Centre for Low Carbon Futures 2050

Liquid Air Energy Network

Liquid Air Technologies –

a guide to the potential

UNIVERSITY OF BIRMINGHAM

CENTRE FOR CRYOGENIC ENERGY STORAGE

Contents

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PREFACE

2013 is the year liquid air 'arrived' as a serious energy technology. Following a report by the Centre for Low Carbon Futures and a conference with the industrial and business community at the Royal Academy of Engineering, liquid air technologies are now widely recognised as offering the potential to deliver reductions in fuel bills, air pollution and carbon emissions, while simultaneously boosting energy security and creating jobs.

The Government is clearly convinced of the potential, and has so far this year committed significant £millions to fund immediate demonstration projects in grid and transport applications and a new multi-million pound research institute, the Birmingham Centre for Cryogenic Energy Storage. The debate has broadened rapidly to encompass not simply the benefits of individual technologies, but also the potential for a joined-up 'liquid air economy'. Like any potentially disruptive technology, the benefits of liquid air would need to be significant for it to achieve widespread adoption in business and society at large. But what would that mean?

A liquid air economy would convert 'wrong time' renewable energy into a form that can be used equally well in a wide range of applications – from electricity storage and generation to vehicles including buses and lorries. It would help tackle three of the toughest challenges of the low-carbon transition: balancing an electricity grid increasingly dominated by intermittent renewables; economically reducing transport emissions; and harvesting low grade waste heat throughout the economy.

Based on an old idea, the liquid air economy is being made possible by the work of UK entrepreneurs, engineers and academics, and plays to British strengths in cryogenic and mechanical engineering. In May, the Centre for Low Carbon Futures published a report, *Liquid Air in the energy and transport systems: opportunities for industry and innovation in the UK*, which estimated the value to Britain from liquid air energy storage alone at £1 billion and 22,000 jobs. Those jobs could well favour the Midlands, the North of England and Scotland.

Two people have been instrumental in laying the foundations for this opportunity. One is an archetypal British inventor, Peter Dearman, who made the big leap forward in engine efficiency and converted a car in his garage to prove his idea. The other is Professor Yulong Ding who, working with Peter, led the early work to invent Liquid Air Energy Storage for grid-scale application and is today the new Chamberlain Chair at the state of the art Birmingham Centre for Cryogenic Energy Storage, where he will lead the next phase of research and development of liquid air technologies.

The liquid air economy is no silver bullet, but it does offer a unique combination of energy, environmental and economic benefits. What's more, since liquid air is based on existing components and supply chains, a liquid air economy could develop far sooner than some other approaches. What we need now is a roadmap to take us from here to there, and this briefing paper is the first step, recognising any such map must identify human, business and technological scenarios.

Professor Richard A Williams, OBE FREng FTSE,
University of Birmingham

1. SUMMARY AND RECOMMENDATIONS

Liquid air 'arrived' in 2013 as a serious energy technology, capable of delivering major economic and environmental benefits.

Government, universities and investors have clearly recognised the potential of liquid air, but its future success is far from guaranteed. Like all novel technologies, liquid air must cross the 'valley of death' between demonstration and commercialisation – where most fail. On the other side of the valley lies the possibility of a joined-up 'liquid air economy', where liquid air is widely deployed to deliver major reductions in fuel consumption, cost, carbon emissions and local air pollution, as well as economic growth and new jobs. The question now is how to get from here to there.

Working with the Centre for Low Carbon Futures, the Liquid Air Energy Network was established to answer that question. We shall publish a series of reports to explore in more detail the potential routes to market, barriers to entry and the research and development required.

In this first briefing note, we summarise the environmental and economic potential of each of the various liquid air technologies currently available or being developed, and then explore how these could integrate into the wider energy system to form a 'liquid air economy'. We present an indicative timeline showing the progress of liquid air against policy targets, and reach some broad conclusions about how to maximise the chances that liquid air delivers its potential.

We recommend that liquid air stakeholders should collaborate to:

- develop and maintain technology and product roadmaps for both grid and transport applications. These roadmaps, produced by consensus, should be aligned with broader government and industry roadmaps, and aimed to maximise the economic and environmental opportunity for UK plc;
- explore the global opportunities for liquid air across industry and transport, in both developed and developing economies, and quantify the market potential for UK plc;
- map potential sources of liquid nitrogen supply and demand to determine where best to carry out field trials and early deployment;
- develop models to explore the potential benefits of integrating grid and transport applications through multi-purpose liquid air plants;
- work with government to make sure liquid air is recognised even better in the policy and funding framework;
- start to inform the public of the benefits and safety of liquid air technologies.

To achieve this, LAEN has established three working groups covering grid energy storage, transport, and integrated modelling, with members drawn from industry, universities, technology developers and expert consultancies. The grid and transport groups will each develop and maintain a technology roadmap and common research agenda to guide academic and industrial research; set targets; identify areas of UK strength and weakness; and maximise the benefit to UK plc.

The Liquid Air Transport Technology Group has already started work to identify the research needs of liquid air transport applications across passenger, commercial and off-road vehicles. The first iteration of the transport roadmap will be published as part of our next report, *Liquid Air on the Highway*, which is jointly funded by the TSB. The grid and integrated modelling groups will begin work shortly, and their conclusions will be reflected in further reports over the coming year.

2. OVERVIEW

2013 was the year liquid air 'arrived' as a potentially significant energy technology. The idea – developed in Britain – of using cryogenic air or nitrogen as an energy storage medium has been gaining momentum for nearly a decade, but this year liquid air has, for the first time, gained widespread recognition:

- the Automotive Council has incorporated liquid air into its technology roadmaps;
- the Centre for Low Carbon Futures (CLCF) published an in-depth report into its potential, launched at a conference at the Royal Academy of Engineering;
- the University of Birmingham opened a dedicated research facility, the Centre for Cryogenic Energy Storage (BCCES), with funding from the Engineering and Physical Sciences Research Council (EPSRC);
- the Liquid Air Energy Network was founded to ensure the UK captures the full energy, environmental and economic benefits;
- organisations developing liquid air technologies have so far won significant £millions in government funding for technology development, market studies and demonstrations.

These developments provide compelling evidence of how seriously liquid air is now being taken as a potentially powerful low-carbon energy vector.

The reason liquid air is making such an impact is that many experts now agree it could help solve some our toughest energy challenges. Although the concept itself is deceptively simple (see Box 1 on page 4), liquid air has many potential applications: balancing an electricity grid increasingly dominated by intermittent renewable generation; providing a cheap and convenient low-carbon transport fuel; and harvesting waste heat throughout the economy.

