ENERGY STORAGE: THE MISSING LINK IN THE UK'S ENERGY COMMITMENTS.

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> **UK GOVERNMENT NEEDS TO WORK WITH INDUSTRY TO PRODUCE A COMPREHENSIVE ENERGY STORAGE ROADMAP TO FULLY MAXIMISE OUR ENERGY UTILISATION POTENTIAL.**
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This report highlights the need for the Westminster and Holyrood governments to prioritise the development and deployment of energy storage technologies if they are to ever meet targets for renewable energy use and reductions in greenhouse gas (GHG) emissions. This report also provides a comprehensive review of current energy storage technologies for electricity, heat and transport, and highlights the need for a broader spectrum of consideration and understanding in how these can be used to meet our future energy needs and targets.

This report has been produced in the context of the Institution's strategic themes of Energy, Environment, Education, Manufacturing and Transport and its vision of 'Improving the world through engineering'.

Cover image:
The London Array is the world's largest offshore wind farm. Its 175 turbines are capable of generating enough power to supply nearly half a million UK homes and reduce harmful CO_2 emissions by over 900,000 tonnes a year. Energy storage would help ensure the Array's power is fully utilised.

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Aquamarine Power's Oyster 800 Wave Energy Converter in operation.

EXECUTIVE SUMMARY

REALISING OUR 2020 AND 2050 TARGETS

Government aspirations for a reduction in greenhouse gas (GHG) emissions are driving the deployment of renewable energy technologies across the globe. In the UK this is evident in the targets that have been set in response to both the EU Renewable Energy Directive 2009 and the 2008 Climate Change Act. In the case of the former, the UK is committed to meet 15% of its overall energy demand from renewable sources by 2020, and the latter sets a legally binding target to reduce GHG emissions by 80% relative to 1990 levels by 2050. In Scotland, the devolved administration has set itself the additional target to deliver the equivalent of 100% of the country's gross electricity consumption from renewables-sourced generation by 2020.

It is important in this regard however to note the possible effects Scottish independence could have on a future UK renewable strategy. The Scottish Government has aspirations post-independence to develop a market in the sale of 'green' energy to the rest of the remaining UK and beyond, and without Scotland in the union there would likely have to be renegotiation of the UK's renewable energy targets within the context of both the remaining UK and wider EU.

In the short term, in order to meet the 15% target set by the EU, the UK Government is focusing on the deployment of readily available mature technologies that can deliver electricity from renewable energy sources, largely wind and solar. In the longer term, the Government also anticipates meeting the target set by the Climate Change Act through the use of a broad range of 'low-carbon' electricity generation to power a largely electricity-based economy. This will drive further deployment of renewables, adding wave and tidal generation to the mix. The Scottish aspiration for a substantial component of electricity generation sourced from renewables is self-evident in its 2020 target. This electricity-centred approach presents significant technical challenges, not least in dealing with the fact that the renewable sources of energy being utilised are largely intermittent and have seasonal variation, but also in the requirement to replace large amounts of heat and transport infrastructure with electricity-powered technologies. The latter is indicated by the fact that UK energy demand annually is currently about 41% heat and 33% transport, with only 26% being for electricity.

THE INTERMITTENCY CHALLENGE

The intermittency challenge of renewable sources arises from the fact that the wind does not always blow, the sun does not always shine and the waves are not always in motion at times when consumers demand electricity. On the other hand the converse is also true, in that consumer demand for power can be low when renewable energy sources are highly active. Even tidal sources of energy are problematic in this respect, as although they are predictable years in advance, because the times at which electricity generation can take place are dictated by the progress of the lunar cycle, synchronisation with customer demand will not always occur.

This issue of so-called 'wrong time' electricity generation leads to technical challenges in balancing supply and demand across the power transmission and distribution system. Currently in such cases the renewable generators are often simply switched off. Under existing market arrangements, an energy company unable to supply its electricity output to the grid is entitled to 'constraint payments'. Even at present levels of renewables deployment, these constraint payments are becoming a major concern to consumers, who are effectively funding the non-supply of electricity; National Grid constraint payments to wind farm operators were about £34 million between 2011 and 2012 (on just one day in August 2013, £1.84m was paid to operators of 28 wind farms in Scotland to turn off their turbines and not generate electricity). This figure represents just over 10% of the total paid to all generators. However given that less than 5% of electricity is currently produced from wind sources, as the installed capacity of renewables increases in the future the issue of payments will likely become of increasing concern.

The traditional approach to solving the balancing problem of not having sufficient power, which in the past has arisen when baseload generation has been insufficient to meet peak demand, has been to install back-up power generation in the form of spare flexible gas turbine capacity. However, the latter is a source of GHG emissions, in the form of carbon dioxide (CO_2), and therefore using this solution to mitigate the intermittency of renewables would ultimately be a step in the wrong direction, if the goal is to move to low-carbon generation sources.

THE ENERGY STORAGE SOLUTION

Energy storage provides a potential route to a solution to this challenge, in that it would enable wrong-time electricity generated from intermittent renewable sources to be put to use at times when consumer demand is higher than baseload provision and renewables supply is at low levels. It would also help to address the seasonal challenge. In this regard consumer demand for power and heat is typically higher in the winter months than in the summer, and longer-term storage would allow energy from renewable sources to be carried over from one season to the next. The use of energy storage in both these ways would allow greater returns on investment to be made from deployed renewable energy technologies. Other benefits from storing energy in the UK can include deferring the costs associated with upgrading energy distribution systems to supply expanding towns and urban areas, as well as allowing communities to become more self-sufficient in energy sourcing and management. The latter helps build national and local resilience to the impacts of extreme weather and other disruptive events – the need for this having been clearly highlighted recently in the January 2014 storms and floods – as well as encouraging citizen engagement in the transition to a low-carbon economy.

A wide range of technologies are either currently in development or already commercially available to store energy, the most widely known being those of batteries and pumped storage, and most are based on mechanical, chemical or thermal processes. In order to store electricity, because it is an energy vector and not a form of primary energy, it is necessary to use the power to drive a process that coverts the electricity into another energy form. For example, electricity can be used to drive compressors to pressurise air for storage in underground caverns, to power chillers to liquefy air that can then be stored as a cryogen, or to accelerate flywheels to higher rotational velocities. When power needs to be returned from these stores, the processes can be reversed to drive turbines through depressurisation or thermal expansion or deceleration (‘braking’) respectively. Storing heat is in many ways more straightforward, and at the simplest level involves the use of insulated tanks containing a material in which a temperature change can be induced, such as water, sand or ceramics. Other methods can involve using the heat in chemical reactions that can later be reversed to recover heat, such as inducing phase changes in materials or thermochemical processes. However, the biggest challenge for heat, and possibly the principal reason it has not been paid sufficient attention in the past, is the widely distributed nature of both domestic and industrial heat use in the UK. There is much to be learnt from Denmark in this regard.

Another area of particular challenge is that of energy storage for transport vehicles, which today is almost universally supplied by fossil fuel-based hydrocarbon liquid fuels carried in onboard tanks. Given that the UK Government’s aspiration for lowering emissions from the land-based component of this sector (cars, lorries, trains etc) is largely based on electrification, the current focus is primarily on batteries as a replacement energy store. Another option which has had high levels of attention is that of converting to a hydrogen-based system. However, in both cases it is possible that the engineering, time and cost involved in undertaking a large-scale replacement of the nation’s extensive liquid-fuels infrastructure, with the necessary low-carbon recharging infrastructure, may have been significantly underestimated. Alternative energy storage possibilities could include biofuel and synthetic fuel systems, which can make full use of the existing liquid fuel infrastructure, as well as novel approaches such as liquid air and flywheels that have potential in niche applications.

In recognition of the need to enable an increase in the deployment of renewable energy systems in the UK, and the importance of heat and transport energy demand alongside that for electricity, the Institution of Mechanical Engineers has produced this comprehensive review of storage technologies. In addition to understanding the possible applications, advantages, disadvantages, state of development, availability and sustainability of each of the technologies, it is important to know what needs to change to motivate the further development and deployment of such systems. In this regard, the first step is for UK Government to work closely with industry to produce a roadmap for energy storage to achieve its full potential, not only in terms of its contribution to achieving the nation’s emissions reductions, but also in unlocking overseas export potential for UK technology and engineering. Such a roadmap should, in addition to electricity applications, consider heat and transport.

Energy storage has been hailed by UK Energy & Climate Change Minister the Rt Hon Gregory Barker MP as a 'silver bullet' and the Rt Hon David Willetts MP, Minister for Universities & Science, as one of the 'eight great technologies which will propel the UK to future growth'. However, in order to turn these political statements into reality, the UK Government needs to recognise that, as with all 'decarbonisation' technologies during the transition to a low-carbon economy, energy storage infrastructure comes with upfront costs for development and deployment that will need publicly funded R&D budgets, market restructuring and market support, and will add to consumer energy bills. It is important that the longer-term benefits for energy security, increased resilience, community market participation, export opportunities and ultimately lower energy costs, are recognised as worth the short-term investment.

RECOMMENDATIONS

The Institution of Mechanical Engineers encourages adoption of the following recommendations:

1. **Government needs to focus on heat and transport, as well as electricity**. It is well understood that security of supply is crucial and that decarbonisation of the UK energy system desirable, but in contrast to past thinking it should not be confined to simply having sufficient electricity generating capacity to 'keep the lights on'. With a growing amount of the UK's fossil fuel supplies being imported, and rapidly increasing global competition for remaining resources, it is in the national interest to utilise freely available indigenous renewable resources for heat and transportation as well as electricity generation. Government needs to work with the engineering community to develop new and innovative systems that include energy storage to cope with the intermittency and seasonality challenges that these renewable sources present.
2. **Government must recognise that energy storage cannot be incentivised by conventional market mechanisms**. It is unlikely that the nation's long-term decarbonisation objectives will be met without significant deployment of energy storage capability, yet there are no plans in the UK for significant levels of energy storage. To date very little public investment has been made in research, development and demonstrator activity and, as yet, there is no existing or proposed incentivisation scheme for energy storage deployment. In order to stimulate the sector and ensure that UK has the capability to deliver energy storage, as well as exploit emerging export opportunities, new public finance and business models are required to fund this key element of the nation's future energy system. The Government must lead the way for industry by developing a clear roadmap for the development, demonstration and deployment of energy storage in the UK and create an energy storage shop window to the world.
3. **The UK must reject its obsession with 'cheapness' in the energy sector**. Despite current concern over rapidly increasing energy costs, and the reactive political promises that are unlikely to be fulfilled, it is evident that whatever form of energy is used in the UK, costs will have to continue to rise into the future. In comparison with other European countries, the UK has for decades focused on keeping energy prices artificially low, which has led to over-consumption of energy, while the necessary demand-side reduction measures have not been put in place. This attitude must change and an alternative culture developed which recognises the value of energy and drives sus tainable change in the nation's energy system.

For the Scottish Government to achieve its ambition of the equivalent of 100% gross electricity consumption from renewables, parallel deployment of energy storage technologies is needed to ensure the energy produced during periods of low demand is not wasted.

WHY ENERGY STORAGE?

‘Energy storage’ is one of the ‘buzz phrases’ of today’s energy world. However, as with many similar technically based topics, it appears to be widely misunderstood. Governments can see energy storage as a tool to help them meet their renewable energy targets. Environmentalists see it as a means of enabling reductions in CO_2 and other greenhouse gas (GHG) emissions, and energy suppliers see it as a route to optimised performance, ‘asset-sweating’ and savings on some conventional infrastructure investment. All of these are indeed valid perspectives and possible outcomes, but it is important to understand what energy storage is and, more importantly, what it can and cannot do.

In the natural world, energy storage as a process is as old as the universe itself. The energy present at the initial formation of the universe has been stored in stars, such as the Sun, and is now being used by humans directly, ie. through solar heating, indirectly via conversion into electricity from solar photovoltaic cells, through biofuels, or through the burning of fossil fuels such as coal, oil and natural gas. As an engineered process, energy storage is accomplished by devices or physical media that store energy to perform a useful operation at a later time. As our civilization has progressed, energy useful to humans has been stored in the form of wood stacks, coal heaps, oil tanks, gas pipelines and so on. These types store the energy in a different form from that ultimately required (eg as heat or electricity). However, they have been predominantly based on the use of ‘fossil’ hydrocarbons, which for a variety of reasons, including climate change, global population growth, substantial global increases in energy demand and resource depletion, do not provide a sustainable way forward. In essence, storing energy allows people to balance the supply and demand of energy.

