CCS deployment strategies for significant commercial-scale deployment to occur. The availability of substantial accessible supplies of sustainable biomass without impacting on eco-system services and food production is the first key factor in scaling up BECCS. BECCS will be a more costly and less efficient form of power generation than simple low carbon power generation as might be achieved via ordinary CCS. As a result, studies aimed at optimizing the cost and efficiency penalty of BECCS are essential. Also, it will be vital that this distinction is recognised and supported through appropriate policy instruments to enable its deployment. However, since the primary purpose of BECCS is power generation and negative emission is a by-product, BECCS does not need the same level of policy support as technologies purely for negative emissions (Mac Dowell & Fajardy, 2016).

Another key factor in preventing the wide-spread use of BECCS technology is the weak infrastructure for CO₂ transport and storage. Furthermore, the public perception of BECCS needs to be re-shaped via available methods. More research is also needed to be done on the impacts of

BECCS on global market and a comprehensive detailed life-cycle analysis on the entire BECCS cycle.

There are also inherent challenges with biomass combustion that must be appropriately addressed to make biomass combustion viable. Biomass has a less energy density compared to conventional fossil fuels. On the other hand, biomass combustion can lead to a challenging ash deposition which leads to corrosion and also adversely affects the heat transfer efficiencies in boilers. These, in large-scale operations, will lead to frequent shutdowns and additional maintenance and thus an increase in both capital and operating costs of plants. Therefore, further research is required to investigate methods to feasibly reduce ash deposition in biomass-fired and co-fired plants and also to study the effects of various deposition species on the operation of plants. Depending on the biomass composition, the nature of the deposited ash varies and therefore, it is also essential to further study the effect of compositional variation in biomass on ash distribution features during combustion. With a CO₂ capture unit, it becomes also of key importance to minimise the contamination of the working solvent in scrubbers with any ash-related species and therefore, appropriate plans must be devised in order to clean up the generated flue gas associated with any biomass-fired boiler.

5.2 Bio-char

Description of the technology

Bio-char is produced by combusting carbon-rich biomass in a low (or no)-oxygen atmosphere. This process is called pyrolysis and takes place at temperatures below 700 °C. During this process three products are often generated: a carbon-rich solid *i.e.* bio-char, a gas (syngas) and a liquid (bio-fuel) by-product. Bio-char can then be either sent to land or used to enrich agricultural lands and consequently fixing carbon by keeping carbon in soil for years. The sequestered CO₂ will then stay in soil for hundreds of years by carbon burial, preventing the return of biotic carbon to the atmosphere via decomposition and therefore (McLaren, 2012), serving as a carbon sink (Dang, Wright, & Brown, 2015).

Mitigation potential

Bio-char production and its utilisation as a soil nutrient is also seen as a negative-emission process. The sequestration of CO₂ in bio-char can also help to inhibit the release of N₂O and CH₄ from the soil. In practice, approximately for every square metre of soil, a maximum of 3 kg of bio-char has been recommended per annum (British Biochar Foundation, 2017). Using bio-char in pyrolysis/gasification has a potential capacity of 0.9-3.0 Gt_{CO₂} per annum (McLaren, 2012). In addition to this, the (co-) combustion of bio-char in power plants can also contribute to a reduction in total greenhouse gas (GHG) emissions. For instance, it has been reported that with a co-firing ratio of 10% and 20%, GHG emissions were reduced by 4.2% and 8.7% for 1 kWh electricity generated in contrast to electricity generation by coal only (Dang, Wright, & Brown, 2015).

Through the production of bio-char, almost 50% of the initial carbon is retained in the bio-char. Some analysis has shown that almost 12% of total global CO₂ emissions by land use can be off-set annually in soil via bio-char for soil enrichment and thus, can be a long-term solution for CO₂ mitigation (Talberg, 2009).

Current status of development

Since 1980, field trials have been done across the world to study the application of bio-char on specific soils (Talberg, 2009). There have been several field trials led by Cornell University in several countries including the US, Kenya, China, Paraguay, Colombia, Brazil and Zambia (Department of Crop and Soil Sciences, 2017). The effect of the addition of maize-cobs-based bio-char to soil on crop yield has been also investigated in three regions in Zambia (Martinsen, Mulder, Shitumbanuma, Sparrevik, Børresen, & Cornelissen, 2014). Although there have been many studies on the production and application of bio-char in a range of areas, the use of bio-char as a soil nutrient is still under research investigation and trials: “Bio-char for soil impact” and “bio-char pyrolysis” technologies currently hold TRL values of 1-2 and 3-4, respectively (Lomax, Lenton, Adeosun, & Workman, 2015).

Challenges and innovation needs

An important area for further study is the interaction of bio-char with various soils across the world. This mainly comprises the capacity to use bio-char for soil application *i.e.* as nutrient and/or soil enhancement and also the mean CO₂ residence time in soil, allowing long-term CO₂ capture and potentially establishing a negative emission route.

The techno-economic benefits of bio-char as either fuel or a soil-enhancement product is also highly contextual and requires further studies. This information is vital in order to decide the most appropriate method in bio-char end utilisation.

Scale-up of slow pyrolysis processes also requires further studies. The effect of various operational parameters such as temperature and reaction time on the stability and the yield of bio-char product requires further investigation.

5.3 Ocean Liming (OL)

Description of the technology

In this process, CO₂ is naturally captured from the atmosphere and is stored in the oceans as bicarbonate ions. In this process, limestone is first extracted and calcined during which the generated CO₂ is captured using the available methods *e.g.* post combustion capture scrubbers. The produced calcium oxide is then shipped to the ocean and is directly dispersed in large scale. The resulting increase in the pH of the surface water then leads to a rapid absorption of the atmospheric CO₂. This technology has a TRL value of 2-4 (McLaren, 2012).

Mitigation potential

Limestone deposits cover about 10% of the earth’s land surface, and are distributed widely. Thus, availability of limestone is unlikely to be a limiting factor in this process. Also, the cost of crushed limestone is approximately USD 8/t, half of which is typically attributed to crushing energy *i.e.* a material cost of USD 4/t. It has been calculated that based on a global scale industry (4500 sites and 100 dedicated vessels) sequestering 1 GtCO₂/year, would consume approximately 1% of current global energy production (Renforth, Jenkins, & Kruger, 2013). Also, for the OL technology to

reduce a 0.1 ppm reduction in CO₂ concentration per annum, an average total cost of around USD 90/tCO₂ has been estimated (McGlashan, Shah, Caldecott, & Workman, 2012).

Current status of development

The OL process involves two key steps: a) the calcination of crushed limestone in high-temperature kilns and its post grinding and b) the transportation of the primary limestone and the lime product. When deployed at a scale to reduce atmospheric levels of CO₂ in the order of ppm levels, the entire process comprising the transport, slaking and dispersion will need a fleet of vessels similar in size to the world's aggregate transportation fleet. Sea transport is therefore, the main bottleneck and is a critical disadvantage to the technology advancement (McGlashan, Shah, Caldecott, & Workman, 2012). At present, the cost to carry out this process varies between 72 and USD 159 /tCO₂, depending on the feedstock and process used. The technology is energy intensive requiring between 0.6 and 5.6 GJ thermal and 0.1 and 1.3 GJ electrical per tonne of capture CO₂ (Renforth, Jenkins, & Kruger, 2013).