The CLCF report, based on contributions from a broad group of industrial and academic experts, found liquid air could for example:

- provide a cost-effective means of storing grid electricity in bulk to help balance intermittent renewable generation and reduce grid emissions, creating an industry worth at least £1bn per year and 22,000 jobs;
- reduce diesel consumption and carbon emissions in buses and freight vehicles by 25% using liquid air / diesel hybrid engines;
- cut carbon emissions from refrigeration on food lorries by at least 23% based on current grid average electricity, with potential for over 90% in future, and eliminate local air pollution from this source;
- strengthen UK energy security: a single gasometer-style tank of liquid air could make good the loss of 5GW of wind power for three hours – equivalent to almost 10% of the UK's peak electricity needs.

Liquid air also has two important industrial advantages. First, liquid air technologies can be produced largely from existing components and supply chains, meaning they should be quicker to market than other novel technologies at a nominally similar stage of development. For example, Highview Power Storage demonstrated the storage of grid electricity using liquid air in 2011, and the Dearman Engine Company will start to test its novel liquid air piston engine on a vehicle in 2014.

Second, there already exists a fuel production and distribution network throughout the developed world. For technical reasons (see Box 1) the industrial gas companies have substantial quantities of spare *liquid* and *gaseous* nitrogen production capacity, which could be used in place of liquid air to support early deployment. In Britain, the surplus nitrogen gas vented every day could be enough to power 310,000 homes or fuel well over 40,000 buses, equivalent to the entire UK bus fleet – although this would require investment in additional liquefiers.[1] The spare liquid nitrogen production capacity is also significant and available immediately without further investment, and its potential will be assessed in our forthcoming report, *Liquid Air on the Highway*. In any event, refuelling infrastructure poses no 'chicken and egg' dilemma for liquid air – a major advantage over other energy vectors.

Liquid air could help solve some of our toughest energy challenges.

[1] 8,500 tonnes of liquid air per day / 200kg per bus per day = 42,500 buses

2. OVERVIEW

Britain has a long history of letting brilliant inventions slip from its grasp; liquid air can avoid that fate.

Despite the growing awareness of its technical and industrial advantages, however, there is no guarantee that liquid air will actually progress to mass deployment. Like all novel technologies it must make the transition between demonstration and commercialisation – when most fail. On the other side of this 'valley of death' lies the possibility of a joined-up liquid air economy, where liquid air is widely deployed to deliver major reductions in fuel consumption, cost, carbon emissions and local air pollution, as well as economic growth and new jobs. The question now is how to get from here to there.

The question is especially acute in Britain, which has a long history of letting brilliant inventions such as advanced battery technologies slip from its grasp to be exploited overseas. "Liquid air has the potential to open a global market worth tens of billions of pounds," said John Hayes MP as Minister of State for the Department of Energy & Climate Change in 2012. But that will only be true if we first develop the technology at home.

This problem is already being tackled in some sectors. In the motor industry, for example, the government and the Automotive Council have jointly committed £1 billion to fund the new Advanced Propulsion Centre, intended to ensure that British advances in vehicle technology are developed to commercial production at home. It is encouraging, therefore, that the Automotive Council has recognised the potential of liquid air in its latest technology roadmap. But this does not mean stakeholders can relax; there is a great deal more work to be done to ensure liquid air survives the valley of death.

BOX 1: What is liquid air?

Air turns to liquid when refrigerated to -196C, and can be conveniently stored in insulated but unpressurised vessels. Exposure to heat (including ambient) causes rapid re-gasification and a 700-fold expansion in volume, which can be used to drive a turbine or piston engine to do useful work. The main potential applications are in electricity storage and transport, and in both, liquid air can provide the additional benefit of waste heat recovery and/or cooling.

Since the boiling point of liquid air (-196C) is far below ambient temperatures, the environment can provide all the heat needed to make liquid air boil. However, the low boiling point also means the expansion process can be boosted by the addition of low grade waste heat (up to +150C), which other technologies would find difficult to exploit and which significantly improves the overall efficiency. Liquid air can also exploit the waste cold from LNG re-gasification to improve the efficiency of liquefaction and reduce costs.

As with batteries or hydrogen, the purpose of liquid air is to store 'wrong time' low or zero carbon electricity, which can then be used to displace high carbon coal or gas in electricity generation and petrol or diesel in vehicles. The carbon intensity of liquid air depends on the source of electricity used to make it, and most industrial liquefiers operate at night when greenhouse gas emissions of grid electricity are lower than average. New liquefiers could be integrated with renewables to produce effectively zero carbon liquid air.

Liquid air and nitrogen are in any case zero-emission fuels at their point of use, offering the same potential for dramatic local air quality improvement as electricity or hydrogen. A liquid air engine is likely to be significantly quieter than a well-silenced petrol or diesel engine, and would be made of common and easily recyclable materials.

Liquid air is not yet produced commercially, but liquid nitrogen, which makes up four fifths of the atmosphere and can be used in the same way as liquid air, is produced throughout the industrialised world. The industrial gas companies have large amounts of spare nitrogen production capacity for the simple reason there is far more nitrogen than oxygen in the atmosphere but proportionately less commercial demand. This surplus could be used in place of liquid air to support early deployment (see main text). In future, liquid air would be cheaper to produce than liquid nitrogen, because there is no need to separate the nitrogen and oxygen, meaning liquefaction requires less equipment and around a fifth less energy.

BOX 2: The liquid air economy

Liquid air technologies could be developed piecemeal, but the environmental and economic benefits would be far greater if they were integrated with each other, and with the existing energy infrastructure, to store and make use of 'wrong time' energy. When the diverse roles of liquid air – electricity storage, generation, transport fuel and cooling – are all supplied from a single tank of cryogenic fluid, we could begin to talk of a joined-up 'liquid air economy'.