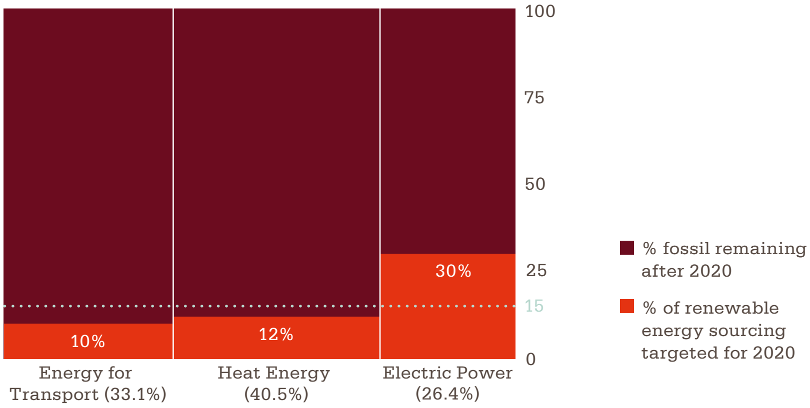


Figure 1: UK energy consumption by application and 2020 targets for renewable sourcing
(© Engineered Solutions; Permission Granted)

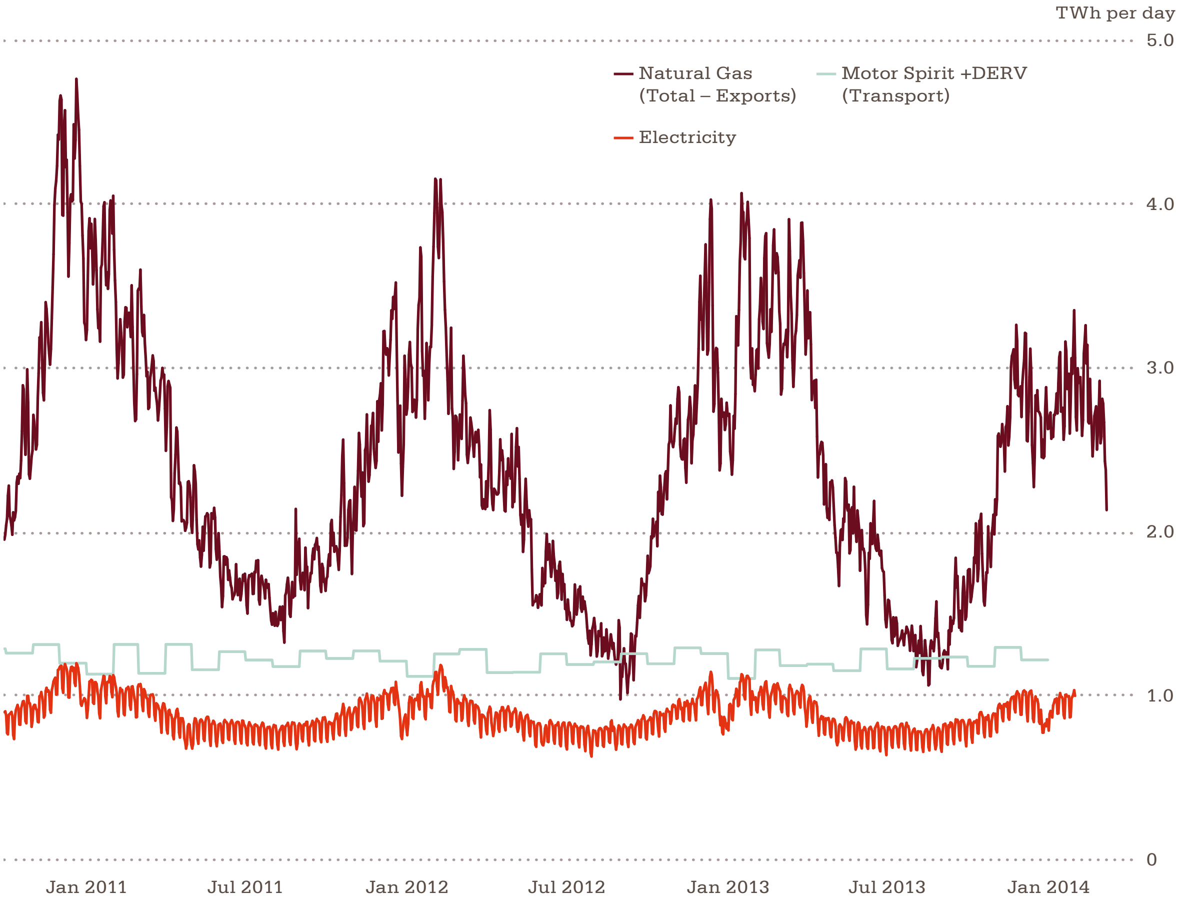
Energy storage became a dominant factor in economic development with the widespread introduction of electricity. Unlike other common natural energy storage systems in prior use, such as wood, oil, gas or coal, electricity must be used as it is being generated, or converted immediately into another form of energy such as potential, kinetic or chemical. A decade ago, Sandia National Laboratories in the USA proposed 14 different ‘benefits’ which could be derived from energy storage for electricity[1], ranging from price arbitrage to power quality improvement. The specific benefits would vary, depending on local circumstances, but it is worth noting that energy storage is not confined to applications in ‘renewable energy’ as it can be used with energy derived from any source ie. fossil fuels. Furthermore, reductions in GHG emissions are not directly attributable to energy storage as it is an enabling technology. Emission savings are therefore indirectly achieved when its use allows a greater proportion of renewable energy to be deployed in the system.

In the public’s mind, energy storage is most commonly associated with electricity. However, it is needed for all forms of energy that we use, including heat and transport. According to the UK’s Renewable Energy Strategy (2009)[2], the approximate split of total energy demand in the UK as a whole is (see **Figure 1**): Heat: 600TWh/y (40.5%); Transport: 490TWh/y (33.1%); Electricity: 390TWh/y (26.4%). Electricity is therefore the smallest area of energy demand, yet it commands the highest level of attention by both government and the media.

In Scotland, there is even less dependence on electricity than for the UK as a whole; recently released data[3] shows a demand split of: Heat: 50%; Transport: 30%; Electricity: 20%. This demonstrates that an undue focus on energy storage for electricity, according to these statistics, is misplaced.

Figure 2 illustrates recent work by the University of Sheffield[4] which examined the UK energy demand figures, based on actual data reported by the Department of Energy and Climate Change (DECC). This diagram generally confirms the energy split described in **Figure 1**, however additionally shows that while in the transport sector energy consumption remains fairly constant over the year, there is a clear seasonal weighting for electricity demand: from a peak demand of c.1.2TWh/d in winter to c.0.8TWh/d in summer. This means that any national energy storage system must be capable of seasonal variations and not merely daily, or shorter, fluctuations. Nevertheless, the seasonal variations in electricity demand are almost negligible when compared with gas demand, which in a UK context can be taken as a proxy for heat demand. **Figure 2** clearly shows a winter peak demand of c.4.0TWh/d compared with a summer demand as low as c.1.0TWh/d, or approximately a factor of four variance. This indicates the enormous range potentially required for seasonal heat energy storage.

Figure 2: UK energy consumption, Oct 2010–March 2014
(© Grant Wilson, Sheffield University; Permission Granted)



UK ENERGY AND EMISSIONS POLICY

Renewable energy provision is a substantial part of current UK energy policy and commitment.

The EU Renewable Energy Directive (RED-2009)[5] sets the relatively short-term goal of meeting Europe-wide targets that require the UK to deliver 15% of the nation's total energy demand from renewable resources by 2020, from a starting point of just 1.3% in 2005. This target is legally-binding with penalties if they are not met, and was a commitment willingly entered into by the UK. However, despite this, the UK has been stalling in its deployment of the equipment and infrastructure required to achieve the target, and the recent series of prolonged delays in finalising the details of the Energy Bill and associated Electricity Market Reform (EMR) have exacerbated the challenge.

In addition, the UK's Climate Change Act (2008) places a legally binding longer-term commitment on future Governments to achieve an 80% reduction in the nation's GHG emissions by 2050 relative to 1990 levels. The Low Carbon Transition Plan (2009)[6] added a further interim target of a 34% reduction (relative to 1990 levels) to be achieved by 2020. Government aspirations for delivering against both of these highly ambitious targets focus strongly on reductions of CO_2 emissions in the UK's electricity generation sector, followed by widespread electrification of both transport and heating. In this regard, the Committee on Climate Change (CCC), the Government's independent advisor, predicts that in order to meet such an objective the UK generating system will need to be largely free of GHG emissions by 2030 and that by 2040 most transport and heating must be transitioned to electricity-based technologies[7]. **Figure 2** suggests that the 'electrification' of heat will be exceptionally difficult to achieve. In addition to the infrastructure challenges such a strategy raises, not least of which is in the widespread replacement of the dominant gas fuelled boiler, the implied low return on investment (RoI) for new electric powered equipment that is operational for only 3–4 months of the year may well prove unacceptable to most investors.

Assuming that the electrification strategy is pursued, both the CCC and DECC anticipate that this will lead to a doubling of the UK's electricity requirements by 2050. However, given that only about a quarter of current energy demand is supplied by electricity this desired outcome appears to be extremely challenging, particularly at a time when UK nuclear and coal fired power generation capacity is being shut down at a faster rate than new capacity is being built to replace it. Realistically, these targets can be met only through focussing on the total energy mix, not just electricity, and transitioning to a high proportion of renewable and other low GHG-emitting sources in transport and heat applications as well as power generation. Further, given that many renewable energy resources are both intermittent and seasonably variable in nature, energy storage solutions will be increasingly needed to help manage the growing proportions of these technologies in all three areas.

ENERGY STORAGE FOR ELECTRICITY

Energy storage is, given both the UK and Scottish Government's focus on the power sector as the route to meeting the EU targets, particularly and urgently required to support electricity generation from 'intermittent' renewable resources. Indeed, The Electricity Storage Network (ESN) recently suggested that a UK target of 2GW of additional electricity storage capacity, to be installed by 2020, would be appropriate. The requirement is exacerbated by the promotion of the use of wind and solar (through photovoltaics) resources over other forms of renewable energy. However, even the technologies which are regarded as the near future for renewable energy, eg wave and tidal, while certainly more predictable, are still 'wrong-time' electricity generators; that is they generate electricity at times when inflexible baseload generators, such as nuclear, are already producing all that the transmission system requires to meet demand. Currently in such cases the renewable generators are often simply switched off. Under existing market arrangements, a generator unable to supply its electricity to the grid in this way is entitled to 'constraint payments'. Even at present levels of renewables deployment, these constraint payments are becoming a major concern to consumers, who are effectively funding the non-supply of electricity; National Grid constraint payments to wind farm operators were about £34 million between 2011 and 2012[8] (in just one day in August 2013, £1.84m was paid to operators of 28 wind farms in Scotland to turn off their turbines and not generate electricity[9]). This annual figure represents just over 10% of the total paid to all generators. However given that less than 5% of electricity is currently produced from wind sources, as the installed capacity of renewables grows in the future the issue of payments will likely become of increasing concern. Virtually any form of energy storage could alleviate this problem, by allowing surplus generation of this type to be used at a different time or place, where demand exists.

As the market is increasingly penetrated by energy from intermittent renewable resources, it follows that more 'back-up' (traditionally provided in the form of fossil fuel fired power stations), or alternatively storage capacity, will be required to ensure that energy demand can always be met. The strategic use of energy storage would not only solve the 'wrong time' electricity problem but also improve the performance (increase of efficiency and reduction of cost) of the electricity system as a whole. In addition to allowing optimised use of all generation assets, whether based on renewable sources or not, and thus enabling a better return on asset investment to be achieved, the deployment of distributed energy storage systems can also help avoid or defer expensive transmission/distribution infrastructure investment, particularly in expanding urban communities.

ENERGY STORAGE FOR HEAT

As previously noted, around 40% of UK energy consumption (and >50% in Scotland) is in the form of heat, largely associated with domestic and commercial heating of buildings, as well as the heating requirements for a wide range of industrial processes. Despite this substantial demand, relatively little attention has been paid by either UK or Scottish governments to the development of heat management and storage strategies. There are essentially three ways in which heat energy can be stored:

Sensible Heat Storage where thermal energy is stored as a result of a change in a material's temperature. The most widely-used material is water, but other materials such as rock, sand, ceramics and clay can also be used.

Latent Heat Storage where thermal energy is stored and released as a result of a change in a material's physical state (eg liquid-to-solid). Materials used to store latent heat are termed 'phase-change materials' (PCMs).

Thermochemical Heat Storage where heat is applied to certain materials that, on heating, undergo a reversible chemical reaction with an enthalpy change as a result of the breaking and forming of chemical bonds. Examples include the dehydration or thermal decomposition of metal salts, or dehydration of framework materials such as zeolites.

To some extent the lack of attention to this area is likely to be, in part, due to the fact that the potential demand for energy storage of heat in the UK is largely distributed and mostly exists at an individual building scale. However, **Figure 2** clearly shows that heat is not only by far the largest area of energy demand but also the area, by a significant margin, with the largest seasonal variation. At the same time, a great deal of heat is wasted through a combination of poor insulation, sub-optimal heat transfer processes, and through conversion losses associated with electricity generation. Since many heating requirements rely ultimately on the combustion of fossil fuels, inevitably this has a substantial impact on the release of CO_2. Furthermore, with the ever-increasing price of fuel and electricity, there are significant economic impacts for both domestic and industrial customers. Hence there is a very strong driver towards the utilisation of renewable heat, and a key enabling technology for renewable heat must be effective heat storage.

The basic concept of heat energy storage should be familiar to the majority of people in the UK as a result of its traditional, though decreasing, use in a domestic setting for hot water. According to the Centre for Low Carbon Futures (CLCF), almost 14m households in the UK still have a hot water cylinder, giving a maximum combined storage capacity of around 80GWh[10]. However, the installation of this kind of heat storage is on the decline with 80% of sales of new boilers being of the gas 'combi' variety that do not require a hot water tank. Moreover, in the UK, we have historically been notoriously wasteful of our heat energy with many such tanks inadequately insulated.