Challenges and innovation needs

Based on the energy requirement for this process, the cost of OL is intrinsically linked to global energy prices, which are likely to increase in the coming century. The variation in the operating costs within acceptable norms can result in a final price range between USD 64 to 173/tCO₂. At present, these costs are stemmed from the uncertainty in geological sequestration of CO₂ and the cost of energy. The energy associated with the calcination process also needs to be further optimised as it needs less energy compared to the cement kiln. The OL final costs are comparable with the direct air capture (DAC) and bioenergy carbon capture and storage (BECCS) processes (Renforth, Jenkins, & Kruger, 2013). Future research is therefore, needed to optimise the process costs. In terms of research, large distribution of lime across the whole ocean can pose major intervention into the natural balance of the environment (McGlashan, Shah, Caldecott, & Workman, 2012), therefore, it is vital to further probe into the actual effect of a limited scale deployment of this technology on ocean acidification and the disturbance of ecosystems. There are currently preventative protocols such as London Convention which must be critically reviewed prior to the process being scaled up to beyond pilot scale.

5.4 Soda/Lime Process

Description of the technology

In this technology an aqueous sodium hydroxide solution is used to directly capture CO₂ from the air in a conventional scrubbing column. The resulting sodium carbonate is then passed through a causticizer and finally a calciner in which CO₂ is regenerated for compression, transport and storage (McGlashan, Shah, Caldecott, & Workman, 2012).

Mitigation potential

The soda/lime process may seem complicated; however, this process is relatively easy to develop and operate as most of its process components have already been in large-scale operations for years. The overall effect of this process is, in fact, generating a concentrated CO₂ stream from a

very dilute CO₂ source *i.e.* atmospheric air while continuously re-circulating the working reagents. Therefore, in terms of mitigation impacts, this process offers the ease of operation and reliability compared to other direct air capture processes. However, there are still energy-related obstacles inherent to this process which are yet to be addressed.

Current status of development

Although the sub-processes integrated in a conceptual soda process plant are all well understood and have been long used on industrial scales (e.g. in chemical and cement industries), the application of soda lime in direct air capture is still under study and requires further investigation for large-scale deployment. Soda-lime has a TRL value of 3-4 (McLaren, 2012). This entire process was first fully conceptualised in 2004 (Zeman & Lackne, 2004). Since then, there have been several techno-economic analyses on the entire process (Kruger, 2010; Stolaroff, Keith, & Lowry, 2008). However, to the knowledge of the author, there has not been any full-cycle experimental nor pilot-scale investigation reported in this area.

Challenges and innovation needs

In terms of technicalities, soda process is a better understood technology compared to the other negative emissions technologies. Therefore, cost estimates are more accurate and there are fewer associated technological risks. However, this technology is the most costly compared to other air capture processes; in order to meet a 0.1 ppm reduction in the atmospheric CO₂, this process would cost approximately USD 155/tCO₂ total and would require 200 absorption units. Furthermore, the energy requirement in this process is significantly high. Another important challenge in the location of the plant. During this process, water is lost from the scrubbing columns as a result of the air passing through them. This will consequently, impacts the optimum location for the plant (McGlashan, Shah, Caldecott, & Workman, 2012).

Owing to the energy-intensity of the lime-soda process, the viability of this process is highly dependent on the local energy *i.e.* fuel costs. Therefore, this process could be more economical to operate in regions with lower costs of fuels. It is therefore, essential to minimise the operating costs of this process in order to make it viable on large scales. Therefore, further studies on the process optimisation and energy integration are seen to be of critical importance. Further research is especially required to be done on (McGlashan, Shah, Caldecott, & Workman, 2012): (1) Development of novel working sorbents, (2) minimisation of capital costs of plants and (3) improvement of the process thermodynamics. Finally, it is equally important to develop CO₂ transportation and storage facilities linked to these sites in order to make this process possible.

6 Energy Storage

6.1 Thermal Cycle

Description of the technology

This category encompasses a number of technologies, all of which store heat energy within insulated repositories, but involve different modes of operation. Liquid air energy storage (LAES) involves the

liquefaction of air, during times of peak supply. This liquid air is stored in a tank, and brought back to a gaseous state (by exposure to ambient air or with waste heat from an industrial process) at times of peak demand, and uses that gas to turn a turbine and generate electricity. Pumped heat energy storage (PHES) involves the pumping of heat from a cold gravel tank to a hot gravel tank at times of peak supply, and the use of this temperature difference to drive a turbine to produce electrical energy at times of peak demand. Both technologies tend to operate at higher efficiencies if co-located with a facility able to provide industrial waste heat (Luo et al., 2015).

Mitigation potential

Thermal cycle technologies offer the possibility of storing relatively large quantities of energy over a period of hours, helping to contribute to balancing intermittent supply from renewables to variable demand. There are no specific geographical requirements for thermal technologies, offering an advantage over pumped hydropower and compressed air energy storage, but they often operate at higher efficiencies if co-located with an industrial facility able to provide waste heat.

Current status of development

The UK firm Highview Power Storage successfully operated a pilot LAES plant at 350kW/2.5MWh from 2011 – 2014, and are currently constructing a 5MW/15MWh plant, expected to be operational from mid 2016 (Highview Power Storage, 2016). The UK firm Isentropic were developing PHES, and constructed prototype plants, but went into administration in 2016 (Isentropic, 2016).

Challenges and innovation needs

Key developments in this technology are likely to come as a result of learning through larger scale demonstration projects, and specific redesign of components. Development of new and better materials storage of heat is an area of significant attention in research (Cabeza, 2014), and learning from innovations in heat pumps and thermal stores could feed in to developments in these technologies.

6.2 Flywheels

Description of the technology

Flywheels are accelerated by a motor using electricity. The electrical energy is then stored as the mechanical inertia of the rotating flywheel. This energy can be retrieved when the process is reversed with the motor acting as a brake in generator mode to extract the energy. (Arup, 2012) Flywheels can be classified into two groups, low speed and high speed. Low speed flywheels are made of steel and rotate below 6,000 rpm. High speed flywheels use advanced composite materials, such as carbon-fiber, which can run up to 100,000 rpm. (Luo et al., 2015) Flywheels exhibit rapid response times, high power density, high efficiency (up to 95%) and a virtually unlimited number of cycles owing to the use of robust mechanical components (Arup, 2012; Luo et al., 2015).

Mitigation potential

Flywheels could play an important role in frequency response, rapidly providing and absorbing electrical energy when output from renewables fluctuates. Flywheels only supply power only for a short durations (~15min) as a result of their low energy and high self-discharge rates (up to 20% of stored capacity per hour). However, flywheels for long-term operation up to several hours are currently being studied (Luo et al., 2015). Whilst relatively little formal analysis of environmental impact has been carried out, flywheels rely on robust mechanical components, and are reported to have a low carbon footprint (Oberhofer and Meisen, 2012).