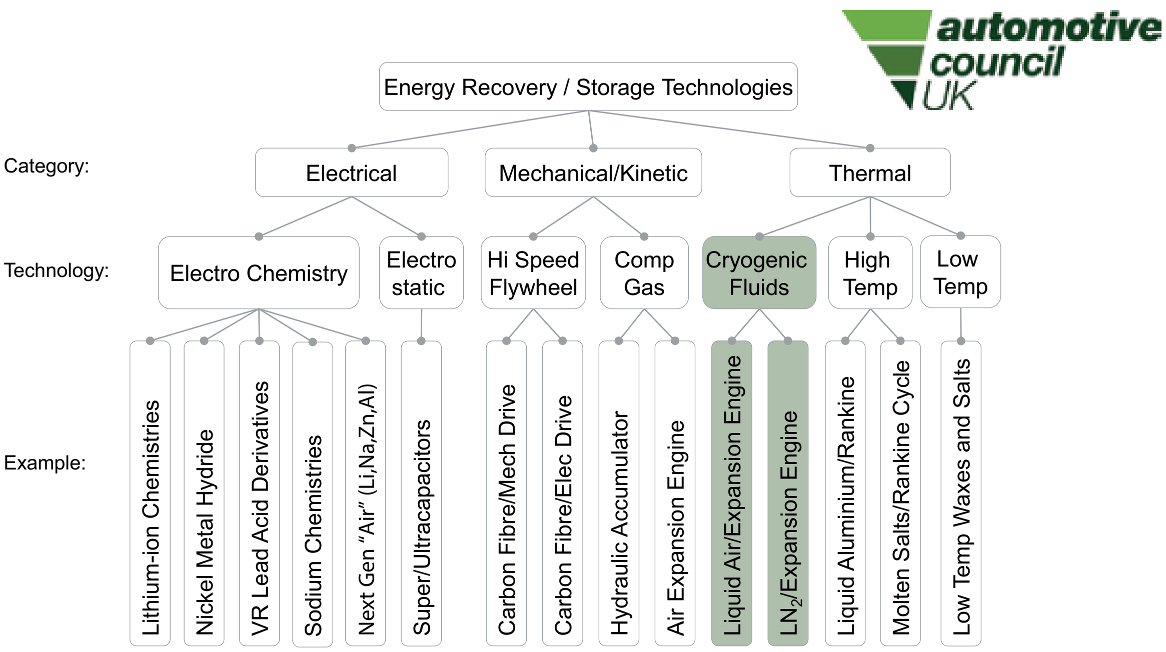
A promising place to start would be the eleven industrial gas production sites across Great Britain, which have substantial surplus production capacity for liquid nitrogen – which performs much the same as liquid air – and a nationwide tanker distribution network. These could supply liquid nitrogen to storage tanks in locations such as industrial parks, bus and haulage depots, and town centres up and down the country. Once the surplus liquid nitrogen capacity has been put to good use, new air liquefiers harnessing wrong-time renewable energy could be built in strategic locations to expand supply.

A new storage tank or liquefier sited at an industrial park, for example, might supply a range of neighbouring businesses for different purposes. A datacentre might need liquid air for cooling and for a cryogenic back-up power generator, while a logistics company might want fuel for diesel/liquid air hybrid lorries and zero-emission forklift trucks. The liquefier could be integrated with a cryogenic generator and a nearby biomass power station to create an efficient energy storage plant, absorbing low carbon electricity overnight and delivering it back to the grid at peak times, while converting the waste heat from the biomass plant into extra power.

A supermarket distribution hub, on the other hand, might install a large liquid air tank, to be regularly refilled from the nearest liquefier, which could support its lorry refrigeration units, forklift trucks and a back-up generator for emergency power. A metropolitan bus depot could adopt a similar approach, with a large tank to support both its bus fleet, and a generator for grid balancing.

The potential of liquid air is only beginning to become apparent, and it seems likely that further opportunities will emerge as our understanding improves. For a fuller exploration of the liquid air economy, please turn to section 4.

Britain could start to build a 'liquid air economy' based on spare industrial gas production capacity.



Vehicle energy and storage technologies. *Source: Automotive Council.*

3. LIQUID AIR TECHNOLOGIES

The breakthrough came when the British inventor Peter Dearman invented a novel and far more efficient liquid air engine.

Liquid air cars were first produced as long ago as the early 1900s, but in those days the technology was cumbersome and inefficient, and soon eclipsed by the internal combustion engine (ICE). The breakthrough came in the early years of this century when the British inventor Peter Dearman (pictured) patented a novel and far more efficient approach with the Dearman engine. The concept was further developed in collaboration with scientists at the University of Leeds, and it soon became clear the liquid air cycle could also be applied to the bulk storage of grid electricity and many other applications. Liquid Air Energy Storage was demonstrated on the grid in 2011 and the Dearman engine will start on-vehicle testing in 2014.

TRANSPORT

The Dearman Engine

The Dearman engine (DE) is a novel piston engine powered by the vaporisation and expansion of liquid air or nitrogen. The novelty lies in the use of a heat exchange fluid (HEF) that promotes extremely rapid rates of heat transfer inside the engine, allowing the DE to dispense with the bulky and inefficient external heat exchanger that handicapped earlier cryogenic engine designs. First, warm (or even ambient temperature) HEF is injected into the cylinder, followed by liquid air or nitrogen. Then, as the fluids mix, direct heat transfer causes the cryogen to boil and expand, so pushing the piston down. The HEF continues to provide heat throughout the power stroke, leading to efficient 'isothermal' expansion. Afterwards the cool gaseous air exhausts harmlessly to the atmosphere while the HEF is re-heated and re-used.

The Dearman engine could be used in a number of configurations: on its own, as the 'prime mover' or principal engine of a zero emissions vehicle (ZEV); combined with an internal combustion engine (ICE) to form a 'heat hybrid'; or as a power-and-refrigeration unit.

Peter Dearman has already demonstrated his engine in a modified car, and the Dearman Engine Company (DEC) is building a prototype, to begin on-vehicle field trials in 2014, with Technology Strategy Board grant funding. The DE's Technology Readiness Level (TRL, on a scale of 1 to 10) is currently rated at 4. However, since the engine is made largely from existing piston engine components, its development is expected to be shorter than that of other novel engine designs. DEC expects its refrigeration unit to go into fleet trials (TRL7) by the end of 2015.[2]

[2] The TRLs cited in this document are those of the Automotive Council. For definitions please see page 23

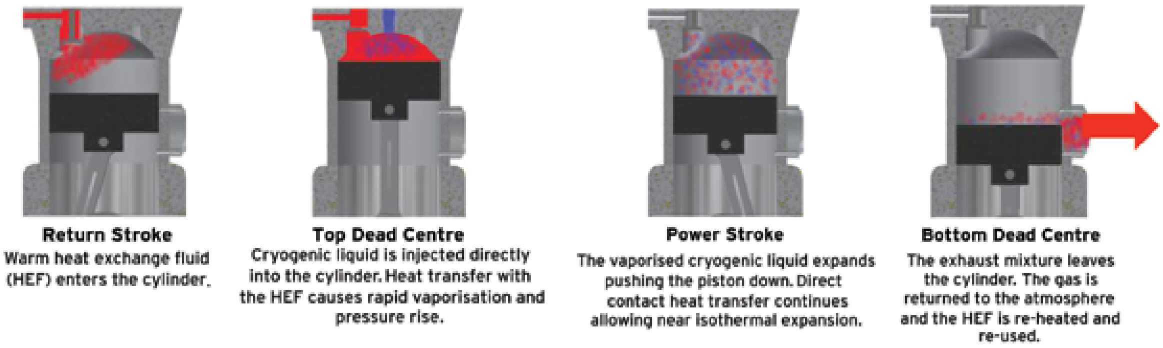
Peter Dearman, inventor. *Source: Dearman Engine Company.*

Dearman Engine ZEV

Used on its own, the Dearman engine is a zero emissions engine whose exhaust consists only of clean, cold air or nitrogen. It is also capable of low carbon emissions depending on the carbon intensity of the electricity used to produce the cryogen. On the basis of the projected emissions of overnight[3] electricity in 2030, the DE would have lower lifecycle carbon emissions than both electric (EV) and fuel-cell (FCV) vehicles.