The other major traditional form of heat energy storage in the UK is electric storage heaters. These use off-peak electricity to store heat (in high density bricks), which is released throughout the course of the day. Around 1.6m dwellings in the UK (mostly flats) still have storage heaters as their primary heating system. However, conventional 'night storage heaters' are notoriously poor at delivering heat energy for peak evening consumption and could not realistically be used as part of a nationwide energy storage strategy.

ENERGY STORAGE FOR TRANSPORT

In terms of conventional energy storage systems, it is in the field of transport energy that most people are probably familiar with the concept of 'energy storage'. Other than in some rail transport applications which collect electricity from overhead catenary or third-rail supply systems, almost all vehicles carry stored energy, in the form of fuel, along with the vehicle. This takes the form of petrol and diesel for road vehicles, aviation fuel (kerosene) for aircraft, bunker oil for ships and even, historically, coal for steam locomotives. Ongoing technological development since the dawn of the Industrial Revolution has ensured that energy conversion from the stored fuels into motive power has become increasingly more efficient and power recovery systems (eg regenerative braking) increasingly commonplace. However, the issue remains that the vast majority of fuels stored on board vehicles are derived from fossil hydrocarbons, which are clearly not desirable for many reasons, including climate change, population growth, increasing energy demand, resource depletion and pollution from spillages. While it is undeniable that improvements in vehicle fuel economy over the past few years have been substantial, this is still not truly sustainable in the longer term, especially in the light of globally-rising car ownership and annual distances travelled. For this reason, it is imperative to develop alternative fuels (with lower GHG-emissions potential) and energy sources, as well as different energy conversion devices in which they can be used.

It is in the field of energy storage for transport that most work still needs to be done. As already noted, the CCC's solution to decarbonisation of the transport sector is based almost entirely on electric vehicles, powered by various types of battery energy storage that is replenished from a UK electricity system with low-GHG emissions. It is however possible that this view underestimates the scale of the decarbonisation challenge and that the future for the transport sector will be much broader-based; using a variety of technologies including biofuels, electrical and hybrid systems, hydrogen (particularly using fuel cells) and liquid nitrogen (based, for example, on the Dearman engine concept), all of which will require some form of storage, as well as mechanical systems, such as Flywheel Energy Storage Systems (FESS).

COMMUNITIES AND ENERGY STORAGE

Active public attention to energy storage is generally focussed at large, utility-scale systems, such as pumped hydro, which have potential environmental and ecological implications for our landscape. Although this is indeed a crucial application, if national and international targets are to be met, energy storage systems are also a valuable resource at local community scale with ‘distributed’ systems. In this regard, most types of energy storage (for electricity, heat and transport) can help with community stakeholder engagement in the deployment of renewable energy resources and help to build community resilience against future shocks, such as those related to extreme weather, climate change and security of fuel supply, for example.

In such circumstances, there are good reasons for local communities and even more isolated homes and farms to have their own capacity to both source and store energy; this is true both to provide full redundancy of systems, in the case of failure of the external supply, and also to give greater flexibility of operations to achieve energy self-sufficiency and independence. The latter will become more important as the gas and electricity grids become increasingly overloaded. However, although it is now easier than ever before to generate renewable electricity and source heat at community scale (small wind, solar PV and thermal, micro-hydro, heat pumps, biomass boilers etc), small-scale energy storage systems are still not being installed at the same rate.

Although the requirement for centralised energy storage will likely always be present to some degree, the level of ‘distributed’ energy generation and storage is likely to grow at a much faster rate in the future to cope with radical changes in the patterns of supply and demand in the whole energy system. Many of the different technologies discussed in the ‘comprehensive review of energy storage’ chapter of this report are also available at small-scale. This is particularly true of the various types of battery, which can be incorporated into Uninterruptible Power Supply (UPS) systems with small devices already commercially available for micro-CAES and mini-hydrogen systems. More effective insulation of hot water storage systems and the increasing availability of domestic-scale PCM-based thermal storage systems also make this realistic for local heat storage.

CAPACITY AND RANGE OF ENERGY STORAGE SYSTEMS

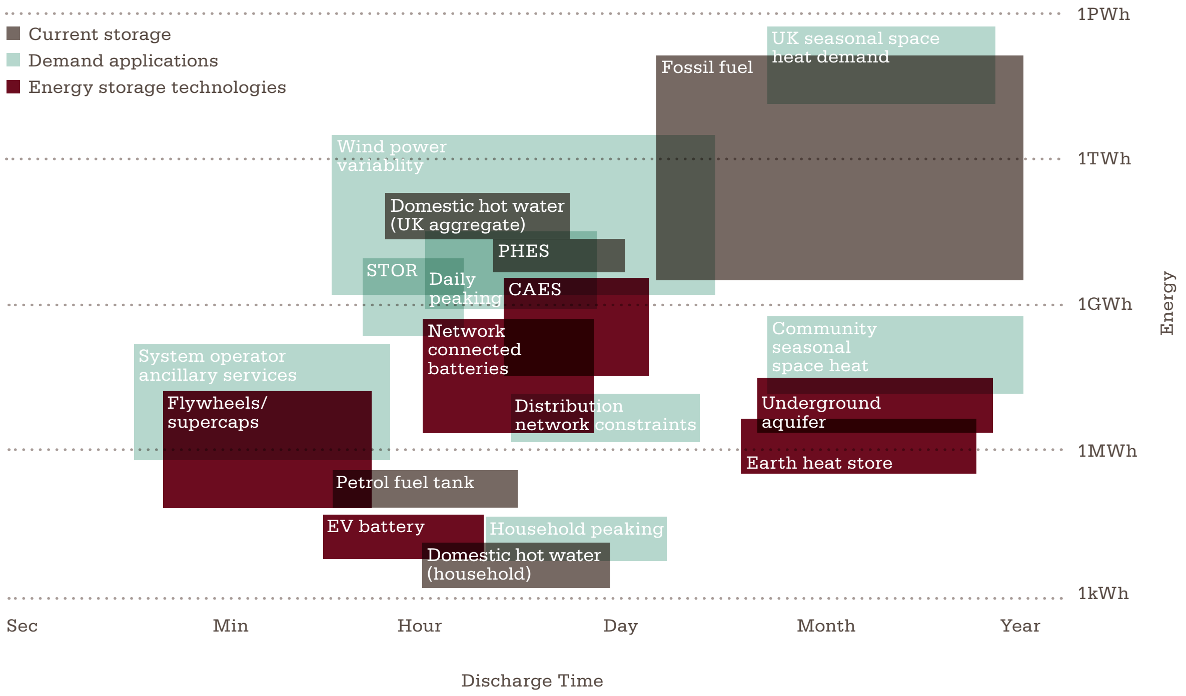
As noted by the Energy Research Partnership, ERP, coping with a strong seasonal profile of energy demand for heat and ensuring security of energy supply at timescales of seconds to years will be critical in energy storage systems.[11] Furthermore, to cover all of the areas of energy demand, energy storage systems have to range in capacity from a few milliwatts to hundreds of megawatts and supply energy ranging from milliwatt-hours to terawatt-hours (for definitions, see page 44). This means that there is no possibility that a single solution for energy storage can be developed, and that several technologies will have to be developed simultaneously; **Figure 3** is based on the work of ERP and illustrates the potential capacity and discharge time of a range of energy storage technologies against demand applications. It is essential that we move away from merely looking at the installed capacity (kW, GW) of an energy storage system and carefully consider how much energy (kWh, TWh) can be delivered and over what period (hours, days, months).

Wherever possible, as examples are given throughout this report, we will endeavour to give the ratings in the format: 'installed capacity/ energy produced, eg "40kW/400kWh".

ENERGY STORAGE IN SCOTLAND

Although this report is primarily intended to cover the application of energy storage systems throughout the UK, it is recognised that there is a particular potential need in Scotland. This is due to the much higher proportion of intermittent renewable electricity generation being deployed in that country, both now and in the near term future.[12] Scotland's First Minister, Alex Salmond MSP, has stated an ambition for Scotland to generate the equivalent of 100% of gross electricity consumption from renewable sources by 2020. To achieve this outcome, the strategy adopted by the Scottish Government is to encourage the over-installation of wind resources (this is what the "equivalent of 100%" renewable electricity target means in practice) to achieve a theoretical maximum output on certain days. However, clearly it is inefficient to overdeploy equipment in order to generate a set amount of electricity from renewable resources at a given time if the energy cannot be either used or stored. Without significant parallel deployment of energy storage, the potential excess of supply over demand will simply be 'constrained off' and the benefit irretrievably lost at a cost.

Figure 3: Capacities/Discharge Times for Energy Storage Systems [Adapted from the work of reference 11]



The rise of renewable sources in Scotland's electricity generation mix during the past decade has been dramatic, with DECC figures showing penetration at 36.3% in 2011, up from 12% in 2000. This increase has in absolute terms come primarily from wind sourced energy, installed capacity of which has risen from 36MW in 2000 to 3,016MW in 2011 (3% to 63% of installed renewable capacity over this period). In 2000, 4% of total generation from renewable sources came from wind and this rose to 51% by 2011.[13] Against this background the penetration of wind energy utilisation, along with that of other renewables in Scotland, are projected to increase with a further 13GW of capacity currently under construction or within the planning process.[14] This clearly demonstrates the urgent need for either 'back-up' generation, almost certainly using fossil fuels, or some type of energy storage. This need increases if Scotland decides to become an independent nation, particularly as the Scottish Government have aspirations post-independence to develop a market in the sale of 'green' energy to the rest of the remaining UK and beyond. Energy storage would be a key enabler in such a strategy, facilitating the storage of energy for later sale into export markets at optimum price points.

The 'Energy Storage and Management Study'[15], which was issued by the Scottish government in 2010, projected several scenarios for the proportion of generation coming from renewable sources in relation to gross electricity consumption in 2020. An interim target was also set for renewable generation to achieve 50% of gross consumption by 2015. It was projected that 15.2TWh would be generated in 2015 from 5,500MW of installed wind, tidal and wave capacity. The study also cites Portuguese government research, which suggests that a ratio of 3.5MW of installed wind capacity to 1MW of pumped hydro storage would be appropriate for grid balancing purposes.
For the purpose of making a simple 'order of magnitude' estimate of Scotland's storage capacity requirement, expanding these definitions on the supply side to include tidal and wave, and relating them to non-specific storage capacity, the 5,500MW projected implies a need for 1,571MW of installed storage.

For 2020, the scenarios considered in the study do not cover the stated Scottish ambition for renewables generation equivalent to 100% of gross consumption. However, scenarios one (76%) and two (120%) can reasonably be averaged to a comparable 98% of consumption from renewable sources. This averaged projection gives 31.8TWh of generation from 10,800MW of combined wind, wave and tidal capacity. Using the same 3.5:1 ratio as above, 3,086MW of storage would be required. Current energy storage capacity in Scotland is a little over 745MW and is largely based on the Foyers and Cruachan pumped-storage hydroelectric facilities.

The Electricity Network Steering Group has estimated that £5.7 billion needs to be invested in upgrading Scotland's electricity infrastructure to cope with power flows from increasingly decentralised and intermittent generation, and to facilitate increased export of electricity to England and Wales.[16] In their 'Gone Green 2011' model, which matches Scotland's 2020 renewables target, in northern Scotland the combined renewable capacity increases from 900MW to 7,200MW, with central and southern Scotland combined growing from 1,400MW to 4,700MW. Decentralised storage may also provide benefits in accommodating decentralised and variable sources of supply. At the ratio of 3.5:1 these supply capacities would equate to 2,057MW across northern Scotland and 1,343MW of storage across the centre and south.

It should be noted that the analysis based on this data is only for the electricity sector and, as already highlighted elsewhere, electricity amounts to only 20% of total energy demand in Scotland. The demand for heat energy (50%) and energy for transport (30%) will also require energy storage, similar to the rest of the UK, particularly in regard to the longer term targets for 2050. The lower population density in Scotland, compared to the rest of the UK, will make this an even greater challenge.

ENERGY STORAGE: THE MISSING LINK

The Institution of Mechanical Engineers recognises the potential of energy storage technologies to help the UK achieve its legally binding long-term (2050) commitment to reduce the nation's GHG emissions, as well as deliver against the EU Directive requirement to source 15% of UK energy from renewables by 2020. Additionally the Institution understands the importance of energy use in both heat and transport in meeting these UK obligations. This report therefore builds on previous studies of UK energy storage to include a wide range of technologies for the storage of heat and transport energy. An impartial analysis of the environmental dimension of sustainability for each of these technologies, with particular reference to materials of construction and the ready availability of operating fluids or media, is also included.

Consideration of sustainability must however, by definition, also account for anticipated economics. In this regard, previous reports by both the Carbon Trust[17] and CLCF[10] have provided estimates of costs for a range of energy storage technologies. For completeness **Table 1** provides a comparison of the data presented in those two reports and shows the wide variation in these estimates. This illustrates how difficult it is to put an accurate cost on different technologies at very different stages of development. Until all of the technologies described become mainstream (like Pumped-storage Hydroelectricity and some batteries currently are), there are few accurate benchmarks for manufacturing and/or construction costs. Current indications of cost are highly conjectural and therefore a source of substantial uncertainty if used as a basis for strategic decision-making.