Current status of development

Around 1 GW of stationary flywheels are installed worldwide. Thereof, 900 MW are flywheels used in fusion reactors. The remaining 100 MW of flywheels are used in stationary storage applications. They are mostly used to maintain power quality for the grid and have an energy capacity of around 20 MWh. (Sandia National Laboratories, 2015)

Challenges and innovation needs

Due to the robust housing and operation in a vacuum, flywheels are relatively expensive at 1,000 – 2,000 £/kW. (Akhil et al., 2013; Luo et al., 2015) Improved flywheel material could increase rotation speed, which would translate into even higher power densities, and could ultimately reduce cost. Flywheels for long-term operation up to several hours are currently being studied (Luo et al., 2015)

6.3 Power-to-Gas

Description of the technology

Power-to-Gas (PtG) plants convert electricity into hydrogen (H₂) or synthetic methane (CH₄, natural gas). This gas is then stored in tanks, caverns or the gas grid and can be re-electrified, used in transport, heat generation or in industrial applications as feedstock. Whether producing hydrogen or methane, electricity is first converted into H₂ using an electrolyser. Electrolyser types include alkaline, proton exchange membrane (PEM) and solid oxide (SOEC). Alkaline electrolysers represent the most mature and lowest cost of these technologies, but PEM has the advantages of more rapid response, operation at higher pressures, and a more rapid level of innovation. SOEC is not currently commercial, but represents a potentially promising electrolysis technology. H₂ may be further processed to CH₄ by combining it with carbon dioxide (CO₂) in thermo-chemical or biological reactors, using catalysts or bacteria respectively, at an additional monetary and system efficiency cost.

Mitigation potential

By converting electricity into a gas, PtG plants can make renewable power available for other energy sectors (transport, heat) and the chemical industry. Given that energy conversion and storage is decoupled, large amounts of energy can be stored while utilizing existing gas network infrastructure, which could make this technology particularly attractive for seasonal storage. Analysis of wind/electrolysis systems indicates that wind turbines contribute a much larger fraction of embedded

energy than electrolysers. Little attention has so far been directed to the toxicity of materials used in electrolysis systems (Bhandari et al., 2014).

Current status of development

While alkaline electrolysis is relatively mature with an installed capacity of 7.5 – 12 GW worldwide, there are only around 50 PtG pilot plants with a total capacity of below 20 MW using alkaline or PEM electrolysis systems (Gahleitner, 2013; Schoots et al., 2008). SOEC remains at laboratory stage.

Challenges and innovation needs

High electrolyser cost represents the most important barrier to PtG deployment. Relatively low efficiencies and relatively slow response to changes in power supply represent additional limitations (Bertuccioli et al., 2014). Cost reduction could be achieved by technical improvements such as increasing current densities, reducing catalyst loadings, operating at higher temperatures or developing higher or differential pressure systems. Manufacturing scale-up by production automation, cost-effective production methods and supply chain development are also likely to play an important role in reducing costs. Another field for innovation is the systems integration, including the methanation step.

6.4 Lithium-Ion Battery

Description of the technology

Lithium ion batteries are an electrochemical technology, typically received by the end user as a packaged battery unit. This unit will consist of a number of lithium ion cells together with packaging, thermal management systems, and electronics for battery management. During charging and discharging, lithium ions suspended in an electrolyte shuttle between a cathode and anode within the cells. Lithium ion batteries exhibit very different costs and performance depending on materials used, and the mechanical structure of the battery itself.

Mitigation potential

Lithium-ion batteries are capable of operating at off-grid scales, have relatively high cycle life, respond quickly demand and high volumetric and gravitational energy densities. They are suitable for frequency response, and balancing supply and demand throughout the day, but their capital cost per capacity is likely to make them unsuitable for storage over longer periods.

Current status of development

Lithium ion batteries are relatively mature for consumer electronics applications (Hanna et al., 2015), increasingly mature for electric vehicles (~1.2 million vehicle stock in 2015) (International Energy Agency, 2016) and less mature for stationary applications (~1GW/1GWh installed) (US Department of Energy, 2016). However, alongside improvements associated with industrial manufacturing, LiBs remain

an area of active academic and industrial research, both at a fundamental chemistry level, and at manufacturing and engineering levels in order to improve cost, lifetime, and safety of devices (Brandon et al., 2016a; Cluzel and Douglas, 2012a).

Challenges and innovation needs

Improvements in manufacturing procedures and basic chemistry could reduce cost, increase energy density, cycle life, safety, recyclability, and dependence on scarce materials (such as nickel and cobalt). Research is directed towards the development of new materials at a laboratory scale (Brandon et al., 2016a; Cluzel and Douglas, 2012b; Crabtree et al., 2015), new processing techniques (Green et al., 2003; Li and Wang, 2013), and better understanding of the behaviour and degradation processes associated with device operation, and how these can be best controlled (Grolleau et al., 2014; Hunt et al., 2016; Idaho National Laboratory, 2015; Wang et al., 2011). There exist a number of possible post lithium-ion technologies with similar battery architectures, which could eventually offer similar or better performance at a lower material cost (such as sodium-ion and lithium-sulphur). However, these technologies currently remain at demonstration stage.

6.5 Redox Flow Battery

Description of the technology

Flow batteries use two liquid electrolytes, one positively charged, and one negatively charged as energy carriers. The electrolytes are separated using a membrane, which selected ions pass through and undergo chemical reactions during charge and discharge. The electrolytes are stored in separate tanks and is pumped into the battery when required, allowing the size of electrolyte tanks to define capacity. (Arup, 2012) Vanadium redox flow batteries (VRFBs) using vanadium electrolytes represent the most mature redox flow technology. Zinc bromide hybrid flow batteries (ZFB), where zinc is plated and removed during charge and discharge represent another commercialised technology. A number of other chemistries are under development at a fundamental research level (Alotto et al., 2014).

Mitigation potential

Redox flow batteries have the potential to operate at a range of scales, including in a large scale grid context, and an off-grid context. The high cycle life of VRBs makes them promising in terms of cost for long-term applications (over hours). However, very fast response has also been reported for some devices, offering the possibility of contributing to frequency response in the future. Redox flow batteries (RFBs) offer the potential to decouple power and energy, making them particularly versatile in terms of design. ZFBs have a lower cycle life than VRFBs, but rely on more abundant materials, and have the potential to reach lower costs.

Current status of development

The US Department of Energy (DoE) (US Department of Energy, 2016) identify a total of 20 MW/49 MWh of grid-connected VRFB projects, and 1.0 MW/2.6MWh of ZFB projects have been constructed worldwide. An additional 28 MW/107MWh of VRFB and 59 MW/232 MWh of ZFB announced or under construction.

Challenges and innovation needs

Fundamental scientific challenges remain in understanding flow and material behavior, understanding performance degradation, and selection of corrosion-resistant materials for pumps, pipes, etc. These improvements could increase lifetime and power density, driving down system costs (Alotto et al., 2014; Lux Research, 2014; Weber et al., 2011).

6.6 High Temperature, Sodium-based Batteries

Description of the technology

High temperature sodium batteries operate above 250°C. The liquid sodium on the anode is separated by a sodium-ion conducting ceramic electrolyte from the active material on the cathode. (Hueso et al., 2013). The most prominent high temperature batteries are sodium-sulphur (NaS) and sodium-nickel-chloride (Na-Ni-Cl or *Zebra*).

Mitigation potential

High power and high energy density systems are suited for grid-scale balancing of intermittent supply from renewables to variable demand from consumers. Abundant, non-toxic materials promise low material costs and good recyclability. Battery operation is independent from ambient temperatures and allows deep depth-of-discharge at relatively high cycle life. (Hueso et al., 2013; Luo et al., 2015)

Current status of development

With 530 MW/3,700 MWh installed capacity, Sodium-Sulphur batteries are one of the most commonly employed storage technologies for grid-scale applications. Sodium-Nickel-Chloride batteries were piloted in EVs in the 1990s/2000s and around 18 MW/ 50 MWh are currently installed in grid-scale applications (NGK, 2015; Sandia National Laboratories, 2015).