Liquid air or nitrogen has a similar energy density to that of an EV battery but is far quicker to refuel – taking minutes not hours. So as a ZEV the Dearman engine lends itself to vehicles that are shorter range, have a lower power requirement or operate on a single site. Modelling by E4tech suggests potential markets include fork-lift trucks, mining, airports, inland waterways, 3-wheel taxis (or 'tuk tuks') for emerging markets and, in future, city cars.

[3] The carbon intensity of overnight electricity will fall faster than grid average, because of the disproportionate impact of growing wind capacity during periods of low demand. See CLCF, *Liquid Air in the energy and transport systems*, 2013



The Dearman cycle. *Source: Dearman Engine Company.*

The Dearman engine can be combined with a conventional engine to make a highly efficient 'heat hybrid'.

Dearman Engine 'heat hybrid': waste heat recovery and cooling

Because the Dearman engine is powered by the vaporisation of a cryogenic liquid, its work output can be raised by the addition of low grade waste heat from another source - such as an internal combustion engine (ICE).

An ICE loses roughly two thirds of the energy contained in its fuel as waste heat – about one third each through the radiator and exhaust. The heat lost through the radiator is low grade (~100C) which conventional technologies find difficult to harvest. However, since the DE bottom temperature is -196C, even low grade waste heat can be converted into shaft power at practical conversion efficiencies of up to 50%. The cooling loop of a diesel engine contains a mixture of water and glycol – just like the heat exchange fluid in a Dearman engine. This means the ICE waste heat could be transferred either directly, combining radiator fluid and HEF in a single circuit, or indirectly, via two separate circuits connected by a heat exchanger. There is nothing to stop an ICE-DE 'heat hybrid' incorporating other technologies to harvest higher grade waste heat from the ICE exhaust.

A heat hybrid would convert waste heat from the ICE into extra shaft power through the Dearman engine. This could be used to supply temporary peaks in power load such as pulling away, acceleration or going uphill, and would allow the ICE to be downsized and run more efficiently. The DE also has the advantage of displacing a material portion of transport related emissions into an energy vector – liquid air or nitrogen – that can be produced from low- or zero-carbon sources. These characteristics mean the ICE-DE heat hybrid lends itself to use in buses, coaches, rubbish trucks, lorries, urban delivery vehicles and a range of more specialist heavy duty and off-road equipment. An ICE-DE heat hybrid could consume up to 25% less diesel – so reducing the overall fuel bill – and deliver progressively larger emissions savings as the carbon intensity of grid electricity falls.

If the vehicle also needs air conditioning, the case for the DE strengthens further – particularly in hotter climates – since the engine extracts both power and cold from the same unit of liquid air. This is particularly interesting for buses, where using a DE to provide auxiliary power for cooling and lighting (the 'hotel load') would allow 'stop-start' technology to be introduced, meaning the ICE is turned off completely when the vehicle is stationary at bus stops or in traffic, which can cut diesel consumption by another 10%.

The DE waste heat recovery concept is currently at TRL3. However, the Dearman Engine Company predicts full scale prototype demonstration (TRL6) by the end of 2016.

Dearman Engine Refrigeration (Power and Cooling)

The Dearman engine can also operate as a zero emission and highly efficient Transport Refrigeration Unit (TRU) for vans, lorries and shipping containers ('reefers'), because it extracts both shaft power and cold from the same unit of liquid air or nitrogen, delivering immediate savings in fuel costs and carbon emissions. These savings will become increasingly significant since the global refrigerated vehicle market is booming – driven largely by changing diets in the developing world – and expected to double to £6.8 billion in 2018.

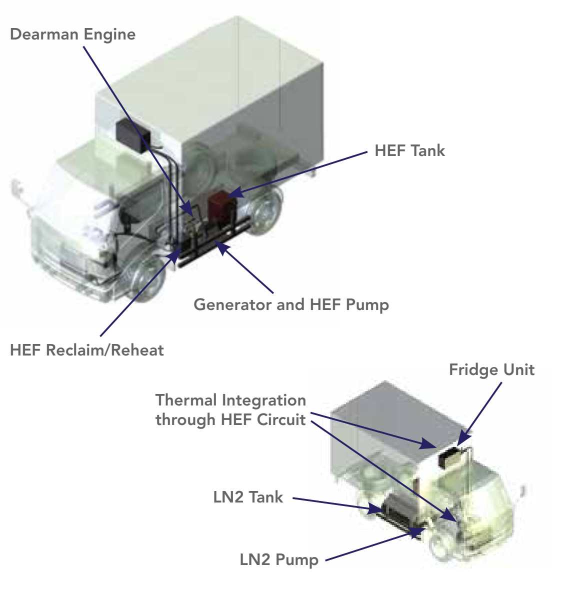
A Dearman engine refrigeration unit could produce CO_2 savings of more than 90%.

At present, transport refrigeration is overwhelmingly powered by diesel – either through a compressor driven by the vehicle's main engine, or a separate TRU. Refrigeration alone can consume as much as 20% of a lorry's fuel, and cause CO_2 emissions of up to 48 tonnes per vehicle per year. Diesel TRUs also emit high levels of nitrogen oxides (NOX) and particulate matter (PM) and are noisy, which can restrict their ability to make urban or night-time deliveries. Any technology that can reduce fuel costs, emissions and noise will clearly present a strong business, environmental and social case.

Vehicle manufacturers and industrial gas producers have begun to offer vehicle refrigeration based on liquid nitrogen evaporation, such as natureFridge's ecoFridge system, and around 1,000 units are now in use. Such systems are zero emission at the point of use and quieter, so capable of making night-time deliveries. Liquid nitrogen is either sprayed directly into the trailer where it evaporates and displaces warmer air with inert cryogenic gas, or it is passed through a heat exchanger that cools the air in the compartment indirectly. The direct approach is about 30% more efficient than the indirect, but requires additional safety measures to prevent the driver entering the compartment until excess nitrogen is vented. Neither approach, however, extracts any power from the evaporation process.