Table 1: Cost Comparison of different Energy Storage [Technologies taken from reference 17 and reference 10]

Cost Comparison of different Energy Storage Technologies	**Carbon Trust**[17]		**CLCF**[10]	
	Indicative Cost		Indicative Cost	
	US$ / kW	US$ / kWh	US$ / kW	US$ / kWh
PHES	1500–4300	250–430	600–2000	5–100
CAES – underground	1000–1250	60–125	400–1150	2–120
CAES – above ground	1950–2150	390–430		
CES	n/a	n/a	900–2000	260–530
Hydrogen	n/a	n/a	1500–10000	6–725
Flywheel	1950–2200	7800–8800	250–25000	1000–14000
Batteries:				
Redox flow – Zn/Br	1450–2015	290–1350	600–2500	150–1000
Redox flow – V/V	3000–3700	620–830		
Lithium-based	1085–4100	900–6200	400–1600	600–3800
Metal-Air	n/a	n/a	100–1700	10–340
Sodium-based	3100–4000	445–555	350–3000	300–500
Nickel-based	n/a	n/a	400–2400	800–1500
Advanced Lead Acid	950–4600	625–3800	n/a	n/a
Lead Acid	n/a	n/a	50–600	200–400
SMES	n/a	n/a	200–350	1000–10000
Supercapacitor	n/a	n/a	25–510	300–20000

WHAT NEEDS TO CHANGE?

Successive governments, both in Westminster and Holyrood, have committed to highly-ambitious targets for long-term reductions in GHG emissions and short-term deployment of renewable energy technologies, with some targets to be met as soon as 2020.

From an engineering perspective, there is as yet still no clearly-defined, technically robust route to delivering against these targets and a lack of understanding by both politicians and the public alike on what needs to be done, at what scale, to achieve a secure and sustainable outcome. In particular, the differing requirements both now and in the future for the electricity, heat and transport sectors, as well as the magnitude of energy demand in the latter two, appears to be lost in a policy landscape almost exclusively focussed on electricity alone. In Scotland, for example, even if the 2020 target of generating the equivalent of 100% of Scottish electricity consumption from renewable sources is met, this will only represent a total of 20% of all energy from renewables, rather than the 30% goal. Government must shift from its current focus on the electricity sector as the only way forward and rethink its strategy for achieving the targets for transport and, in particular, heat, which is by far the largest sector of energy demand.

Given the current focus on the power sector, most recent increases in the proportion of renewables in the UK have largely taken the form of wind and, to some degree, solar PV, electricity generation technologies. Both wind and solar are “intermittent” sources of energy which require back-up capacity to ensure that supply can be maintained at all times, traditionally this is delivered in the form of other ‘on-demand’ generation (usually fossil fuel based) technologies, but an alternative is the use of some form of energy storage. Indeed, there is already a large and growing asset base of wind generation technology both onshore and offshore in the UK and Scotland, with considerably more already consented and in planning. In Scotland, in 2012, more than 30% of the nation’s actual electricity demand was provided from renewable resources, mostly wind. This number will continue to grow annually and will ultimately become the biggest single source of electricity generation in Scotland. Provision of sufficient energy storage capability will make much better use of the wind asset and avoid the necessity for GHG emitting fossil fuel back-up plant. It will also help restrict potential growth in the size of constraint payments made to power companies.

The UK has many examples of energy storage technologies in various stages of development and there is an opportunity to capitalise on this position in both domestic and overseas markets as they emerge. There is, however, investment in energy storage taking place in Europe (Germany, Italy and Scandinavia), the USA and Japan which, by comparison to UK investment in this area to-date, relatively high. Government must therefore act swiftly to create the right environment necessary to encourage UK energy storage technologies to develop further, in particular with a focus on supporting commercial scale demonstrators, and establish market incentives for their deployment and use in the UK market. In this regard, Government should recognise that energy storage infrastructure will come at a price and it must therefore make the case to the public that the relatively short-term investment cost is worth the long-term gains in energy security, increased resilience, export opportunities and, ultimately, lower relative energy costs.

In planning an investment strategy it will be important however for Government to understand that there is no ‘silver bullet’ technology in energy storage and as such a wide range of capacities and applications will need to be encouraged. Nevertheless, front-runners for initial deployment will be those that are based on well-proven component technology and use sustainable materials and media. Given the number of technology options, potential applications and different stages of development, it will be important for Government to work with industry to create a clear roadmap for the development, demonstration and deployment of energy storage; and it is essential that this route be based on the most sustainable solutions, not simply the cheapest.

RECOMMENDATIONS

In recognition of the increasing deployment of intermittent renewable energy systems in the UK, and the importance of heat and transport energy demand alongside that for electricity, the Institution of Mechanical Engineers encourages adoption of the following recommendations in order to help meet the nation's short-term and long-term targets for reducing GHG emissions:

1. **Government needs to focus on heat and transport, as well as electricity**. It is well understood that security of supply is crucial and that decarbonisation of the UK energy system desirable, but in contrast to past thinking it should not be confined to simply having sufficient electricity generating capacity to 'keep the lights on'. With a growing amount of the UK's fossil fuel supplies being imported, and rapidly increasing global competition for remaining resources, it is in the national interest to utilise freely-available indigenous renewable resources for heat and transportation as well as electricity generation. Government needs to work with the engineering community to develop new and innovative systems that include energy storage to cope with the intermittency and seasonality challenges that these renewable sources present.
2. **Government must recognise that energy storage cannot be incentivised by conventional market mechanisms**. It is unlikely that the nation's long-term decarbonisation objectives will be met without significant deployment of energy storage capability, yet there are no plans in the UK for significant levels of energy storage. To-date very little public investment has been made in research, development and demonstrator activity and, as yet, there is no existing or proposed incentivisation scheme for energy storage deployment. In order to stimulate the sector and ensure that UK has the capability to deliver energy storage, as well as exploit emerging export opportunities, new public finance and business models are required to fund this key element of the nation's future energy system. The Goverment must lead the way for industry by developing a clear roadmap for the development, demonstration and deployment of energy storage in the UK and create an energy storage shop window to the world.
3. **The UK must reject its obsession with 'cheapness' in the energy sector**. Despite current concern over rapidly-increasing energy costs, and the reactive political promises that are unlikely to be fulfilled, it is evident that whatever form of energy is used in the UK costs will have to continue to rise into the future. In comparison with other European countries, the UK has for decades focussed on keeping energy prices artificially low, which has led to over-consumption of energy while the necessary demand-side reduction measures have not been put in place. This attitude must change and an alternative culture developed which recognises the value of energy and drives sustainable change in the nation's energy system.

The pumped-storage hydroelectric (PSHE) facility at Cruachan can generate up to 440MW of electricity during peak demand.

ENERGY STORAGE FOR ELECTRICITY

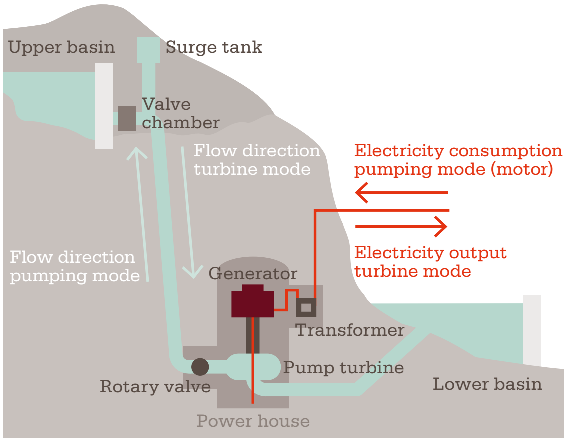
i. Pumped-storage Hydroelectricity (PSHE)

Pumped-storage hydroelectric (PSHE) is by far the most established and publically understood utility scale energy storage technology; it stores energy, in the form of water, in an upper reservoir, pumped from another reservoir at a lower elevation, see **Figure 4**. During periods of high electricity demand, power is generated by releasing the stored water through turbines in the same manner as a conventional hydropower station. During periods of low electricity demand, and when cheap or surplus electricity is available to the grid, the upper reservoir is recharged by using electricity to pump the water back to the upper reservoir. Although some efficiency losses are inevitable, PSHE plants are usually highly efficient, with 'round-trip' (ie. electricity-to-electricity) efficiencies reaching >80%.

Reversible pump-turbine/motor-generator assemblies can act as both pumps and turbines and are fully-proven commercially. In terms of sustainable materials and fluids, materials of construction of the pump/turbines are standard for this application and are not in short supply globally; the operating fluid is water, which is freely available in many parts of the world (sea-water may also be used but this may require some more sophisticated corrosion-resistant materials).

PSHE has the highest capacity of the energy storage technologies known and tested; it can be practically sized up to around 4GW capacity. PSHE has been providing energy storage capacity and transmission grid ancillary benefits since the 1920s. In the USA alone there are 40 plants with a total power capacity of 20GW, nearly 2% of the capacity of the electrical supply system. In 2009, the world's PSHE generating capacity was over 100GW.

Figure 4: Schematic diagram of a typical PSHE system



The largest PSHE systems in the world are shown below;

PSHE Plant	Country	Capacity [MW]
Bath County, VA	USA	3,003
Guangdong	China	2,400
Huizhou	China	2,400
Okutataragi	Japan	1,932
Ludington, MI	USA	1,872

and for comparison, the four existing PSHE facilities in the UK are:

PSHE Plant	Country	Year	Capacity [MW]
Dinorwig	Wales	1984	1,728
Foyers	Scotland	1975	305
Cruachan	Scotland	1965	440
Ffestiniog	Wales	1963	360

These UK facilities provide the nation with a total of around 30GWh/d, which is an extremely small proportion of even daily electricity demand. SSE, which owns the Foyers plant in Scotland's Great Glen has proposed two new PSHE plants close by, one at Balmacaan and the other at Coire Glas. Each of these proposed plants would by rated at 600MW and be capable of supplying up to 30GWh/d.

Summary of PSHE

Advantages

- Only commercially-proven large scale energy storage system.
- Uses a commonly-available operating fluid – water.
- Sustainable use of materials.
- Relatively high 'round trip' efficiency.

Disadvantages

- Requires suitable topography – only suited to relatively mountainous regions with space for a large elevated reservoir.
- Topographical requirement can lead to environmental and/or ecological concerns.
- Not suitable for drier, flatter parts of the UK, eg SE England, where the highest demand exists.
- Large civil engineering project with high Capex (although relatively low on a £/MWh basis).

ii. Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage (CAES) plants are generally similar to pumped hydro power plants in terms of their applications, output and storage capacity. However, instead of pumping water from a lower to an upper reservoir during periods of excess power, in a CAES plant, ambient air is compressed and then stored under pressure, generally in an underground cavern (although surface systems are possible). When electricity is required, the pressurised air is released and expanded in a gas expansion turbine driving a generator for power production.

Underground CAES storage systems are the most cost-effective, with storage capacities up to 10GWh, while surface units are typically smaller and more expensive, with capacities around 60MWh. There are two operating first-generation CAES systems: one in Germany and one in Alabama, USA.

CAES Plant	Country	Year	Capacity [MW]	Energy [MWh]
McIntosh, AL	USA	1991	290	870 (3h)
Huntorf	Germany	1978	110	2860 (26h)

The main characteristic of CAES is that due to the high isentropic exponent of air, the temperature of compression is very high, resulting in very high discharge temperatures from the compressor. The air is normally stored at a pressure of about 70bar. This heat of compression has to be extracted during the compression process, using inter-coolers and an after-cooler.

Diabatic CAES

In a conventional Diabatic system, see **Figure 5**, the loss of heat energy has to be compensated for during the gas expander (power generation) phase by heating the high pressure air in combustors, usually using natural gas; though it is also possible to use the heat of a combustion gas turbine exhaust in a recuperator to heat the air from storage before the expansion cycle.

Alternatively the heat of compression can be thermally stored before entering the cavern and used for adiabatic expansion extracting heat from the thermal storage system. This minimises specific gas consumption and reduces the associated CO_2 emissions, by 40–60% depending on whether the waste heat is used to warm up the air in a recuperator. The electrical 'round-trip' efficiency is approximately 42% without, and 55% with waste heat utilisation.

Both the Huntorf and McIntosh CAES plants use single-string turbo-machines where the compressor-motor/generator-gas expander are both located on the same shaft and are coupled via a gear box. In future CAES plants, the motor-compressor unit and the turbine-generator unit are likely to be decoupled for greater plant flexibility.

Adiabatic CAES

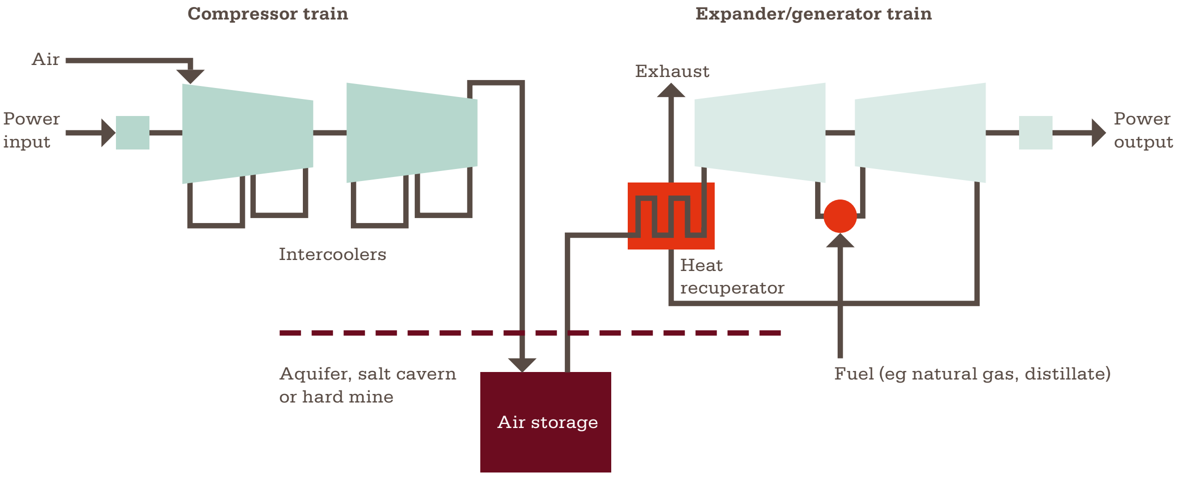
A much higher efficiency, approximately up to 70%, can be achieved if the heat of compression is recovered and used to reheat the compressed air during the expansion process through the turbine. This means that there is no longer any need to burn extra natural gas to pre-heat the decompressing air. An international consortium headed by the German energy company RWE is currently working on the development of the necessary components and the heat storage for an adiabatic CAES project called ADELE (der Adiabate Druckluftspeicher für die ELEktrizitätsversorgung). The pilot plant is scheduled to start operations in 2018.