Challenges and innovation needs

The relatively high energy/ power ratio make the batteries ill-suited for high power applications. Sodium and Sulphur can cause a violent reaction when the separating ceramic ruptures. As a result Sodium-Sulphur cells are hermetically sealed making external temperature control impossible. (Hueso et al., 2013) Inorganic solid electrolytes are promising high ionic conductivity at lower temperatures (<200°C), which could increase cycle life, reduce the need for external heat provision and increase safety.

References

- AAC, 2017. Aluminium smelting greenhouse performance [WWW Document]. Australian Aluminium Council. URL <http://aluminium.org.au/climate-change/smelting-greenhouse-performance>
- Abdul Quader, M., Ahmed, S., Dawal, S.Z., Nukman, Y., 2016. Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO₂) Steelmaking

- (ULCOS) program. *Renewable and Sustainable Energy Reviews* 55, 537–549. doi:10.1016/j.rser.2015.10.101
- Afroughsabet, V., Biolzi, L., Ozbakkaloglu, T., 2016. High-performance fiber-reinforced concrete: a review. *J Mater Sci* 51, 6517–6551. doi:10.1007/s10853-016-9917-4
- Akhil, A.A., Huff, G., Currier, A.B., Kaun, B.C., Rastler, D.M., Chen, S.B., Cotter, A.L., Bradshaw, D.T., Gauntlett, W.D., 2013. DOE / EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA, Sandia National Laboratories.
- Algae Biomass Organization, 2017. Algae Industry - All About Algae [WWW Document]. URL <http://allaboutalgae.com/commercial-production/> (accessed 2.22.17).
- Allanore, A., Yin, L., Sadoway, D.R., 2013. A new anode material for oxygen evolution in molten oxide electrolysis. *Nature* 497, 353–356. doi:10.1038/nature12134
- Alotto, P., Guarnieri, M., Moro, F., 2014. Redox flow batteries for the storage of renewable energy: A review. *Renewable and Sustainable Energy Reviews* 29, 325–335. doi:10.1016/j.rser.2013.08.001
- Arup, 2012. Five minute guide - Electricity Storage Technologies. doi:10.1007/978-88-470-1998-0_8
- ATAG, 2014. Aviation Benefits Beyond Borders. Air Transport Action Group.
- AVOID 2, 2015. AVOID 2 climate change research programme [WWW Document]. URL <http://www.avoid.uk.net/> (accessed 12.12.16).
- Bertuccioli, L., Chan, A., Hart, D., Lehner, F., Madden, B., Eleanor Standen, 2014. Fuel cells and hydrogen Joint undertaking Development of Water Electrolysis in the European Union.
- Bhandari, R., Trudewind, C.A., Zapp, P., 2014. Life cycle assessment of hydrogen production via electrolysis - A review. *Journal of Cleaner Production* 85, 151–163. doi:10.1016/j.jclepro.2013.07.048
- Brandon, N.P., Edge, J.S., Aunedi, M., Barbour, E., Bruce, P., Carter, D., Chakrabarti, B., Esterle, T., Somerville, J., Ding, Y., Fu, C., Grant, P., 2016a. UK Research Needs in Grid Scale Energy Storage Technologies.
- Brandon, N.P., Edge, J.S., Aunedi, M., Barbour, E.R., Bruce, P.G., Chakrabarti, B.K., Esterle, T., Somerville, J.W., Ding, Y.L., Fu, C., Grant, P.S., Hall, P.J., Huang, C., Leng, G.H., Li, Y.L., Martins, V.L., Navarro, M.E., Posada, J.O.G., Rennie, A.J.R., Rogers, D.J., Strbac, G., Villar, S.P., Yufit, V., Wang, J., Worsley, D.A., 2016b. UK research needs in grid scale energy storage technologies (White Paper).
- Budischak, C., Sewell, D., Thomson, H., Mach, L., Veron, D.E., Kempton, W., 2013. Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. *Journal of Power Sources* 225, 60–74. doi:10.1016/j.jpowsour.2012.09.054
- CAAFI - Fuel Readiness Tools [WWW Document], n.d. URL <http://www.caafi.org/information/fuelreadinesstools.html#FRL> (accessed 2.22.17).
- Cabeza, L.F., 2014. *Advances in Thermal Energy Storage Systems: Methods and Applications*. Elsevier.
- Campbell-Dollaghan, K., n.d. Australian Magenta Ponds Are The World's Largest Beta-Carotene Farm [WWW Document]. URL <https://www.gizmodo.com.au/2013/06/australian-magenta-ponds-are-the-worlds-largest-beta-carotene-farm/> (accessed 2.22.17).
- Carrington, D., n.d. EasyJet's plans for a hybrid fleet, using hydrogen fuel cells [WWW Document]. CNN. URL <http://www.cnn.com/2016/02/02/aviation/easyjet-hybrid-plane-hydrogen-fuel-cell/index.html> (accessed 1.26.17).
- Cluzel, C., Douglas, C., 2012a. Cost and performance of EV batteries - Element Energy report for Committee on Climate Change [WWW Document].
- Cluzel, C., Douglas, C., 2012b. Cost and performance of EV batteries - Element Energy report for Committee on Climate Change [WWW Document].
- Crabtree, G., Kócs, E., Trahey, L., 2015. The energy-storage frontier: Lithium-ion batteries and beyond. *MRS Bulletin* 40, 1067–1078. doi:10.1557/mrs.2015.259