Direct refrigeration by liquid nitrogen. *Source: natureFridge.*

The refrigeration unit currently being developed by the Dearman Engine Company is a significant advance on existing technologies, since it uses liquid air or nitrogen to produce both cooling and shaft power. First the cryogen is vaporised in a heat exchanger in the refrigeration compartment, so cooling it down; then the high pressure gas is used to drive the Dearman engine, whose shaft power can be used to drive a conventional refrigeration compressor or for auxiliary power. This would produce even greater 'well-to-wheels' emissions savings compared to diesel. If a diesel TRU emits 48 tonnes of CO_2 per year, the DE system would emit a maximum of 37 tonnes based on the carbon intensity of today's UK grid electricity, and less than 4 tonnes in 2030, a saving of more than 90%.[4]



Dearman power and refrigeration engine. *Source: The Dearman Engine Company.*

A Dearman power and refrigeration engine would deliver financial as well as carbon savings. Modelling by E4tech shows that a liquid air combined cold and power unit designed to cool a 40' reefer to -20C would pay for itself in under three months. Dearman expects the refrigeration unit will be in fleet trials by the end of 2015.

Auxiliary Power Unit (APU)

A power and cooling engine could also be put to good use in a mobile Auxiliary Power Unit. APUs are typically used on long distance lorries where the driver sleeps in a bunk in the cab; running a small auxiliary diesel unit to supply the 'hotel load' of lighting, electrical appliances and air conditioning saves a great deal of fuel and cost compared to idling the vehicle's main engine all night. However, increasingly stringent and widespread anti-idling regulation is creating pressure to develop a zero-emissions alternative to the diesel APU. Where only electricity is needed, a battery powered APU is the most competitive option, but where air-conditioning is also required, the liquid air power and cooling APU would be significantly cheaper to buy and run.

[4] Estimates Dearman Engine Company and E4tech. UK grid carbon intensity $547gCO_2/kWh$ today, $50gCO_2/kWh$ projected in 2030

The Ricardo split cycle liquid nitrogen engine

Whereas the Dearman engine uses liquid air or nitrogen as fuel, the auto engineering consultancy Ricardo is developing a novel ICE that would run primarily on petrol or diesel but incorporate a quantity of cryogenic gas into the cycle to make it significantly more efficient.

In the Ricardo split cycle design, compression and combustion take place in separate cylinders. Efficiency is raised by combining the high compression ratios of an ICE with the heat recovery of a gas turbine. Reconciling these otherwise incompatible features requires the intake air be actively cooled so that compression is 'isothermal' – meaning the air stays at a roughly constant temperature – which the Ricardo design achieves by injecting liquid nitrogen. This reduces the work required for compression, and means exhaust heat can be recovered through a heat exchanger to expand the compressed air as it enters the combustor (for a fuller description please see the CLCF report cited on page 25).

Modelling conducted under the TSB 'CoolR' programme has suggested the Ricardo split cycle engine would be 60% efficient, compared to around 40% for modern diesels. The TSB has now awarded Ricardo a grant to develop the engine hardware.

Ricardo believes the engine will initially be deployed on heavy duty vehicles – rail, marine, lorries, and off-road applications – which are big enough to accommodate an extra tank for liquid nitrogen, and where the diesel savings would be sufficient to offset some additional infrastructure cost. A standard heavy duty vehicle with a diesel tank of 240 litres would be able to reduce this to 170 litres with the split cycle engine, but would also require a nitrogen tank of 1.1m3 – roughly the same size as would be needed to convert the vehicle to compressed natural gas (CNG). In this example, diesel consumption would fall by almost 30%, and depending on cost assumptions for fuel and nitrogen, financial savings could be as much as 20%. The Automotive Council roadmap shows the Ricardo split cycle engine to be in volume production by 2020.

GRID

Liquid air can also be used to provide both bulk electricity storage and back-up generation, and these applications are already well on their way to commercialisation. At its pilot plant in Slough (pictured, page 11), Highview Power Storage has successfully demonstrated two models: the Liquid Air Energy Storage (LAES) system, in which air is liquefied, stored and used to generate electricity on a single site; and the Cryogenset, a generation-only device, supplied with liquid air or nitrogen by road tanker from an industrial gas production facility. While each would perform a different role, both can exploit waste heat and provide cooling, and could therefore integrate with a wide range of grid, industrial and commercial equipment to increase their energy return. LAES could also exploit waste cold – from LNG re-gasification, for example – during liquefaction. Energy storage and back-up generation are expected to become increasingly important as Britain installs ever more intermittent renewable generation capacity over the coming decades. The Dearman Engine Company is developing a smaller scale generator based on its liquid air piston engine.

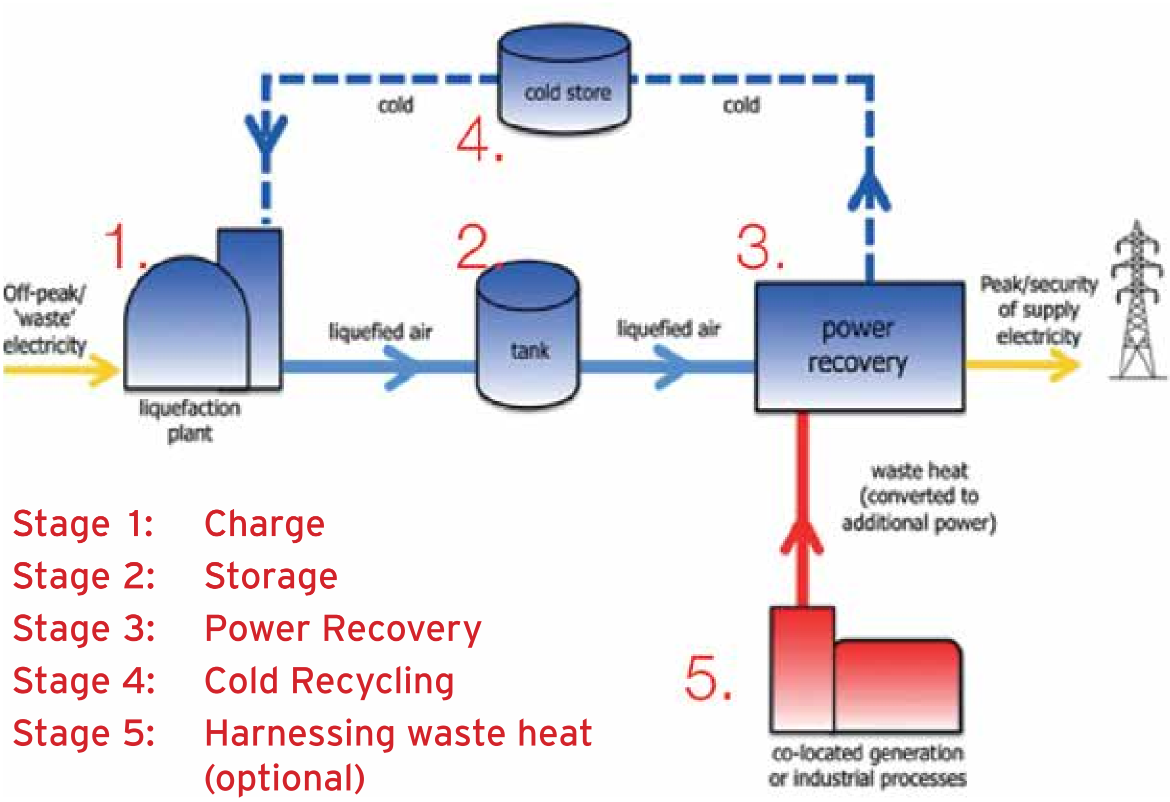
Liquid Air Energy Storage (LAES)