Isothermal CAES

Isothermal CAES is an emerging technology which attempts to overcome some of the limitations of traditional (diabatic or adiabatic) CAES. Traditional CAES uses turbomachinery to compress air to around 70 bar before storage. Without inter-/after-cooling, the air would heat up to around 900K, making it impossible (or prohibitively expensive) to process and store the gas. Instead the air undergoes successive stages of compression and heat-exchange to achieve a lower final temperature close to ambient. In Advanced-Adiabatic CAES the heat of compression is stored separately and fed back into the compressed gas upon expansion, thereby removing the need to reheat with natural gas.

Isothermal CAES is technologically challenging since it requires heat to be removed continuously from the air during the compression cycle and added continuously during expansion to maintain an isothermal process. However, companies developing Isothermal CAES expect a potential round-trip efficiency of 70–80%.

Figure 5: Schematic diagram of a typical CAES system



Storage Options for CAES
Independent of the selected method, very large stores are required because of the low storage density. Preferable locations are in artificially constructed salt caverns in deep salt formations. Salt caverns are characterised by several positive properties: high flexibility, no pressure losses within the storage, no reaction with the oxygen in the air and the salt host rock. If no suitable salt formations are present, it is also possible to use natural aquifers (although there is a danger of oxygen reacting with rock and any micro-organisms). Depleted natural gas fields are also being investigated for CAES; however, in addition to the issues mentioned above, the mixing of residual hydrocarbons with compressed air has to be considered.

Summary of CAES

Advantages

- Considerable experience, gained over many years (though only two utility-scale storage systems exist, world-wide, with a few more planned).
- Uses a commonly-available, sustainable operating fluid – ambient air.
- Sustainable use of materials for large turbo-machines.

Disadvantages

- Large CAES systems require suitable geology, close to energy demand; salt caverns are ideal but are very expensive to develop and there are very few suitable sites in the UK.
- Low 'round-trip' efficiency unless 'adiabatic' or 'isothermal', neither of which is yet commercially proven.

iii. Cryogenic Energy Storage (CES)

Cryogenic Energy Storage (CES), sometimes referred to as Liquid Air Energy Storage (LAES) uses liquefied air or liquid nitrogen, which can be stored in large volumes at atmospheric pressure.[18] "Cryogenic" refers to a gas in a liquid state at very low temperatures. Uniquely, CES systems can also harness low grade waste heat from co-located processes, converting it to power.

Although novel at a system level, the components and sub-systems of CES systems are mature technologies available from major OEMs and, as a whole, the technology draws heavily on established processes from the turbo-machinery, power generation and industrial gas sectors, particularly from the Air Separation industry, which uses identical equipment. Furthermore, the turbo-machinery is virtually identical to that used in CAES systems and requires no rare or unsustainable materials of construction. A 350kW/2.5MWh CES demonstration plant has been under operational testing by the UK company Highview Power Storage, in Slough, UK, since summer 2011.

In 2013, the UK government has provided £6m to support funding of a dedicated Centre for Cryogenic Energy Storage, based at the University of Birmingham, to advance technology development and research in this field. In addition, DECC awarded £8m to Highview Power Storage and Viridor in February 2014 to help build a 5MW/15MWh demonstrator alongside a landfill gas generation plant where it will utilise waste heat.

CES involves three core processes (see **Figure 6**):

Charging: The system operates by using electrical energy (excess or off-peak) to drive a conventional air liquefier. Extracting ambient air from the surrounding environment, the gas is cleaned, compressed and cooled until the air undergoes a phase change to a liquid, thereby producing a storage medium which is 4–6 times more energy dense than compressed air at 200bar (and approx. 700 times more dense than atmospheric air).

Storage: The liquid air is stored in an insulated tank at low pressure, which functions as the energy store. Again, this equipment is widely deployed as bulk liquid LNG, nitrogen or oxygen storage (2,000t–200MWh equivalent – to 100,000t tankage, enough for 10GWh).

Discharging (Power Recovery): When power is required, liquid air/N_2 is drawn from the tank and pumped to high pressure. Ambient heat is applied to the liquid air via heat exchangers resulting in a phase change from liquid air to a high pressure gas which is then used to drive an expansion turbine generator.

Efficiency improvements: During the power recovery process, very cold gas is exhausted, which is then recycled back into liquefaction process (stage one) reducing the energy demands for producing liquid air.

The introduction of low-grade waste heat (sub 120°C) into the power recovery system (process stage 3) increases the amount of power which can be extracted. Low-grade waste heat is readily available from traditional thermal power generation plants and many industrial processes such as the manufacturing of steel, cement, and chemicals. Using waste heat of c.115°C, very common in a wide variety of processes, the electrical round-trip efficiency may potentially be as high as 70%.

By integrating low grade waste heat, CES can penetrate currently untapped markets, and potentially increase the energy efficiency of manufacturing and existing thermal power generation methods.

Summary of CES

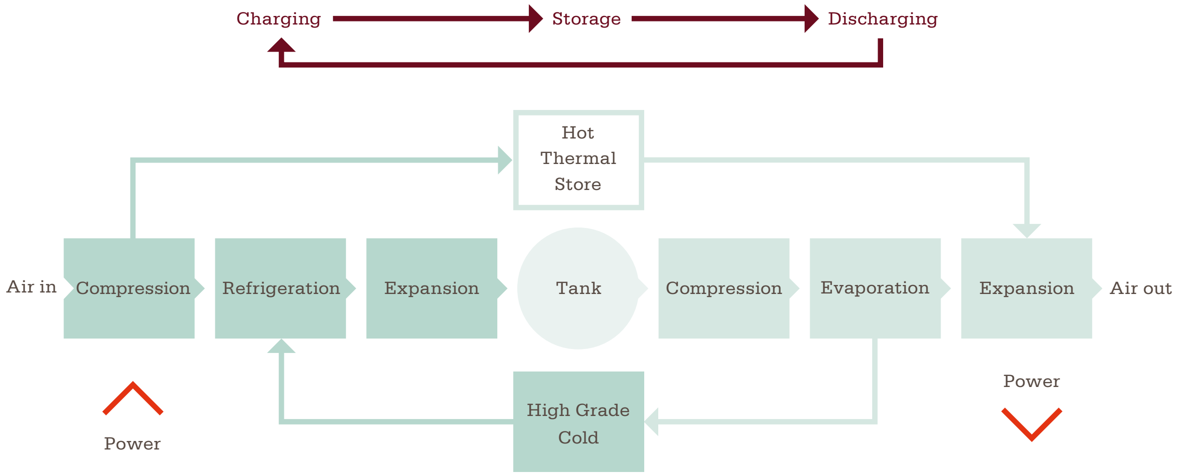
Advantages

- Builds on well-proven and understood Air Separation technology – over 100 years' experience.
- Uses commonly-available operating fluids – atmospheric air or nitrogen.
- Requires no particular topography or geology for siting – can be sited in optimum location.
- No unsustainable or exotic materials used in process or machines.
- Well-established global supply chain for all major components.
- Density ratio of 700:1 (at atmospheric pressure) ensures small physical footprint.

Disadvantages

- 'Round-trip' efficiency of the basic cycle is relatively low, but can be considerably improved by thermal integration.

Figure 6: Schematic diagram of a CES (LAES) system



iv. Hydrogen Energy Systems (HES)

Hydrogen is different from the three other candidates for utility-scale energy storage considered so far, in that it has a high calorific value and is therefore in itself useful as a fuel, rather than simply an energy vector. However, unlike air and water, hydrogen is not freely available and once extracted from other substances is extremely hard to contain, as it is the lightest element in the Periodic Table.

Nevertheless, hydrogen is a very valuable product with annual production of 55Mt/y and a market value of c.£100m[19]; most hydrogen is used in industrial processes, such as synthetic fertiliser manufacture, fuel desulphurisation, etc. However, >95% of the currently available hydrogen in the world is so-called ‘brown’ hydrogen and is derived from fossil hydrocarbons, so cannot be considered truly sustainable. Despite this, there is a growing amount of ‘green’ hydrogen now being produced, mainly by the electrolysis of water.

Renewable Hydrogen Production

Alkaline electrolysis is a mature technology for large systems, whereas PEM (Proton Exchange Membrane) electrolysers are more flexible and can be used for small decentralised solutions. The conversion efficiency for both technologies is about 65–70% (lower heating value). High temperature electrolysers are currently under development and could represent a very efficient alternative to PEM and alkaline systems, with efficiencies up to 90%.

Table 2: Underground gas storage sites in operation

Operator & Location	Storage	Gas Type	Gas Capacity Million Nm^3	Capacity Tonne	Equivalent Energy Storage GWh	Year
Teesside, UK	Salt cavern	Hydrogen	1	85 as H_2	3.3	1970s
Conoco, Clemens, USA	Salt cavern	Hydrogen	30	2,500 as H_2	100	1985
Air Liquide, Spindletop, USA	Salt cavern	Hydrogen	85	7,250 as H_2	280	2011
Gaz de France, Beynes, France	Aquifer	Towns gas	330	28,000 as H_2	1,080	1956
Scottish Power, Hatfield Moor, UK	ex-Gas field	Methane	120	75,000 as CH_4	1,200	2000
SSE, Aldbrough, UK	Salt cavern	Methane	270	173,000 as CH_4	2,700	2012
Humbly Grove, UK	Gas field	Methane	300	192,000 as CH_4	3,000	2005
SSE, Hornsea, UK	Salt cavern	Methane	312	200,000 as CH_4	3,100	1979
Centrica, Rough, UK	ex-Gas field	Methane	3,300	2,100,000 as CH_4	33,000	1984

Hydrogen Storage

As with the other energy storage technologies considered, excess electricity can be converted into hydrogen by electrolysis. The hydrogen can then be stored and eventually re-electrified. The 'round trip' efficiency is currently as low as 30–40% but could increase up to 50% as more efficient technologies are developed. Despite this low efficiency, the interest in hydrogen energy storage is growing due to the much higher storage capacity compared to batteries (small scale) or pumped hydro and CAES (large scale).

Small amounts of hydrogen (up to a few MWh) can be stored in pressurized vessels at 100–300 bar, or liquefied at 20.3K (-253°C). Alternatively, solid metal hydrides or nanotubes can store hydrogen with a very high density. Very large amounts of hydrogen can be stored in man-made underground salt caverns of up to 500,000m^3 at 200 bar, corresponding to a storage capacity of 167GWh hydrogen (100GWh electricity).

The compression of hydrogen to the pressures required for storage is not straightforward, as the gas has such a low molar mass (2); this means that it tends to 'slip' back towards the low pressure end of the compressor creating more inefficiencies. Medium pressures require piston-type compressors, while the very high pressures (700 bar) being developed for transport applications tend to be of diaphragm type. Compressors at these pressures are inevitably expensive, although they do not require rare or unsustainable materials.

Hydrogen Re-Electrification

Hydrogen can be re-electrified in fuel cells with efficiencies up to 50%, or alternatively burned in combined cycle gas turbine (CCGT) power plants (efficiencies as high as 60%).

Other Uses of Hydrogen

Because of the limited 'round trip' efficiency, direct uses of 'green' hydrogen are under development, classified as follows:

- **Power-to-Power** (store hydrogen, then use for power generation with internal combustion engines (ICEs), gas turbines and fuel cells.
- **Power-to-Gas** (inject hydrogen into the natural gas networks, this gas can then go into either heat or power as above).
- **Power-to-Transport** (use hydrogen for road transport, either IC engines or fuel cells).
- **Power-to-Chemicals** (use hydrogen in sustainable chemicals manufacture, eg ammonia or methanol).

Summary of HES

Advantages

- Hydrogen is a highly versatile medium with high calorific value, as such it is useful as a fuel and a 'zero-carbon' energy vector.
- Most hydrogen processes are well-proven and should be scalable for utility-scale storage.

Disadvantages

- 'Containment' issues, especially at high pressures (eg 700 bar).
- Needs considerable development work for hydrogen to be a truly 'sustainable' fluid.
- Hydrogen storage systems tend to have very low 'round-trip' efficiencies.