- Darling, R.M., Gallagher, K.G., Kowalski, J.A., Ha, S., Brushett, F.R., 2014. Pathways to low-cost electrochemical energy storage: a comparison of aqueous and nonaqueous flow batteries. *Energy Environ. Sci.* 7, 3459–3477. doi:10.1039/C4EE02158D
- DfT, 2007. Low Carbon Transport Innovation Strategy.
- Elgowainy, A., Han, J., Wang, M., Carter, N., Stratton, R., Hileman, J., Malwitz, A., Balasubramanian, S., 2012. Life Cycle Analysis of Alternative Aviation Fuels in GREET. Argonne National Laboratory.
- Epstein, A.H., 2014. Aeropropulsion for Commercial Aviation in the Twenty-First Century and Research Directions Needed. *AIAA Journal* 52, 901–911. doi:10.2514/1.J052713
- Erickson, E.M., Markevich, E., Salitra, G., Sharon, D., Hirshberg, D., Llave, E. de la, Shterenberg, I., Rosenman, A., Frimer, A., Aurbach, D., 2015. Review—Development of Advanced Rechargeable Batteries: A Continuous Challenge in the Choice of Suitable Electrolyte Solutions. *J. Electrochem. Soc.* 162, A2424–A2438. doi:10.1149/2.0051514jes
- Fairs, M., 2015. Bamboo fibre is stronger and cheaper than steel says ETH professor [WWW Document]. *Dezeen*. URL <https://www.dezeen.com/2015/11/04/bamboo-fibre-stronger-than-steel-dirk-hebel-world-architecture-festival-2015/> (accessed 2.22.17).
- Fennell, P.S., Florin, N., Napp, T., Hills, T., 2012. CCS from industrial sources. *Sustainable Technologies, Systems and Policies*.
- Ferreira, N.M., Kovalevsky, A.V., Ferro, M.C., Costa, F.M., Frade, J.R., 2016. A new concept of ceramic consumable anode for iron pyroelectrolysis in magnesium aluminosilicate melts. *Ceramics International* 42, 11070–11076. doi:10.1016/j.ceramint.2016.04.004
- Florin, N., Fennell, P.S., 2010. Carbon capture technology: future fossil fuel use and mitigating climate change (Briefing Paper No. 3). Grantham Institute for Climate Change.
- Fotouhi, A., Auger, D.J., Propp, K., Longo, S., Wild, M., 2016. A review on electric vehicle battery modelling: From Lithium-ion toward Lithium–Sulphur. *Renewable and Sustainable Energy Reviews* 56, 1008–1021. doi:10.1016/j.rser.2015.12.009
- Gahleitner, G., 2013. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *International Journal of Hydrogen Energy* 38, 2039–2061. doi:10.1016/j.ijhydene.2012.12.010
- George, B., Pancha, I., Desai, C., Chokshi, K., Paliwal, C., Ghosh, T., Mishra, S., 2014. Effects of different media composition, light intensity and photoperiod on morphology and physiology of freshwater microalgae *Ankistrodesmus falcatus* – A potential strain for bio-fuel production. *Bioresource Technology* 171, 367–374. doi:10.1016/j.biortech.2014.08.086
- Giesekam, J., Barrett, J., Taylor, P., Owen, A., 2014. The greenhouse gas emissions and mitigation options for materials used in UK construction. *Energy and Buildings* 78, 202–214. doi:10.1016/j.enbuild.2014.04.035
- Global CCS Institute, 2016a. Introduction to industrial carbon capture and storage (Special Report), Global Status of CCS.
- Global CCS Institute, 2016b. The Global Status of CCS: 2016.
- Grande, L., Paillard, E., Hassoun, J., Park, J.-B., Lee, Y.-J., Sun, Y.-K., Passerini, S., Scrosati, B., 2015. The Lithium/Air Battery: Still an Emerging System or a Practical Reality? *Advanced Materials* 27, 784–800. doi:10.1002/adma.201403064
- Green, M., Fielder, E., Scrosati, B., Wachtler, M., Moreno, J.S., 2003. Structured Silicon Anodes for Lithium Battery Applications. *Electrochemical and Solid-State Letters* 6, A75. doi:10.1149/1.1563094
- Grolleau, S., Delaille, A., Gualous, H., Gyan, P., 2014. Calendar aging of commercial graphite / LiFePO₄ cell e Predicting capacity fade under time dependent storage conditions. *Journal of Power Sources* 255, 450–458. doi:10.1016/j.jpowsour.2013.11.098
- Gurwick, N.P., Moore, L.A., Kelly, C., Elias, P., 2013. A Systematic Review of Biochar Research, with a Focus on Its Stability in situ and Its Promise as a Climate Mitigation Strategy. *PLOS ONE* 8, e75932. doi:10.1371/journal.pone.0075932

- Hanna, R., Gross, R., Speirs, J., Heptonstall, P., Gambhir, A., 2015. Assessment Innovation timelines from invention to maturity. UKERC Technology and Policy Assessment.
- Hiebler, H., Plaul, J.F., 2004. Hydrogen Plasma Smelting Reduction - an Option for Steelmaking in the Future. *Metalurgija* 43, 155–162.
- Highview Power Storage, 2016. Projects [WWW Document].
- Hisatomi, T., Kubota, J., Domen, K., 2014. Recent advances in semiconductors for photocatalytic and photoelectrochemical water splitting. *Chem. Soc. Rev.* 43, 7520–7535. doi:10.1039/C3CS60378D
- Hueso, K.B., Armand, M., Rojo, T., 2013. High temperature sodium batteries: status, challenges and future trends. *Energy & Environmental Science* 6, 734. doi:10.1039/c3ee24086j
- Hunt, I.A., Zhao, Y., Patel, Y., Offer, G.J., 2016. Surface Cooling Causes Accelerated Degradation Compared to Tab Cooling for Lithium-Ion Pouch Cells. *Journal of the Electrochemical Society* 163, 1846–1852. doi:10.1149/2.0361609jes
- Idaho National Laboratory, 2015. Vehicle Battery Testing [WWW Document]. URL <https://avt.inl.gov/content/vehicle-battery-testing>
- IEA, 2016. Energy Technology Perspectives 2016. International Energy Agency.
- IEA, 2012. Energy Technology Perspectives 2012 Pathways to a Clean Energy System. International Energy Agency.
- IEA, 2010. Energy technology perspectives 2010: scenarios and strategies to 2050. IEA ; OECD, Paris, France.
- International Energy Agency, 2016. Global EV Outlook 2016 Beyond one million electric cars.
- IPCC, 2014. Fifth Assessment Report - Mitigation of Climate Change.
- Isentropic, 2016. Technology [WWW Document]. URL <http://www.isentropic.co.uk/Technologies> (accessed 5.18.16).
- Javadian, A., Wielopolski, M., Smith, I.F.C., Hebel, D.E., 2016. Bond-behavior study of newly developed bamboo-composite reinforcement in concrete. *Construction and Building Materials* 122, 110–117. doi:10.1016/j.conbuildmat.2016.06.084
- Knop, K., Hallin, M., Burstroem, E., 2008. Ulcored SP 12 Concept for minimized CO2 emission, in: Proceedings of the 4th Ulcos Seminar.
- LCICG, 2014. Co-ordinating Low Carbon Technology Innovation Support: The LCICG's Strategic Framework. The Low Carbon Innovation Co-ordination Group.
- Li, X., Wang, C., 2013. Engineering nanostructured anodes via electrostatic spray deposition for high performance lithium ion battery application. *Journal of Materials Chemistry A* 1, 165–182. doi:10.1039/c2ta00437b
- Liu, C., Dasgupta, N.P., Yang, P., 2014. Semiconductor Nanowires for Artificial Photosynthesis. *Chemistry of Materials* 26, 415–422. doi:10.1021/cm4023198
- Liu, C., Gallagher, J.J., Sakimoto, K.K., Nichols, E.M., Chang, C.J., Chang, M.C.Y., Yang, P., 2015. Nanowire-bacteria hybrids for unassisted solar carbon dioxide fixation to value-added chemicals. *Nano Lett.* 15, 3634–3639. doi:10.1021/acs.nanolett.5b01254
- Liu, T., Wang, J., Hu, Q., Cheng, P., Ji, B., Liu, J., Chen, Y., Zhang, W., Chen, X., Chen, L., Gao, L., Ji, C., Wang, H., 2013. Attached cultivation technology of microalgae for efficient biomass feedstock production. *Bioresource Technology* 127, 216–222. doi:10.1016/j.biortech.2012.09.100
- Luo, X., Wang, J., Dooner, M., Clarke, J., 2015. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy* 137, 511–536. doi:10.1016/j.apenergy.2014.09.081
- Lux Research, 2014. Lower-cost Flow Batteries to create \$190 Million Energy Storage Market in 2020 [WWW Document]. URL <http://www.luxresearchinc.com/news-and-events/press-releases/read/lower-cost-flow-batteries-create-190-million-energy-storage>
- Magnuson, A., Anderlund, M., Johansson, O., Lindblad, P., Lomoth, R., Polivka, T., Ott, S., Stensjö, K., Styring, S., Sundström, V., Hammarström, L., 2009. Biomimetic and Microbial