LAES is a novel, large-scale, long duration energy storage system based on standard components from the industrial gases and power generation industries. Electricity is used to drive an air liquefaction plant to produce liquid air, which is then stored in an insulated tank. When power is required, the liquid is pumped to high pressure, and then through a heat exchanger where it converts into a high pressure gas that drives a turbine to generate electricity. Cold from the evaporation is recycled to reduce the energy required by the liquefier, and waste heat from the liquefier or an external source increases the energy recovered from the expansion of liquid air. At commercial scale (10-250MW), LAES is expected to have a 'round trip' efficiency of 60%. After extensive testing at the pilot plant, the system is currently at TRL7 (on a scale of 1-10), and since it is based on existing components, developers Highview Power Storage expect progress to full commercialisation to be relatively rapid.

The Ricardo split cycle engine would be 60% efficient, compared to around 40% for modern diesels.

3. LIQUID AIR TECHNOLOGIES

Balancing the grid will require increasing amounts of storage to absorb 'wrong time' energy. Liquid air is one of the few technologies able to provide large-scale plants in the short term.



Liquid Air Energy Storage cycle. *Source: Highview Power Storage.*

Balancing the electricity grid will become increasingly challenging as the proportion of intermittent renewable generation continues to rise. This is not simply a question of holding power stations in reserve for when the wind drops, but also being able to absorb excess wind power when there is too little demand – often at night – a role for which storage is ideally suited. If such 'wrong time energy' is stored and used to displace fossil generators at peak times, CO_2 emissions are reduced and 'constraint' (compensation) payments to wind farm operators avoided.

However, current storage technologies – including pumped storage, Compressed Air Energy Storage (CAES) and grid batteries – all suffer significant drawbacks. By contrast, LAES has no geographical constraints, contains no toxic or exotic materials, and is expected to be long lasting (30+ years) and low maintenance. Since it is built from proven, large-scale components that are already widely used in the industrial gas and power generation industries, LAES is one of the few technologies capable of providing plants of 50-100MW and 100sMWh in the near term. It is also more flexible than some other forms of storage since power (MW) and energy (MWh) can be configured independently according to need. At commercial scale LAES is likely to be highly competitive; Highview Power Storage projects capital costs for daily-cycling plants will range from £120/kWh for a 200MW plant to £320/kWh for a 10MW plant.

LAES could perform a wide range of roles in the energy system, including:

- store 'wrong time' energy from intermittent renewable generators to displace fossil generation at peak times and reduce CO_2 emissions;
- help 'firm' the output of wind farms, so increasing its value to both wind farm operators and the grid;
- provide response, reserve, black start and ancillary services to network operators;
- improve network asset management, by allowing operators to defer or reduce the cost of upgrading transmission and distribution lines;

- provide strategic energy security: a single 'gasometer' style tank of the sort used in the LNG industry could store sufficient energy as liquid air to make good the loss of 5GW of wind power for three hours.

LAES and waste heat

Like the Dearman engine, LAES is inherently capable of exploiting low grade waste heat (<150C), which other technologies find difficult to harvest, and converting it into power at high levels of efficiency. During power generation, waste heat from the liquefier or an external source is fed into the LAES heat exchanger and this boosts the expansion of the liquid air before it enters the turbine, so increasing the work output. The Highview Power Storage pilot plant at Slough (pictured) incorporates waste heat from the SSE biomass power station next door, and at commercial scale such an arrangement could raise LAES round trip efficiency to around 60%. There are myriad sources of low grade waste heat, meaning LAES could be integrated not only with power generation but also at a wide range of industrial sites. Waste heat recovery could also be achieved using a Cryogenset (see page 14).

Liquid Air Energy Storage pilot plant in Slough. *Source: Highview Power Storage.*

Each year, British industry is estimated to lose as much as 40TWh in waste heat, enough to heat 2.4 million homes. Sources of low grade waste heat include food processing, paper manufacturing, data centres and power plants including biomass, landfill gas and energy-from-waste. Low grade waste heat is sometimes recovered using an Organic Rankine Cycle (ORC) device to generate electricity. These tend to be bulky and inefficient (no more than 25% at scale), but require no fuel or external inputs. LAES is far more efficient – converting waste heat to power at rates of 50% and above – but does require a supply liquid air or nitrogen, typically produced from off-peak electricity. The CLCF report found that where the ratio between peak and off-peak electricity prices is 2.5 or greater, liquid air could represent an economically attractive proposition to process plant operators. Rising renewable generating capacity is expected to push power price volatility well beyond that threshold in the next two decades.

Liquid air could deliver industrial waste heat recovery either through the LAES system or a Cryogenset (see page 14). In either case, any company installing such a device could:

- protect itself from power cuts, which Ofgem predicts will become far more likely by the middle of this decade, using liquid air as an emergency energy store;
- reduce its exposure to peak electricity prices, either through the Triad system or daily arbitrage;
- generate revenue by supplying reserve or other services to the grid;
- recover energy and cost that would otherwise be wasted.

Heat recovery is an integral feature of LAES and is currently at TRL7.