Highview Power's 350kW liquid air (cryogenic) energy storage pilot plant.

v. Pumped Heat Electrical Energy Storage (PHEES)

In Pumped Heat Electrical Energy Storage (PHEES), electricity is used to drive a storage engine connected to two large thermal stores containing mineral particulate (eg gravel). To store energy for electricity, the excess electric power drives a heat pump, which pumps heat from the "cold store" to the "hot store", resulting in the former cooling to around -160°C and the latter warming to around 500°C at 12 bar. To recover the energy, the heat pump is reversed to become a heat engine. The engine takes heat from the hot store, delivers waste heat to the cold store, and produces mechanical work. When recovering the stored energy, the heat engine drives a generator to produce electricity.

PHEES requires the following elements: two low cost (usually steel) tanks filled with mineral particulate and a means of efficiently compressing and expanding gas. A closed circuit filled with the working gas connects the two stores, the compressor and the expander. A monatomic gas such as argon is ideal as the working gas as it heats/cools much more than air for the same pressure increase/drop – this in turn significantly reduces the storage cost. The expected electrical 'round trip' efficiency is 75–80%.

The system uses gravel as the storage medium, so it offers a very low cost storage solution; there are no potential supply constraints on any of the materials used in this system and all materials are considered sustainable. Plant sizes are expected to be in the range of 2–5MW per unit and aggregated units could provide GW-sized installations. The technology is in development stage by the UK company Isentropic Ltd and commercial systems are expected in 2014.

vi. Flywheels (FESS)

Flywheel electricity storage systems (FESSs) can be viewed as kinetic or mechanical batteries; they use excess electricity in a motor which accelerates a rotor (flywheel) to a very high speed, which stores the energy in mechanical/rotational form. This stored energy is converted back by slowing down the flywheel by generating power through a generator. The rotor spins in a nearly frictionless enclosure.

A single flywheel energy storage unit manufactured by Beacon Power can deliver 100kW power and store 25kWh. Such units can be built from modules into large energy storage units, eg for frequency regulation. An example is the first known operating Smart Energy Matrix Frequency Regulation Plant, which comprised 20 such units, with output energy of 5MWh at a power of 20MW.

Flywheels offer rapid response times and very large numbers of charge cycles, but must be housed in robust containment and require high engineering precision components which currently results in a relatively high cost.

Most modern high-speed flywheel energy storage systems consist of a massive rotating cylinder (a rim attached to a shaft) that is supported on a stator by magnetically levitated bearings. To maintain efficiency, the flywheel system is operated in a vacuum to reduce drag. The flywheel is connected to a motor/generator that interacts with the utility grid through advanced power electronics. Some of the key advantages of flywheel energy storage are low maintenance, long life (20 years or tens of thousands of deep cycles), and negligible environmental impact. Flywheels can bridge the gap between short-term ride-through power and long-term energy storage with excellent cyclic and load following characteristics.

Typically, users of high-speed flywheels must choose between two types of rims: solid steel or carbon composite. The choice of rim material will determine the system cost, weight, size, and performance. Composite rims, while expensive, are both lighter and stronger than steel, which means that they can achieve much higher rotational speeds. The amount of energy that can be stored in a flywheel is a function of the square of the rotational speed, making higher rotational speeds highly desirable.

Currently, high-power flywheels are used in many aerospace and UPS applications. Today 2kW/6kWh systems are being used in telecommunications applications. For utility-scale storage a ‘flywheel farm’ approach can be used to store megawatts of electricity for applications needing minutes of discharge duration. Several ‘flywheel farm’ facilities are presently in the planning or construction stages.

Summary of FESS

Advantages

- High power capacity.
- Low maintenance and long life (tens of thousands of deep cycles).
- Negligible environmental impact.

Disadvantages

- Low energy density.
- Precision machining requirement results in relatively high unit costs.

vii. Batteries: Flow-type (sometimes known as Redox Flow Batteries)

A Redox Flow Battery (RFB) is a device that can accumulate (charging mode) and deliver (discharging mode) energy via reversible reduction-oxidation reactions of electrolytes, either in liquid or gaseous form, that are stored in separated storage tanks. The name “redox” refers to chemical reduction and oxidation reactions employed in the RFB to store energy in liquid electrolyte solutions.

In a RFB, power is decoupled from the energy storage capacity since the power is determined by the number of cells and their size, while the energy capacity is a function of the volume and concentration of electrolyte. Redox flow batteries are regarded as being able to operate to high levels of depth of discharge but have lower energy densities. Various redox couples have been tested but only Zinc Bromine (Zn/Br) and all-vanadium (V/V) redox batteries have currently reached commercialisation. For example, ZBB has produced an energy storage unit that can deliver 25kW power and store up to 50kWh of energy. Combined into large modules, such units can store 500kWh energy, with the potential to be up-scaled even further to at least 6MWh.

A few companies manufacture all-vanadium redox flow cells. A typical energy storage unit with 10kW power and 100kWh energy can be modularly up-scaled to deliver 40kW/400kWh of power and energy. Larger systems can be designed specifically to meet higher power and higher energy requirements. Zinc-Bromine and all-vanadium redox batteries have been already developed for applications such as solar energy fuelling stations, telecommunications, and remote area utility power.

The separation of power and energy is a key distinctive of RFBs and also provides design flexibility in their application. The power capability (stack size) can be directly tailored to the associated load or generating asset. The storage capability (size of storage tanks) can be independently tailored to the energy storage need of the specific application. In this way, RFBs can economically provide an optimised storage system for each application.

Finally, RFBs are well suited for applications with power requirements in the range of 10’s of kilowatts to 10’s of megawatts, and energy storage requirements in the range of 500kWh to hundreds of MWh.

Summary of RFBs

Advantages

- Economical, low vulnerability means to store electrical energy at grid scale.
- Greater flexibility to independently tailor power rating and energy rating for a given application.
- High cycle lifetime.
- Electrolytes, particularly vanadium, can be re-used, which contributes to low through-life costs.
- Vanadium, Zinc and Bromine are relatively abundant and sustainable materials.

Disadvantages

- Low energy density.

viii. Batteries: Lithium-based

The first commercial lithium-ion (Li-ion) battery was released by Sony and Asahi Kasei in 1991. These first Li-ion batteries were used for consumer products and many companies are now developing larger-format cells for use in energy-storage applications. It is also expected that there will be significant synergies with the emergence of electric vehicles (EVs) powered by Li-ion batteries.

Li-ion batteries have been deployed in a wide range of energy-storage applications, ranging from energy-type batteries of a few kWh in residential systems with rooftop photovoltaic arrays, to multi-MWh containerised batteries for the provision of grid ancillary services.

There is a wide range of sub-chemistries within the family of Li-ion cells, each of which has specific operational, performance and safety characteristics. Li-ion cells may be produced in cylindrical or prismatic (rectangular) format. These cells are then typically built into multi-cell modules in series/parallel arrays, and the modules are connected together to form a battery string at the required voltage, with each string being controlled by a battery management system. The battery management system, comprising electronic subsystems is an important feature for Li-ion batteries, as the cells should be charged and discharged within controlled parameters, since they lack the capability of aqueous technologies (eg lead-acid batteries) to dissipate overcharge energy. Safety characteristics of Li-ion batteries are ultimately determined by the attributes of system design, including mechanical and thermal characteristics, electronics and communications, and control algorithms, regardless of electrochemistry.

One US company has manufactured Lithium-based electrical energy storage units with 2MW of power and 500kWh of energy and has deployed over 20MW (or ten units) of grid-connected energy storage units since 2008. Another US company has developed a unit providing 1MW power and 250kWh energy, these storage units can be assembled into larger systems. One 1MW/250kWh unit has been operating since 2008.

AES, a US independent power producer, has deployed large scale battery storage, with project sizes in the range 16–32MW. SSE is trialling a 2MW/500kWh Lithium battery in Orkney, which is owned and operated by a contractor. This was commissioned in 2013. The battery is used to store wind energy when there is insufficient export capacity or demand on the islands, thereby saving curtailment of wind generation.

Summary for Lithium-based batteries

Advantages

- High power density.
- High efficiency.
- Reasonable cycle life provided they are not operated over a wide state of charge range.

Disadvantages

- High production cost.
- Requires special charging circuit.
- Lithium is currently used in quantities far lower than that at which it would be if it were utilised for wide-scale energy storage. There is also likely competition with automotive battery production. The combination of these factors would create higher prices and rapid depletion of world reserves, unless alternative technologies were found for both or either of these uses.
- No established infrastructure for recycling of lithium.

ix. Batteries: Metal-Air

Metal-air batteries are the most compact and, potentially, the least expensive batteries available. They are also environmentally benign. The main disadvantage, however, is that electrical recharging of these batteries is very difficult and inefficient. Although many manufacturers offer refuelable units where the consumed metal is mechanically replaced and processed separately, few developers offer an electrically rechargeable battery. Rechargeable metal air batteries typically have a life of only a few hundred cycles and an efficiency of about 50%.

The anodes in these batteries are commonly-available metals with high energy density like aluminium or zinc that release electrons when oxidised. The cathodes or air electrodes are often made of a porous carbon structure or a metal mesh covered with proper catalysts. The electrolytes are often a good OH-ion conductor such as KOH. The electrolyte may be in liquid form or a solid polymer membrane saturated with KOH.

While the high energy density and low cost of metal-air batteries may make them ideal for many primary battery applications, the performance of secondary batteries needs to be confirmed before they can compete with other rechargeable battery technologies.

Summary of Metal-Air batteries

Advantages

- Very high energy density – most compact size.
- Potentially, the least expensive battery available.
- Environmentally benign, readily-available materials.

Disadvantages:

- Electric charging is difficult.

x. High Temperature Batteries: Sodium-Sulphur (NaS)/Sodium Nickel Halide

Sodium Sulphur (NaS) batteries were originally developed by Ford Motor Company in the 1960s but it was not until the 1990s that commercialisation was successful, when the technology was adopted by NGK Insulators and the Tokyo Electric Power Corporation in Japan. NaS batteries use electrodes of molten sodium and sulphur, with a ceramic separator as the conductive electrolyte. To operate, the battery temperature is held in the range of 280–350°C, which can be an operational issue for intermittent operation. The energy storage module based on the NaS battery can provide 50kW power and 360kWh energy.

There are more than 300 NaS energy facilities worldwide, with the largest installation being a 34MW/245MWh unit for wind energy stabilisation in Northern Japan. >270MW of stored energy, suitable for 6 hours of daily peak shaving, has been installed. The demand for NaS batteries as an effective means of stabilising renewable energy output and providing ancillary services is expanding. U.S. utilities have deployed several MW systems for meeting peak demand (peak shaving), backup power, firming wind capacity, and other applications, with several more installations planned.

NaS battery technology has a good reputation for cycle life; however a fire at a NaS battery facility in 2011, which led to the release of some hydrogen sulphide gas, temporarily raised safety concerns, although these appear to have been overcome by design changes.

The ZEBRA or Sodium-Nickel Chloride battery utilizes a molten sodium anode, molten sodium aluminium chloride electrolyte and nickel cathode. Similarly to NaS, it needs elevated temperature to operate, in range of 260–360°C. Initially developed for EV applications, NaNiCl batteries offer a potentially attractive solution for stationary energy storage, offering very low levels of self-discharge and good lifetimes, though there are concerns that energy is required when the battery is not in use to maintain its operating temperature. There are limited grid applications to date, with projects in USA and Europe. A 400kW unit is under development in the USA. More recently, GE has begun manufacturing this technology, renaming it the sodium metal halide battery.

Summary for High Temperature batteries

Advantages

- High power and energy densities.
- High efficiency.
- Readily-available materials.

Disadvantages

- High production costs.
- Some safety concerns (although these are being addressed in design).
- Additional heating power required.

xi. Batteries: Nickel-based

In commercial production since the 1910s, nickel-cadmium (Ni-Cd) is a traditional battery type that has seen periodic advances in electrode technology and packaging in order to remain viable. While not excelling in typical measures such as energy density or first cost, Ni-Cd batteries remain relevant by providing simple implementation without complex management systems, while providing long life and reliable service.

Early Ni-Cd cells used pocket-plate technology, a design that is still in production today. Sintered plates entered production in the mid-20th century, to be followed later by fibre plates, plastic-bonded electrodes and foam plates. Cells with pocket and fibre plates generally use the same electrode design for both the nickel positive and cadmium negative, while sintered and foam positives are now more commonly used with plastic-bonded negatives.

All industrial Ni-Cd designs are vented types, allowing gases formed on overcharge to be dissipated but requiring some degree of water replenishment to compensate. This has led to the implementation of separator designs that allow varying levels of recombination, with some products designed for telecom or off-grid renewable energy applications, achieving near maintenance-free operation with respect to the electrolyte.

Ni-Cd batteries found use in some earlier energy-storage applications, most notably the Golden Valley Electric Association BESS near Fairbanks, AK, USA, sized for 27MW for 15 minutes, commissioned in 2003. Ni-Cd has also been used for stabilising wind-energy systems, with a 3MW system connected to a wind/diesel hybrid system on the former Netherlands Antilles island of Bonaire, commissioned in 2010. This was part of a project for the island to become the first community with 100% of its power derived from sustainable sources.

Summary for Nickel-based batteries

Advantages

- High power and energy densities.
- High efficiency.
- Long lifetime.

Disadvantages

- Construction is relatively expensive.
- Materials are relatively expensive and not plentiful; nickel and cadium have diminishing reserves, with nickel in particular commanding an increasingly high price.
- Environmental considerations limit further deployment of this technology.

xii. Batteries: Lead-Acid type

Lead-acid chemistry is the most mature rechargeable battery technology and is widely used; it is a low-cost and popular storage choice for various applications such as power quality, automotive, UPS, telecommunications and others. Though significantly inferior in terms of power density to lithium-ion, lead-acid batteries are still used for large-scale energy storage. However, its application for energy management has been very limited due to its short cycle life.