- Approaches to Solar Fuel Generation. *Accounts of Chemical Research* 42, 1899–1909. doi:10.1021/ar900127h
- Malik, A., Tamburic, B., n.d. Sustainable oil from algae: the technology is ready, but what about the politics? [WWW Document]. *The Conversation*. URL <http://theconversation.com/sustainable-oil-from-algae-the-technology-is-ready-but-what-about-the-politics-44969> (accessed 2.22.17).
- Moniz, S.J.A., Shevlin, S.A., Martin, D.J., Guo, Z.-X., Tang, J., 2015. Visible-light driven heterojunction photocatalysts for water splitting – a critical review. *Energy Environ. Sci.* 8, 731–759. doi:10.1039/C4EE03271C
- Napp, T.A., Gambhir, A., Hills, T.P., Florin, N., Fennell, P.S., 2014. A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries. *Renew Sustain Energy Rev* 30, 616–640. doi:10.1016/j.rser.2013.10.036
- NGK, 2015. Sodium-Sulfur Battery - Renewable Applications & NAS Battery. Tokyo.
- Nykvist, B., Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change* 5, 329–332. doi:10.1038/nclimate2564
- Oberhofer, A., Meisen, P., 2012. *Energy Storage Technologies & Their Role in Renewable Integration* July 2012.
- Odjadjare, E.C., Mutanda, T., Olaniran, A.O., 2017. Potential biotechnological application of microalgae: a critical review. *Critical Reviews in Biotechnology* 37, 37–52. doi:10.3109/07388551.2015.1108956
- Pultarova, T., 2016. Hydrogen-powered aircraft takes to sky in Germany [WWW Document]. URL <https://eandt.theiet.org/content/articles/2016/09/hydrogen-powered-aircraft-takes-to-sky-in-germany/> (accessed 1.26.17).
- Ranzani, D.C., Wagner, D., Patisson, F., 2013. Modelling a new, low CO2 emissions, hydrogen steelmaking process. *Journal of Cleaner Production* 46, 27–35. doi:10.1016/j.jclepro.2012.07.045
- Robertson, A.B., Lam, F.C.F., Cole, R.J., 2012. A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete. *Buildings* 2, 245–270. doi:10.3390/buildings2030245
- Sakimoto, K.K., Wong, A.B., Yang, P., 2016. Self-photosensitization of nonphotosynthetic bacteria for solar-to-chemical production. *Science* 351, 74–77. doi:10.1126/science.aad3317
- Sandia National Laboratories, 2015. DOE Global Energy Storage Database [WWW Document].
- Schoots, K., Ferioli, F., Kramer, G.J., van der Zwaan, B.C.C., 2008. Learning curves for hydrogen production technology: An assessment of observed cost reductions. *International Journal of Hydrogen Energy* 33, 2630–2645. doi:10.1016/j.ijhydene.2008.03.011
- SETIS, 2011. Energy efficiency and CO2 reduction in the iron and steel industry. European Commission.
- Sirajunnisa, A.R., Surendhiran, D., 2016. Algae – A quintessential and positive resource of bioethanol production: A comprehensive review. *Renewable and Sustainable Energy Reviews* 66, 248–267. doi:10.1016/j.rser.2016.07.024
- Solazyme Ditches Biofuels (& Name) in a World of Cheap Oil [WWW Document], n.d. . *Fortune*. URL <http://fortune.com/2016/03/16/solazyme-teravia-ditches-biofuels/> (accessed 2.22.17).
- Taylor, M.G., 2013. Novel cements: low energy, low carbon cements (No. 12), MPA Cement Fact Sheet. Mineral Products Association.
- UKCCSRC, 2015. RAPID Research and Pathways to Impact Development Handbook 1.1b - Research Area Summaries and Needs. UK Carbon Capture and Storage Research Centre.
- US Department of Energy, 2016. DOE Global Energy Storage Database [WWW Document]. URL www.energystorageexchange.org/ (accessed 4.19.16).
- Vasconcelos, E., Fernandes, S., Barroso de Aguiar, J.L., Pacheco-Torgal, F., 2011. Concrete retrofitting using metakaolin geopolymer mortars and CFRP. *Construction and Building Materials* 25, 3213–3221. doi:10.1016/j.conbuildmat.2011.03.006

- Wang, J., Liu, P., Hicks-garner, J., Sherman, E., Soukiazian, S., Verbrugge, M., Tataria, H., Musser, J., Finamore, P., 2011. Cycle-life model for graphite-LiFePO₄ cells. *Journal of Power Sources* 196, 3942–3948. doi:10.1016/j.jpowsour.2010.11.134
- Weber, A.Z., Mench, M.M., Meyers, J.P., Ross, P.N., Gostick, J.T., Liu, Q., 2011. Redox flow batteries : a review. *Journal of Applied Electrochemistry* 41, 1137–1164. doi:10.1007/s10800-011-0348-2
- Workman, M., McGlashan, N., Chalmers, H., Shah, N., 2011. An assessment of options for CO₂ removal from the atmosphere. *Energy Procedia* 4, 2877–2884. doi:10.1016/j.egypro.2011.02.194
- Xu, L., Guo, C., Wang, F., Zheng, S., Liu, C.-Z., 2011. A simple and rapid harvesting method for microalgae by in situ magnetic separation. *Bioresource Technology* 102, 10047–10051. doi:10.1016/j.biortech.2011.08.021
- Zabalza Bribián, I., Valero Capilla, A., Aranda Usón, A., 2011. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment* 46, 1133–1140. doi:10.1016/j.buildenv.2010.12.002
- ZeroCO₂, 2015. ULCOS Florange Fact Sheet: Carbon Dioxide Capture and Storage Project.
- Zhang, S.S., 2013. Liquid electrolyte lithium/sulfur battery: Fundamental chemistry, problems, and solutions. *Journal of Power Sources* 231, 153–162. doi:10.1016/j.jpowsour.2012.12.102
- A. Contreras, S. Y. (1997). Hydrogen as aviation fuel: A comparison with hydrocarbon fuels. *International Journal for Hydrogen Energy* , 22 (10-11), 1053-1060.
- A. Elgowainy, J. H. (2012). *Life-cycle analysis of alternative aviation fuels in GREET*. Argonne National Laboratory.
- Airbus. (2011, July 6). *Airbus and German Aerospace Centre (DLR) perform research tests for fuel cell powered autonomous taxiing*. From Airbus: <http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/airbus-and-german-aerospace-centre-dlr-perform-research-tests-for-fuel-cell-powered-autonomous-taxi/>
- Ann Magnuson, M. A. (2009). Biomimetic and Microbial Approaches to Solar Fuel Generation. *Acc. Chem. Res* , 42 (12), 1899–1909.
- ATAG. (2014). *Aviation: Benefits beyond borders*. Geneva: Air transport Action Group.
- BANK, T. I.-A. (2010). *An Approach to Reconciling the Financing of Cement Manufacturing Plants with Climate Change Objectives*.
- Benhelal, E., Zahedi, G., Shamsaei, E., & Bahadori, A. (2013). Global strategies and potentials to curb CO₂ emissions in cement industry. *Journal of Cleaner Production* , 51, 142-161.
- Berta Matas Guell, M. B. (2012). *Benchmark of conversion and production technologies for synthetic biofuels for aviation*. SINTEF Energy Research.
- Bob Saynor, A. B. (2010). *The potential for renewable energy sources in aviation*. Imperial College Centre for Energy Policy and Technology.
- British Biochar Foundation. (2017, 2 8). From <http://www.britishbiocharfoundation.org/>
- CAAFI. (2011). *Path to alternative jet fuel readiness*. CAAFI.
- Carbon Engineering. (2017, 2 15). *Carbon Engineering*. From <http://carbonengineering.com/>
- Carrington, D. (2016, January 26). *EasyJet's plan for hybrid fleet, using hydrogen fuel cells*. Retrieved January 26, 2017 from <http://www.cnn.com/2016/02/02/aviation/easyjet-hybrid-plane-hydrogen-fuel-cell/index.html>
- Cotton, C. A., Douglass, J. S., Causmaeker, S. D., Brinkert, K., Cardona, T., Fantuzzi, A., et al. (2015). Photosynthetic constraints on fuel from microbes. 3.