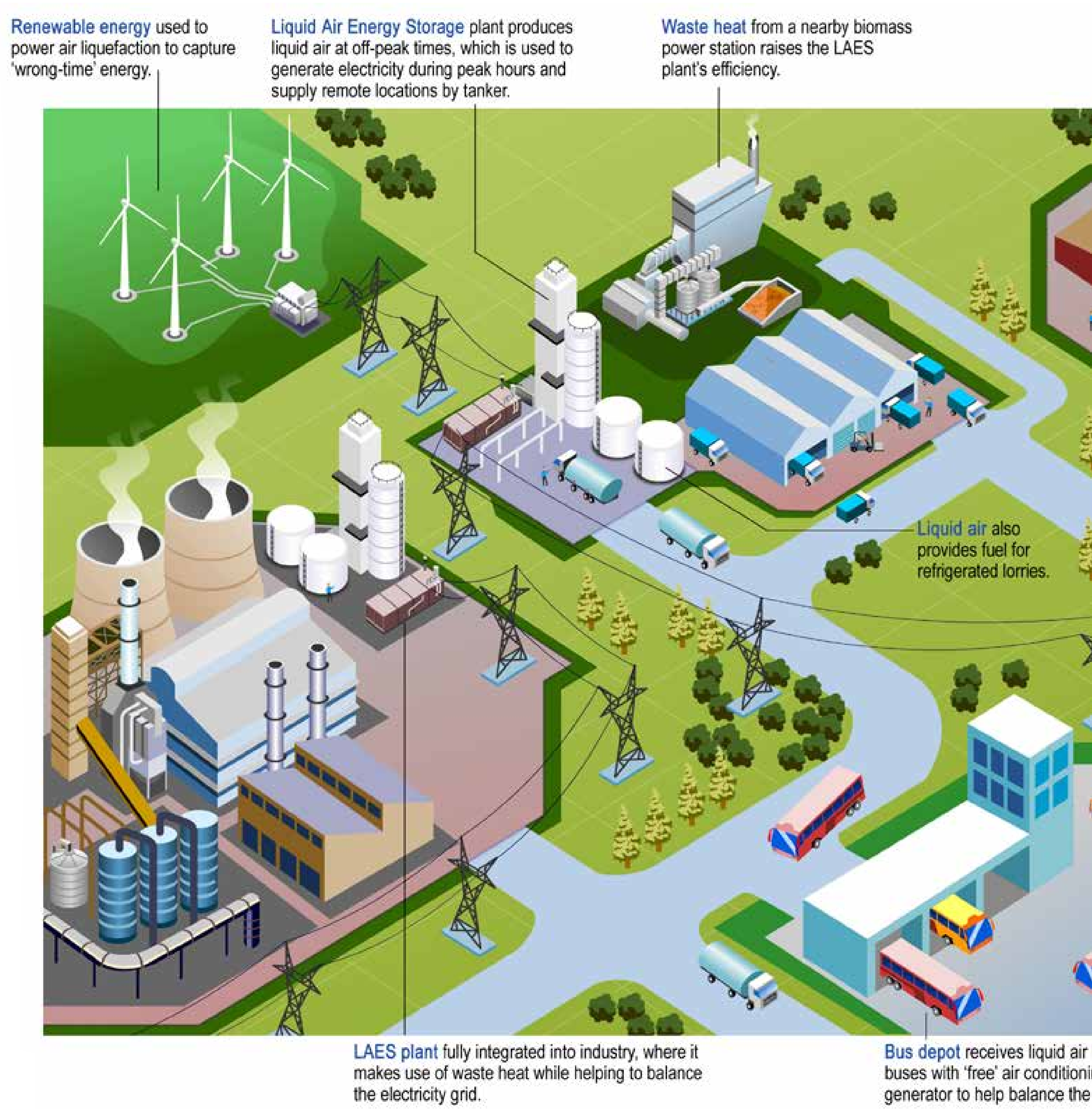
LAES and waste cold

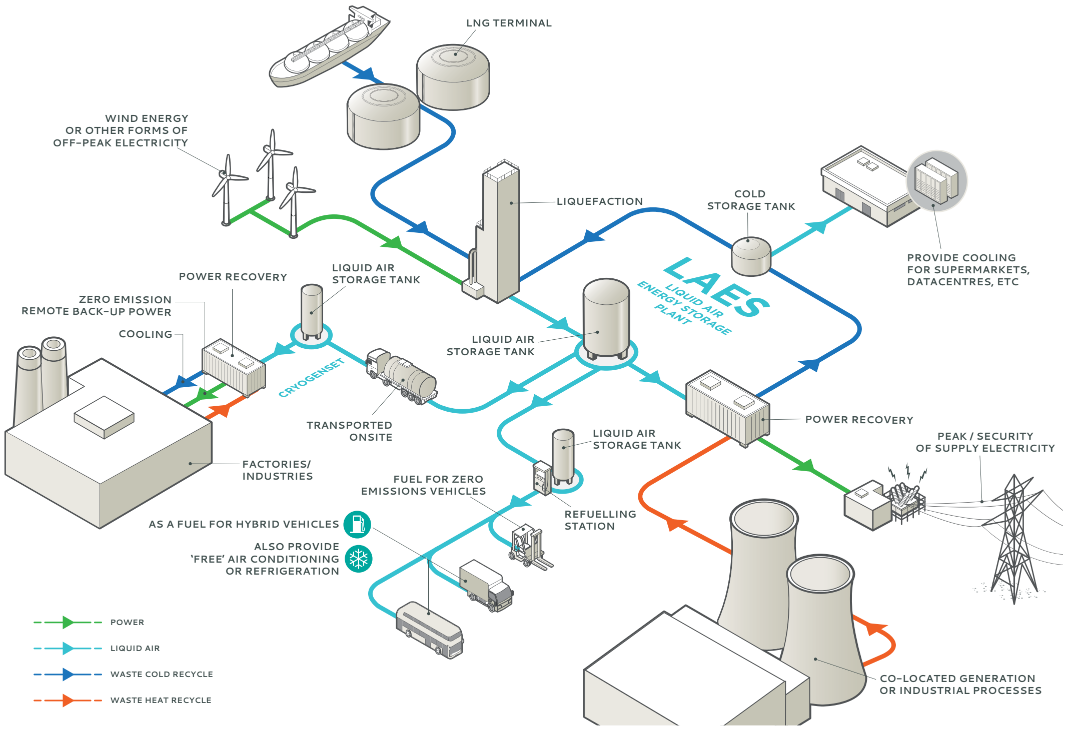
If liquid air can exploit waste heat in the power generation phase, it can also make use of waste cold to raise the efficiency of liquefaction. Britain has three LNG import terminals where large volumes of liquefied natural gas are stored at -160C before being re-gasified to enter the national gas grid. In conventional terminals the LNG is normally warmed by burning some of the natural gas, and the cold given off by evaporation is wasted. However, if air rather than gas is used to warm the LNG, the resulting cold air can be fed into an air or nitrogen liquefier to raise its efficiency dramatically. Where this approach has been adopted at terminals in Japan and Korea the nitrogen liquefier requires *two thirds* less electricity than a conventional unit. Capital costs are roughly double, but developers believe these can be reduced significantly through engineering and process design.

(Continued on page 14)

A single gasometer-style tank could store enough liquid air to make good the loss of 5GW wind power for three hours.

THE LIQUID AIR ECONOMY





Liquid air technologies could integrate with a wide range of equipment across the electricity, gas, transport and industrial sectors to form a 'liquid air economy'. This is not remotely to suggest liquid air is a 'silver bullet', but it could help to tackle some or our toughest energy challenges and deliver major savings in energy, carbon and cost.