A 1MW/1.5MWh lead-acid system by GNB Industrial Power and Exide has been operating for 12 years and was replaced in 2008. Another 1MW/1.2MWh system has been operated by Stadtwerke Herne, Germany, since 1996. Other lead-acid energy systems have been deployed in sizes of 10–20MW. The largest one was a 40MWh system in Chino, California, built in 1988 and which operated for several years.

Advanced lead-acid batteries, including carbon-doping of the electrodes, are being commercialised, with improved cycle life and durability. Storage systems utilising these advanced batteries are expected to start field testing shortly. However, the global scarcity of lead poses large questions for future development.

Summary for Lead Acid batteries

Advantages

- Low capital cost.
- Huge level of experience.
- Established recycling infrastructure for lead.

Disadvantages

- Limited cycle life when deeply discharged.
- Uses unsustainable materials – lead is in short supply globally.

xiii. Superconducting Magnetic Energy Storage (SMES)

A superconducting magnetic energy storage system (SMES) stores energy in a magnetic field created by the flow of electric current in a super-conducting inductor. The super-conducting inductor must be cryogenically cooled below its superconducting critical temperature. Energy is added or extracted from the magnetic field of the inductor by increasing or decreasing the current in the inductor. At steady state, the superconducting inductor does not dissipate energy and therefore the energy may be stored almost indefinitely. A number of systems were deployed in the 1990s but the technology was not adopted widely. New companies are developing SMES devices. A 24kV SMES magnet has been tested at Florida State University, as a research system and a substantial amount of work is being done in Germany on this technology.

SMES technology offers high cycle life and rapid response, but currently has a relatively low energy density and high cost, and requires energy to constantly cool the magnet.

Summary for SMES

Advantages

- High power.
- High cycle life.
- Rapid response.

Disadvantages

- Low energy density.
- High production cost.
- Requires energy to constantly cool the magnet.

xiv. Super-capacitors (EDLC)

Electrochemical Double Layer Capacitors (EDLC), or supercapacitors, store energy in the form of separated charges at porous electrodes divided by an electrolytic solution. Due to their high power density but relatively low energy density, EDLCs are well suited to voltage and frequency stabilisation. EDLC storage technology is slowly being deployed. For example, a demonstration project of 300kWh/100kW uninterruptible power supply system using electrochemical capacitors for bridging power was carried out by EPRI Power Electronics Application Center in 2003. This technology offers high cycle life and rapid response, but currently has a relatively low energy density and high cost, and suffers from a relatively high rate of self discharge when compared to other electrochemical energy storage technologies.

Summary for EDLCs

Advantages

- Long cycle life.
- High efficiency.
- Rapid response.

Disadvantages

- Low energy density.
- High production cost.
- High rate of self discharge.

xv. Graphene Super-capacitors

This is an early-stage technology using graphene, which has the interesting properties of extremely high conductivity, high mechanical strength and potential to be produced in extremely thin layers.

Preliminary work by General Electric has shown extremely high energy densities and fast charge capacity at very small scale.

It is claimed that the material is sustainable but it is not necessarily true. Although it is basically carbon, it is currently made with mineral graphite, reserves of which are already depleted. To be truly sustainable, it would have to be synthesised from other carbon sources.

Summary for Graphene Super-capacitors

Advantages

- High energy density.
- Use of sustainable materials possibly.
- Fast charge capability.

Disadvantages

- Very early stage technology.
- May not be scalable.

The iCon Environmental Innovation Centre in Northamptonshire has been recognised for its progressive design and energy efficiency. Constructed using materials that limit the need for heating or air conditioning it includes phase change panels in the ceiling that can absorb or emit heat, depending on temperature.

ENERGY STORAGE FOR HEAT

i. Hot water systems (Sensible Heat Storage – SHS)

Hot water tanks are one of the best-known thermal energy storage technologies and are fully commercialised. They are already widely used at a building scale in combination with electrical or solar thermal water heating systems to store water over a number of hours from when it is heated (eg at night when electricity is cheaper, or during the day when the sun is shining) until it is needed. In the future, it is likely that larger versions could be combined with heat pumps.

At an even larger scale, hot water storage can also be used in conjunction with district heating (DH) systems when heat is provided from CHP, biomass boilers (including EfW) and/or large-scale solar water heating. Using thermal stores or accumulators allows the CHPDH operator to optimise the fuel utilisation and load factor of a district energy scheme by generating electricity during peak periods and storing any excess heat which can subsequently be distributed when demand is high. The storage efficiency can be further improved by designing to ensure optimum stratification of water in the tank.

According to the Royal Academy of Engineering (RAEng)[20], storing heat is easier and cheaper than storing electricity but is not as cheap as storing oil or coal. A tank of water 5m x 5m x 2m deep, which could be constructed in the basement/cellar of a traditionally-built family house, could store enough heat to warm the house for a month in winter, or longer at milder times of the year. If recharged by solar water heaters and/or off-peak electricity, such a system would be able to match the heating needs of a house with the availability of low-carbon-intensity supplies.

For a district heating scheme, a well-insulated storage tank of similar area to a public swimming pool, could provide the capacity needed for several weeks' storage of heat. Due to economies of scale, large storage tanks are cheaper per unit volume of storage and the heat losses are lower. In Scandinavia, almost all cities and towns have large pressure-less storage tanks (operating to 95°C). The largest of these, in Odense, DEN, is a 75,000m^3 tank at at Fynsværket CHP plant. Some heat transmission systems have semi-pressurised tanks, for example, the 2 x 23,000m^3 tanks at Avedøre CHP plant, operating at up to 120°C.

Tank technology in Denmark has been combined with landfill technology in order to store solar heat at temperatures up to around 85°C from summer to winter in a more cost effective way. The largest in operation in Denmark is a 75,000m^3 pit storage at Marstal, but larger storage facilities, 2–3 times this size, are under development. For these storages, the economy of scale and the further development reduces costs significantly. The all-inclusive cost of storage by this method, from summer to winter (one load cycle), is between £15 and £20 per MWh.

Other methods of storage store heat at a lower temperature, which cannot be used directly for heating, but which can use a heat pump. Larger storage volumes and longer storage periods (up to months) can be achieved by storing hot (or cold) water underground at a modest temperature. Naturally occurring aquifers (eg a sand, sandstone, or chalk layer) are most frequently used. Groundwater is extracted from the layer and then re-injected at a different temperature level at a separate location nearby.

There are also a number of projects worldwide that use underground storage in boreholes, in which vertical heat exchangers are inserted into the underground and thermal energy is then stored in the clay, sand or rock. Boreholes are often used to store solar heat in summer for space heating of houses or offices.

Another alternative is cavern or pit storage, in which large underground water reservoirs are created in the subsoil to serve as thermal energy storage systems. These storage technologies are technically feasible, but the actual application is still limited because of their high investment costs.

Summary for Sensible Heat Systems

Advantages

- Many decades of experience.
- Relatively cheap.
- Economies of scale provide an opportunity, but only in combination with large low-temperature heat loads, from industry and from district heating systems.

Disadvantages

- Low energy density and hence large volumes/masses required.
- Efficiency is low due to heat losses and costs are high for small-scale storage.

ii. Phase-changing materials (Latent Heat Storage – LHS)

To overcome the disadvantages for the smaller-scale SHS, phase-change materials (PCMs) are being explored for thermal energy storage applications. Such chemical compounds can include inorganic salts, (such as sodium sulphate and its hydrates) or organic materials (including paraffins and beeswax) that absorb heat and undergo a phase transition at a particular temperature, for example dissolution or melting. On cooling, the reverse phase transition occurs, eg crystallisation or freezing, and heat is released. PCMs are classified as latent heat storage (LHS) units.

Initially, solid-liquid PCMs behave like sensible heat storage (SHS) materials; their temperature rises as they absorb heat. Unlike conventional SHS, however, when PCMs reach the temperature at which they change phase (their melting temperature) they absorb large amounts of heat at an almost constant temperature. The PCM continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. When the ambient temperature around a liquid material falls, the PCM solidifies, releasing its stored latent heat. A large number of PCMs are available in any required temperature range from -5 up to 190°C. PCMs are very effective at heat storage and can store from 5–14 times more heat per unit volume than conventional storage materials such as water, masonry or rock.

PCMs can be incorporated into containers as a stand-alone store or be included in building materials, eg wall panels, thereby storing solar energy during the day and releasing it during the cold night. Suitable PCMs would ideally meet a number of criteria, including the ability to release and absorb large amounts of energy when freezing and melting, have a fixed and clearly determined phase-change temperature, remain stable and deliver reproducible behaviour over many freeze/melt cycles and be non-hazardous.

Summary for Phase-Change Materials

Advantages

- High energy density and so smaller volumes/masses required.
- Relatively cheap.
- Can deliver heat over a range of temperatures, depending on material.
- Possible to smooth temperature variations.

Disadvantages

- Not suitable for long term storage owing to inevitable heat losses to surroundings.
- Reproducible performance over multiple heating/cooling cycles can be compromised by effects such as incongruent melting of salt hydrates.
- Salt hydrates can cause corrosion of components.
- Organic-based PCMs may be flammable.

iii. Chemical reaction systems

Thermochemical storage is a new and potentially promising concept for heat storage that consists of systems that utilise reversible physicochemical sorption phenomena to store energy. On heating, water (or another volatile component) is desorbed from the material and is then stored separately. This is an endothermic process, often referred to as charging or activation of material. On recombining the desorbed component with the activated material, an exothermic process occurs. Energy can therefore be stored in the activated material for extended periods with negligible thermal losses. This makes the technology attractive for long-term seasonal storage of heat. Energy densities are also higher than for SHS and LHS systems.

Thermochemical storage systems include low-cost crystalline or amorphous silica-based porous materials and their composites (often impregnated with hygroscopic inorganic salt hydrates), zeolites, metal hydroxides and carbonates, and micro-porous aluminophosphates. Requirements for large-scale applications include: a charging temperature below 140°C; an energy density above 250kWh m^{-3}, and resistance to material degradation. Furthermore, the total storage density, which includes all of the components (in particular tanks and heat-exchangers), is sometimes barely above that of water because of the space required for assembly of these components. The economics of this approach are still uncertain, but there is undoubtedly the potential for R&D to improve performance and to reduce costs through mass production.

Summary for Chemical Reaction Systems

Advantages

- High energy density and so smaller volumes/masses required.
- Long-term storage with low heat losses.

Disadvantages

- Energy densities compromised by space required by ancillary components.
- Potential corrosion issues associated with use of salt hydrates.
- Relatively immature technology.

Torotrak plc's Flybrid M-KERS Technology (where the M refers to "Mechanical").

ENERGY STORAGE FOR TRANSPORT

The UK Government's current aspiration for decarbonising the transport sector is largely based on an 'electrified' system that meets the nation's highly ambitious targets for GHG-emissions reductions. In this regard, the Institution has previously noted that this strategy, which is based on a prior decarbonisation of the electricity sector, before widespread electrification occurs, will be extremely challenging to implement in any reasonable timescale, or at a cost that society will be prepared to sustain. Indeed, it is likely to be many decades, if ever, before the UK's electricity-generating capacity is genuinely free from the emissions of CO_2 and other GHGs.

In terms of costs, it is a fact that 'liquid fuels' can be stored on vehicles at high energy densities in simple low-cost storage systems, and are distributed via low-cost, low-loss infrastructures, and this is likely to remain the case for some time to come. However, although these liquid fuels do not have to be limited to conventional fossil fuels, it is likely that competing technologies will struggle to be able to compete on cost grounds in the foreseeable future. As with stationary energy storage systems, there is no 'silver bullet' solution and there is considerable scope for the development of a number of different technologies, many of which will have application in niche markets. This section covers the 'energy storage' technologies for transport that are at, or approaching, commerciality.

i. Biofuel-based systems

Since most land vehicles are currently powered by petrol (gasoline) or diesel liquid fuels, the easiest sustainable replacement fuels are liquid biofuels. The great attraction of liquid biofuels is that they are 'drop in' replacements for the existing fossil-based fuels with similar performance characteristics. Petrol can be replaced by Bioethanol or Biobutanol and diesel fuel by Biodiesel.

Biomethane can also be substituted for fossil fuels, although the internal combustion engine (ICE) needs to be converted to run on gaseous fuel. The storage tanks on board the vehicles are identical to those currently in use. There are, however, some warranty-type issues regarding the direct use of these fuels in existing ICEs, which still need to be resolved by many manufacturers. The current position is that liquid biofuels are most commonly blended with mineral-derived fuels.

Given the EU-wide commitments, under the Renewable Energy Directive, for 10% of energy used in the transport sector to be derived from renewable resources by 2020 (the UK's figure for 2009 was 2.4%) it seems highly probable that liquid biofuels will have to provide the vast majority of this.

With 1st generation biofuels, there were understandable sustainability concerns centered around the 'Food vs. Fuel' debate and whether or not arable land should be prioritised for feeding the world's growing population.