- Dang, Q., Wright, M. M., & Brown, R. C. (2015). Ultra-Low Carbon Emissions from Coal-Fired Power Plants through Bio-Oil Co-Firing and Biochar Sequestration. *Environmental Science and Technology*, 49, 14688-14695.
- Department of Crop and Soil Sciences. (2017, 2 16). *Cornell University, Soil Fertility Management and Soil Biogeochemistry*. From <http://www.css.cornell.edu/faculty/lehmann/research/biochar/biocharproject.html>
- E4tech. (2009). *Review of the potential for biofuels in aviation*. London: E4tech.
- Epstein, A. H. (2014). Aeropropulsion for Commercial Aviation in the Twenty-First Century and Research Directions Needed. *American Institute of Aeronautics and Astronautics, Inc.*, 52 (5), 901-911.
- Forsberg, D. (2014). *World fleet forecast 2014 - 2033*. Avolon.
- Gough, C., & Vaughan, N. (2015). *Synthesising existing knowledge on the feasibility of BECCS*. AVOID 2 programme (DECC).
- Guynn, M. D., Freeh, J. E., & Olson, E. D. (2004). *Evaluation of a Hydrogen fuel cell powered blended-wing-body aircraft concept for reduced noise and emissions*. NASA.
- Hans W. Pohl, V. V. (1997). Hydrogen in future civil aviation. *International Journal of Hydrogen Energy*, 22 (10-11), 1061-1069.
- Heinz G. Klug, R. F. (2001). CRYOPLANE: hydrogen fuelled aircraft — status and challenges. *Air & Space Europe*, 3 (3-4), 252-254.
- ICAO. (2016). *ICAO Global Framework for Aviation Alternative Fuels (GFAAF)*. Retrieved 12 15, 2016 from <http://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx>
- IEA. (2010). *Energy Technology Perspectives 2010*. Paris: International Energy Agency.
- James I. Hileman, D. S. (2009). *Near-term feasibility of alternative jet fuels*. RAND Corporation.
- Jong, S. d., Hoefnagels, R., Faaij, A., Slade, R., Mawhood, R., & Junginger, M. (2015). The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. *Biofuels, Bioproducts and Biorefining*, 778–800.
- Joyce E. Penner, D. H. (1999). *Aviation and the global atmosphere*. Intergovernmental Panel on Climate Change.
- Kemper, J. (2016). Biomass with carbon capture and storage. *ghgt-13*. Lausanne.
- Lomax, G., Lenton, T. M., Adeosun, A., & Workman, M. (2015). Investing in negative emissions. *Nature climate Change*, 5, 498-500.
- Mac Dowell, N., & Fajardy, M. (2016). On the potential for BECCS efficiency improvement through heat recovery from both post-combustion and oxy-combustion. *Faraday Discussions*, 192, 241-250.
- Madden, D. G., Scott, H. S., Kumar, A., Chen, K.-J., Sanii, R., Bajpai, A., et al. (2016). Flue-gas and direct-air capture of CO₂ by porous metal–organic materials. *Philosophical Transactions of the Royal Society A*, 375 (2084).
- Martinsen, V., Mulder, J., Shitumbanuma, V., Sparrevik, M., Børresen, T., & Cornelissen, G. (2014). Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming. *Journal of Plant Nutrition and Soil Science*, 177, 681–695.
- McGlashan, N., Shah, N., Caldecott, B., & Workman, M. (2012). High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection*, 90, 501–510.
- McLaren, D. (2012). A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection*, 90, 489–500.
- McLaren, D. (2011). *NEGATONNES – AN INITIAL ASSESSMENT OF THE POTENTIAL FOR NEGATIVE EMISSION TECHNIQUES TO CONTRIBUTE SAFELY AND FAIRLY TO MEETING CARBON BUDGETS IN THE 21ST CENTURY*. Friends of the Earth.
- Moniz, S., Shevlin, S., Martin, D., Guo, Z.-X., & Tang, J. (2015). Visible-light driven heterojunction photocatalysts for water splitting - a critical review. *Energy & Environmental Science*, 8 (3), 731-759.

- Niven Winchester, D. M. (2013). *Market cost of renewable jet fuel adption in the United States*. partnership for AiR Transportation Noise and Emissions Reduction.
- Novelli, P. (2014). *Sustainable way for alternative fuels and energy in aviation*. the European Comission.
- Pultarova, T. (2016). *Hydrogen-powered aircraft takes to sky in Germany*. Retrieved January 26, 2017 from <https://eandt.theiet.org/content/articles/2016/09/hydrogen-powered-aircraft-takes-to-sky-in-germany/>
- Rebecca Mawhood, A. R. (2014). *Establishing a European renewable jet fuel supply chain: the techno-economic potential of biomass conversion technologies*. Imperieal College London. London: Renjet.
- Renforth, P., Jenkins, B., & Kruger, T. (2013). Engineering challenges of ocean liming. *Energy* , 60, 442-452.
- Sanz-Pérez, E. S., Murdock, C. R., Didas, S. A., & Jones, C. W. (2016). Direct Capture of CO₂ from Ambient Air. *Chemical Reviews* , 116, 11840–11876.
- Schneider, M., Romer, M., Tschudin, M., & Bolio, H. (2011). Sustainable cement production—present and future. *Cement and Concrete Research* , 41, 642–650.
- Smolker, R., & Ernsting, A. (2012). *BECCS (Bioenergy with Carbon Capture and Storage): Climate saviour or dangerous hype?* biofuelwatch.
- Sustainable Aviation. (2015). *Aircraft on the ground CO₂ reduction programme*.
- Takashi Hisatomi, J. K. (2014). Recent advances in semiconductors for photocatalytic and photoelectrochemical water splitting. *Chem. Soc. Rev* , 43, 7520-7535.
- Talberg, A. (2009). *The basics of biochar*. Science, Technology, Environment and Resources Section . Parliament of Australia.
- Tokimatsu, K., Yasuoka, R., & Nishio, M. (2017). Global zero emissions scenarios: The role of biomass energy with carbon capture and storage by forested land use. *Applied Energy* , 185, 1899–1906.
- Wilcox, J., & Herzog, H. (2011). Economic and Energetic Analysis of Capturing CO₂ from Ambient Air. *Proceedings of the National Academy of Sciences of the United States of America* , 108, 20428–20433.
- Xu, J.-H., Yi, B.-W., & Fan, Y. (2016). A bottom-up optimization model for long-term CO₂ emissions reduction pathway in the cement industry: A case study of China. *International Journal of Greenhouse Gas Control* , 44, 199–216.
- Zeman, F. S., & Lackne, K. S. (2004). Capturing carbon dioxide directly from the atmosphere. *World Resource Review* , 16 (2), 157-172.