The UK Government commissioned the Gallagher Review of 2008 to address this issue. The industry responded positively and developed 2nd generation biofuels, based on feedstock which do not compete with food crops. Examples of this are the use of oils from trees such as Jatropha, ligno-cellulosic crops (woody materials not suitable for eating) and waste products from agriculture. More recently, 3rd generation biofuels have been developed, that are derived from microalgae and which, at least theoretically, have a substantially greater yield than other biomass sources. These microalgae require sunlight and CO_2 to grow, so are potentially suitable for biofuel production in the developing world. However, currently algae oil is more expensive than colza, jatropha or sunflower oil; it is also uses very high-tech processes and is far from ideal for developing world applications.

Summary for Biofuel-based systems

Advantages

- Major advantage is applicability to existing vehicle fleets; there is no need to wait 10–20 years for fleets to be replaced.
- Well-known and relatively inexpensive technology.
- Only form of renewable energy which has any chance of meeting the RED 2020 commitments.
- Easy to transport using existing engine/vehicle designs and infrastructure.
- Allows continued development of efficiency and sustainability of well-proven ICE design, instead of moving to an entirely new platform.
- Can be used in combination with electric vehicles in 'hybrid' format.

Disadvantages

- Still has some CO_2 emissions, although can be considered 'carbon-neutral'.
- Although more benign than fossil-fuels, there are the same issues regarding spillages and contamination.
- There are limits to the amount of biomass that can be grown (particularly not to compete with food crops), particularly in the UK.

ii. Electrical systems

Although electrically-powered road vehicles have been developed and available for the past century, they have never really achieved their potential, as the disadvantages have always tended to outweigh the advantages. This is in marked contrast to railway vehicles, which have continued to develop and have, even in the UK, become the most desirable form of propulsion system. However, railway vehicles are predominantly supplied with electricity from overhead or 3rd rail supply systems.

The current push for electric vehicles in the UK largely stems from the King Review of 2007–8, which concluded that electric vehicles (EVs) were the preferred way forward for the UK road transport sector. This move has been further encouraged by the CCC's proposals to meet the UK's CO_2 emissions targets by decarbonisation of the transport sector.

True EVs use an entirely different transmission system to conventional vehicles with traction motors driving the wheels directly. This has the benefit of allowing the use of regenerative braking to help reduce electrical consumption and preserve battery life. Hybrids (HEVs) and plug-in hybrids (PHEVs) tend to use more conventional drive trains with electric motor assistance. In either case, the energy to power the drive motors is stored in batteries of one kind or another, each of which is subject to the descriptions of batteries given in section 3.

The flexibility of Li-ion technology in electric vehicle (EV) applications (from small high-power batteries for power buffering in hybrids, through medium-power batteries providing both electric-only range and power buffering in plug-in hybrids, to high-energy batteries in electric-only vehicles) makes them ideal for use in electric vehicles. However, the grounding of the entire fleet of Boeing 787 Dreamliners in early 2013 following on-board fires in Li-ion batteries has raised serious doubts about the flammability of this battery type.

One of the attractions of EVs is that there are no 'tail pipe emissions'. This is indeed beneficial in urban environments as the air quality is not impaired by the vehicle. There will, of course, be GHG emissions from the tail pipes of hybrid and plug-in hybrid vehicles but these are significantly reduced by the predominant use of the electric motor(s) in urban environments. Nevertheless, the 'zero emissions' claimed for many EVs is misleading, as in the UK the large proportion of national electricity is generated from fossil fuels and this has to be taken into consideration. Although GHG emissions from power stations are anticipated to reduce over time, as non-fossil-fuel electricity becomes more widespread, this is unlikely to be a significant proportion of the mix for the foreseeable future.

The range of EVs remains a concern for vehicles that have to travel even quite moderate distances. Battery exchange systems have been proposed and could well allay some of these concerns though public acceptance of, for instance, putting an old used battery into a new car is, as yet, unknown.

As with all electrical systems, the ideal conductor material is copper, which is in increasing shortness of supply worldwide. As global population and mobility increase, there are likely to be major sustainability issues with the supply of this material.

Summary of Electrical-based systems

Advantages

- Quiet operation with no ‘tailpipe emissions’; air quality benefits.
- Ideal for short journeys, eg urban.

Disadvantages

- Range/performance limitations.
- Issues surrounding long recharging periods and battery changeovers.
- Flammability issues with Li-ion batteries in transport applications.
- Sustainability issues with materials (eg copper and Lithium).
- Overall sustainability is highly dependent on ‘energy mix’ of national electricity supply.

iii. Hydrogen systems

As noted in section 3a)iv on hydrogen energy storage systems, hydrogen is a useful high calorific value fuel which can be used in a variety of ways in vehicular transport. However, due to the extremely low boiling point of hydrogen (-253°C), it is both difficult and expensive to produce liquid hydrogen. To allow practical quantities of gaseous hydrogen to be transported in vehicles, the gas must be compressed to the range 350–700 bar, which is both technically difficult and expensive.

There are two main types of hydrogen vehicle: those using hydrogen as a fuel to the internal combustion engine of the car, and those using hydrogen fuel cells to providing electric power to the vehicle as an EV. The former uses a conventional transmission and wheel-drive system, whereas the latter powers the wheels through traction motors as in a normal EV.

Whichever of these systems is used, the issue remains of the portability of hydrogen. Because hydrogen is the lightest known element, it has to be compressed to very high pressures in order that the volume of the gas is reduced sufficiently to be portable. Although special composite materials have been developed for storage tanks, these are expensive and are unlikely to decrease sufficiently in price with mass production to be in any way competitive with conventional fuel storage tanks.

Furthermore, ‘filling’ stations will require hydrogen compression equipment to deliver the gas at up to 700 bar into the vehicle for storage; there are significant Health and Safety, as well as cost concerns, around this practice. Also, the distance that the vehicle could travel on a full tank of hydrogen is currently similar to that of an EV. Nevertheless, a number of such filling stations are being built, particularly in the USA.

The main attraction of hydrogen as a transport fuel is that there are no GHG-emissions from the tail-pipe. The hydrogen reacts with the oxygen in the atmosphere to form water, which can be considered environmentally benign. However, although hydrogen is in abundant supply globally, it does not exist in free form and has to be manufactured. As noted in section 3a)iv, currently only about 4% of the world’s hydrogen comes from renewable sources and the production processes for this ‘green’ hydrogen are very inefficient.

An alternative use of hydrogen for vehicles is as an additive to other liquid fuels. This is already commonplace as hydrogen is added to conventional fossil fuels to give a leaner ‘burn’ and reduce GHG-emissions. However, the most promising way of using ‘green’ hydrogen for transport is to use it to create a CO_2 neutral liquid fuel by chemically combining it with CO_2 which has been previously captured in a process such as CCS. This produces a synthetic form of Methanol and may be thought of as chemically liquefying hydrogen. The product methanol can then be used as a liquid fuel in an ICE in a similar manner to conventional fossil fuels.

Summary of Hydrogen-based systems

Advantages

- Hydrogen is a highly versatile medium with high calorific value – useful as a fuel.
- Most hydrogen processes are well-proven and should be scalable for utility-scale storage.
- Excellent potential as an additive to other liquid fuels and in the production of synthetic methanol.

Disadvantages

- ‘Containment’ issues, especially at high pressures (eg 700 bar).
- Storage of hydrogen at high pressure on-board vehicles is always going to be expensive and has potential health & safety issues.
- Needs considerable development work for hydrogen to be a truly ‘sustainable’ fluid.

iv. Air/Nitrogen-based systems

The idea of nitrogen as a transport fuel is not new. Scientists first liquefied nitrogen in 1883, and within 20 years the Liquid Air Car Company had produced a vehicle that would run on it. But the idea never took off. While various prototypes were produced over the years, the engine was always very inefficient and was soon eclipsed by the ICE. In principle, any piston-type engine can be made to run on compressed air or nitrogen but, until recently, there were few engines which were dedicated to run on these energy vectors. This changed in the early 2000s with the development of the Dearman engine, which uses a patented, novel and far more efficient approach.[18]

The engineering breakthrough behind the Dearman engine was that, instead of using bulky external heat exchangers to gasify the nitrogen, the liquid could be made to boil after entering the engine cylinder, simply by injecting a small amount of water and anti-freeze to provide the necessary heat. The 'thermal fluid' has more thermal mass than the nitrogen, and so provides plenty of heat to boil it and drive the piston, yet cools by only a few degrees itself. After passing through the cylinder, the fluid is circulated through a radiator to warm back up to ambient temperature. Without this 'thermal fluid', the engine would have to be multi-stage, which is cumbersome, inefficient and expensive. Other than the novel engine design, the vehicle uses a conventional transmission layout.

Although not customarily used as a fuel, liquid nitrogen is a product of a conventional air separation unit (ASU) and is widely available throughout the world. Many existing ASUs, particularly those related to synthetic fertiliser production, already produce liquid nitrogen as a product and have spare production capacity immediately available, without the need for any additional investment. Others, which are dedicated to the production of liquid oxygen, eg for steelworks, could have a liquid nitrogen production retrofitted at relatively low cost.

As noted in section 3a)iii, under 'Cryogenic Energy Storage', the production and storage of liquid air and/or nitrogen is a well-known, well proven and inexpensive process. The operating fluid is ambient air, one of the world's most plentiful resources, and no special or unsustainable materials are used in any part of the process. The exhaust from the vehicle is predominantly nitrogen and there are no GHG-emissions at the tailpipe.

Another advantage is easy refuelling, which would take minutes rather than the hours needed to recharge an EV. The energy transfer rate is almost as good as liquid fossil fuels and because the energy density of liquid nitrogen is low, the range would be similar to that of an EV. The lower cost and greater convenience of liquid nitrogen is likely to be a significant advantage.

Summary of Liquid Air/Nitrogen systems

Advantages

- Builds on well-proven Air Separation technology – over 100 years' experience.
- Uses commonly-available operating fluids – atmospheric air or nitrogen.
- No unsustainable or exotic materials used in process or machines.
- Well-established supply chain for all major components.
- Density ratio of 700:1 (at atmospheric pressure) ensures low space requirement in vehicle.
- Can be rolled-out to commercial users in short-term by installing local storage for refuel at base.

Disadvantages

- Requires new nationwide filling station infrastructure to handle/dispense liquid air/nitrogen for mass rollout in longer term.
- Requires new engine configuration, although can work with existing low-cost transmission systems.

v. Flywheel-based systems

As already noted in section 3a)vi, flywheels can be viewed as kinetic or mechanical batteries; they use electric motors to which accelerates a rotor (flywheel) to a very high speed, which stores the energy in mechanical/rotational form.

In railway and tramway applications, the flywheel is turned by a motor/generator and spun up to speed from a third rail or small on-board engine. The flywheel then turns the motor as a generator, to produce electricity for the traction motors that turn the wheels. The flywheel allows direct capture of brake energy (when slowing down or descending gradients) and its re-use for acceleration ('regenerative braking'). Since the short-term power demand for acceleration is provided by the energy stored in the flywheel, there is no need for a large engine. Flywheel-driven railcars developed by PPM have been successfully used on a short branch line at Stourbridge, West Midlands, since 2009.

Flywheel systems are also being trialled in buses and high-performance cars in hybrid applications. The Flybus consortium has developed a system, which potentiall could cost significantly less than current electric hybrids, using a Ricardo Kinergy flywheel as the energy storage medium and a Torotrak continuously variable transmission (CVT) as the means of transferring energy between the wheels and the flywheel. Expectations are that the Flybus system will be available at significantly lower cost than an electric hybrid, with fuel savings in excess of 10%.

Jaguar's Flybrid project uses a very similar flywheel hybrid system in a high performance car; the flywheel system provides a 60kW power boost, for up to seven seconds a time, and tests indicate fuel economy improvements of up to 20%.

Summary of Flywheel systems

Advantages

- High power capacity.
- Low maintenance and long life.
- Negligible environmental impact.

Disadvantages

- Low energy density.
- Precision machining requirement results in relatively high unit costs.

DEFINITIONS

W (Watt). The watt is a derived unit of power in the International System of Units and is named after the Scottish engineer James Watt. The Watt, defined as one joule per second, measures the rate of energy conversion or transfer.

kW (Kilowatt). A kilowatt is equal to 1,000 watts (or 1.34 horsepower).

MW (Megawatt). A megawatt is equal to 1,000,000 watts. Many wind farms are rated at a capacity between 200–600MW of output.

GW (Gigawatt). A gigawatt is equal to one billion (1,000,000,000) watts. Modern nuclear power plants typically generate between 1–5GW.

TW (Terawatt). A terawatt is equal to one trillion (1,000,000,000,000) watts.

PW (Petawatt). A petawatt is equal to one quadrillion (1,000,000,000,000,000) watts.

kWh (Kilowatt Hour). A kilowatt hour is a unit of energy equal to 1,000 watt hours. As an example, a heater rated at one kilowatt that operates for one hour uses one kilowatt hour of energy. A 60-watt light bulb operating for 100 hours uses 6 kilowatt-hours.

MWh (Megawatt Hour). A megawatt hour is a unit of energy equal to 1,000,000 watt hours.

GWh (Gigawatt Hour). A gigawatt hour is a unit of energy equal to 1,000,000,000 watt hours.

TWh (Terawatt Hour). A terawatt hour is a unit of energy equal to one trillion watt hours. Human total energy consumption in 2008 was about 140,000TWh.

PWh (Petawatt Hour). A petawatt hour is a unit of energy equal to one quadrillion watt hours.

Nm^3 (Normal Cubic Metre). The normal cubic metre is often used to denote gas volumes at some standard condition.

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