Appendix: Full technology list

Subsector	Mitigation Option	Include?	Motivation for inclusion/exclusion
Aviation	Hydrogen-powered planes	Yes	Mitigation potential: High - liq H2 is relatively dense (1000-3100 Mt CO ₂ /y in 2050), TRL: 1-3
	Battery-powered planes	No	Mitigation potential: Low - can't do long distances
	Biofuel-powered planes	Yes	Mitigation potential: High - drop-in for current jets (1000-3100 Mt CO ₂ /y in 2050), TRL: 7-9 but limited alternatives for this sector
Marine transport	H2 fuel cell power	No	Mitigation potential: High (2.5% of current emissions (1 Gt/y); 2-3 Gt CO ₂ / in 2050), TRL: 7-9
	Biofuels	No	Mitigation potential: High (2.5% of current emissions (1 Gt/y); 2-3 Gt CO ₂ / in 2050), TRL: 7-9
	Battery-powered ships for short distances (e.g. ferries)	No	Mitigation potential: Low - can't do long distances so assume only domestic waterborne transport (130 Mt CO ₂ /y in 2010), TRL: 7-9
	Nuclear	No	Mitigation potential: High (2.5% of current emissions (1 Gt/y); 2-3 Gt CO ₂ / in 2050), TRL: 7-9
	Sail	No	Mitigation potential: Low - only replaces a fraction of energy requirements (10-20% of 2.5% (0.25-0.5%) of current emissions), TRL: 7-9
	LNG	No	Mitigation potential: Medium - still emits around half the CO ₂ (50% of marine emissions), TRL: 7-9
	CCS	No	Mitigation potential: Medium - not practical on smaller ships (50% of marine emissions?), TRL: 1-3 but other more suitable alternatives exist
Land transport	Electric vehicles	No	Mitigation potential: High - almost complete replacement of fossil fuel (5.15 Gt CO ₂ , 10% of GHGs in 2010), TRL: 7-9
	Fuel cell electric vehicles	No	Mitigation potential: High - almost complete replacement of fossil fuel (5.15 Gt CO ₂ , 10% of GHGs in 2010), TRL: 7-9
	Autonomous vehicles	No	Mitigation potential: Low (3-25% of road transport emissions; but could perhaps lead to an increase in emissions!), TRL: 7-9

	Biofuels	No	Mitigation potential: High - complete replacement of fossil fuel (5.15 Gt CO ₂ , 10% of GHGs in 2010), TRL: 7-9
Cement Industry	CCS	Yes	Mitigation potential: High - >90% of emissions (7% of current emissions, and growing. At least 2.25 Gt CO ₂ /y in 2050), TRL: 4-6
	Concrete CO ₂ curing	No	Mitigation potential: Low (3.8 Mt/y in EU), TRL: 4-6
	Biomass as a fuel	No	Mitigation potential: Medium - only does 40% of emissions (i.e. combustion) from a BAT Portland cement plant (1.5 Gt CO ₂ /y), TRL: 7-9
Steel industry	DRI with CCS	Yes	Mitigation potential: High (3 Gt CO ₂ /y in 2050), TRL: 4-6
	BF/BOF with CCS	Yes	Mitigation potential: High (3 Gt CO ₂ /y in 2050), TRL: 4-6
	Hydrogen Blast Furnace	Yes	Mitigation potential: High (3 Gt CO ₂ /y in 2050), TRL: 1-3
	Iron ore electrolysis	Yes	Mitigation potential: High (3 Gt CO ₂ /y in 2050), TRL: 1-3
Chemicals Industry	CCS	Yes	Mitigation potential: High (5.5 Gt/y in 2050), TRL: 4-6
	Bio-feedstocks	Yes	Mitigation potential: High , TRL: 1-3
Biofuels supply	Artificial Photosynthesis	Yes	Mitigation potential: Medium, TRL: 1-3
	CCU to fuels	No	Mitigation potential: Low, TRL: 4-6
	Biomass grown on marginal land	No	Mitigation potential: Medium (0.8 Gt CO ₂ /y), TRL: 7-9
	Algae	Yes	Mitigation potential: Medium (30 Mt CO ₂ /y per 1% of non-arable land across 56 countries), TRL: 4-6
	Macroalgae	No	Mitigation potential: Low (160 Mt CO ₂ /y per 1% of global offshore EEZs (117 000 km ²)), TRL: 4-6
The Built Environment	Low-emission steel substitutes	Yes	Mitigation potential: High (1.5 Gt/y in 2050), TRL: 4-6
	Alternative low-carbon, non-Portland cements	Yes	Mitigation potential: High - depends on exact formulation & process (7% of current emissions, and growing. At least 2.5 Gt CO ₂ /y in 2050), TRL: 4-6

	Fuel switch to electricity	No	Mitigation potential: High (3-4 Gt CO ₂ /y in 2040), TRL: 7-9
	Fuel switch to hydrogen (fuel cells)	No	Mitigation potential: High (3-4 Gt CO ₂ /y in 2040), TRL: 7-9
	Fuel switch to biomass	No	Mitigation potential: High (3-4 Gt CO ₂ /y in 2040), TRL: 7-9
	Smart building & heating controls	No	Mitigation potential: Low (0.6-0.8 Gt CO ₂ in 2040), TRL: 7-9
	Passive climate control	No	Mitigation potential: High (1.5-4 Gt CO ₂ in 2040), TRL: 7-9
	Heat networks	No	Mitigation potential: Medium, TRL: 7-9
Electricity Networks & Generation	High penetration of intermittent renewables	No	Mitigation potential: High (13.7 Gt CO ₂ in 2013), TRL: 7-9
	Geothermal	No	Mitigation potential: Low (3.5% of electricity production in 2050 = 800 Mt CO ₂), TRL: 7-9
	Gas used as peaking plants	No	Mitigation potential: High, TRL: 7-9
	Use of biomass	No	Mitigation potential: High (13.7 Gt CO ₂ in 2013), TRL: 7-9
	Emerging generation methods (wave, tidal etc)	No	Mitigation potential: Medium (Wave: 4.6% of 2.11 TW = 97 GW max; or 500-2700 GW max. Tidal: 120 GW; 20-800 GW), TRL: 4-6 but there are many other alternatives for the electricity sector
	Solar PV	No	Mitigation potential: High, TRL: 7-9
	Offshore wind	No	Mitigation potential: High (1-3 TW wind in total in 2030), TRL: 7-9
	Nuclear	No	Mitigation potential: High (13.7 Gt CO ₂ in 2013), TRL: 7-9
	Saline aquifer storage of CO ₂	Yes	Mitigation potential: High (Up to 15 Gt/y), TRL: 4-6
Negative emissions technologies	Direct Air Capture (artificial trees)	Yes	Mitigation potential: High (4 Gt (0.5 ppm) per year), TRL: 1-3
	Ocean Disposal	Yes	Mitigation potential: High (4 Gt (0.5 ppm) per year), TRL: 1-3
	BECCS	Yes	Mitigation potential: High (4 Gt (0.5 ppm) per year), TRL: 4-6

	Biochar	Yes	Mitigation potential: High (4 Gt (0.5 ppm) per year), TRL: 1-3
	Soda-lime	Yes	Mitigation potential: High (4 Gt (0.5 ppm) per year), TRL: 1-3
Electricity Storage	Grid-scale battery storage	Yes	Mitigation potential: High, TRL: 4-6