In a liquid air economy, many different energy services could be provided from a single 'tank of cold'. If a Liquid Air Energy Storage plant were built in a business park, for example, it could liquefy air using lower carbon off-peak electricity, and then use it to generate electricity efficiently at peak times incorporating waste heat from a nearby biomass power station. The LAES plant could also supply liquid air to a neighbouring logistics business to fuel forklift trucks and refrigerated lorries, and by tanker to locations further afield such as supermarkets and bus depots. There the liquid air could be used both for refrigerated and hybrid vehicles – cutting diesel consumption by as much as a quarter – and for emergency back-up power or grid balancing.

Liquid Air Energy Storage plants could be co-located with industry, where they could turn waste heat into additional power, or with LNG terminals, where huge amounts of waste cold could massively increase the efficiency of air liquefaction. We estimate the waste cold from Britain's projected LNG imports in 2030 could produce enough liquid air to fuel 111,000 'heat hybrid' buses – more than 2.5 times the existing fleet.

Liquid air could also be integrated with all sorts of generating capacity – wind, nuclear and gas – to help balance the grid and cut carbon emissions. It could also be integrated into existing industrial gas production sites, which collectively have substantial surplus nitrogen capacity. If used for electricity storage and generation, this surplus would equate to an 800MW power station operating 3½ hours per day, and could be used to displace the highest-carbon generators at peak times with lower carbon electricity.

The potential of the liquid air economy is only beginning to become apparent, and it seems likely that further opportunities will emerge as our understanding improves. The Liquid Air Energy Network has been formed to investigate the possibilities, and will publish its findings in a series of reports over the coming year. For more information, please visit www.liquidair.org.uk.

Liquid Air Energy Storage plants can convert waste heat and waste cold into additional power at high levels of efficiency.

National Grid expects UK LNG imports to rise to 30 billion cubic meters in 2030 ('Gone Green' scenario). If all the cold from this LNG were used in air liquefaction, it could help produce 8.1 million tonnes of liquid air per year. This would consume just 0.97TWh of electricity rather than 3.23TWh that would have been required without the LNG cold. The 8.1 million tonnes of liquid air produced would then deliver 0.81TWh back to the grid over the course of a year, or 0.2% of total UK electricity demand in 2012. Alternatively, that much LNG-assisted liquid air could in principle fuel 9.3 billion car kilometres, equivalent to almost 2% of the distance driven by cars in Great Britain in 2011, or 111,000 heat hybrid buses – more than 2.5 times the existing UK bus fleet.[5] In terms of energy security, an LNG-size storage tank filled with liquid air would represent about 16.6GWh, which could make good the loss of 5GW of generating capacity for 3 hours.

Isle of Grain LNG terminal. *Source: National Grid.*

Cryogenset

The Cryogenset is simply a LAES system without the liquefier. It consists of a storage tank, heat exchanger, turbine and generator, and would be supplied with liquid air or nitrogen by road tanker from an industrial gas production site. This arrangement is designed for circumstances where the generator would be used too infrequently to justify the cost of a liquefier, such as providing emergency back-up power for businesses, and distributed reserve capacity for the grid. It is zero-emissions at the point of use and potentially low carbon, and a potential replacement for a diesel genset. Whereas the LAES system is viable at scales of 10MW-250MW, the optimum size for a Cryogenset is 5MW-10MW. It can also be integrated with sources of waste heat.

Many companies maintain diesel or gas fired generators to provide back-up for essential services in case of power cuts, including water companies, factories, hospitals, telecoms operators and data centres. Some companies with larger generators also help to balance the electricity grid by taking part in STOR (the Short Term Operating Reserve market), as generators held in reserve against a sudden loss of generating capacity or spike in demand. This power is carbon intensive because it is generated from fossil fuels using small inefficient generators, and modelling suggests CO_2 emissions from Cryogensets would be almost 60% lower on the basis of projected overnight electricity in 2030. Diesel generators also emit high levels of NOX and PM pollution – some local authorities such as the City of London have banned their use for grid balancing – whereas Cryogensets exhaust only clean cold air or nitrogen. Any company installing a Cryogenset could increase the security of its electricity supply, reduce its exposure to peak power prices through the Triad system, generate revenue in the STOR market and reduce its emissions.

The prospects for deployment of the Cryogenset are likely to depend on a future legislative framework, but the market potential is set to grow rapidly. National Grid expects its reserve requirement to rise from 3.5GW today to some 8-13GW by 2020. In the 'Gone Green' scenario, by 2025 more than half of the projected 8GW STOR capacity would be provided by new providers rather than the incumbent energy companies. Longer term, the CLCF report found the market opportunity for the Cryogenset could be 30GW by 2050.

Cryogenset and waste heat

Like LAES, the Cryogenset can be integrated into processes that generate waste heat such as biomass power stations or landfill gas generators. Waste heat from the generator would be used to raise specific output of the Cryogenset, while also increasing the effective efficiency of the generator cycle by converting the waste heat to electrical energy. It would also allow the owner to earn additional revenue by providing a range of storage services to the grid. Highview plans to have a 5MW/15MWh Cryogenset integrating waste heat operational in 2015.

[5] 8.1 million tonnes of liquid air / 365 / 200kg per bus per day = 110,958 buses

Small scale cryogenic generators

Because the Cryogenset is based on turbine technology, its minimum practicable power rating is about 1.5MW. Below that size, a cryogenic piston engine such as the Dearman engine could act as a smaller scale electricity generator to provide the same kind of services – emergency back-up and grid balancing. The Dearman Engine Company (DEC) estimates the units would cost about the same as an equivalent-sized diesel genset, but would be zero emissions at the point of use, and lower carbon on the basis of the projected carbon intensity of grid electricity. While the units would be smaller than a Cryogenset, they could be operated in tandem to provide a large amount of distributed grid balancing. DEC has recently won TSB funding for a feasibility study to model the technical and economic potential of this application, and the company expects to build a demonstrator engine in 2015.

4. THE LIQUID AIR ECONOMY

The industrial gases industry has developed over the past century, and most of the country is within easy delivery distance of one of its production sites.

As we have shown, liquid air technologies could integrate with a wide range of equipment across the electricity, gas, transport and industrial sectors to deliver major savings in energy, carbon and cost. This is not remotely to suggest liquid air is a 'silver bullet', but it could help to tackle three of the toughest challenges of the low-carbon transition: balancing an electricity grid increasingly dominated by intermittent renewables (see Box 3, page 19); providing a fast-refuelling and low-carbon transport fuel; and harvesting low grade waste heat. Since these roles can be integrated with each other, and with many existing technologies, we might soon begin to talk of a 'liquid air economy'.

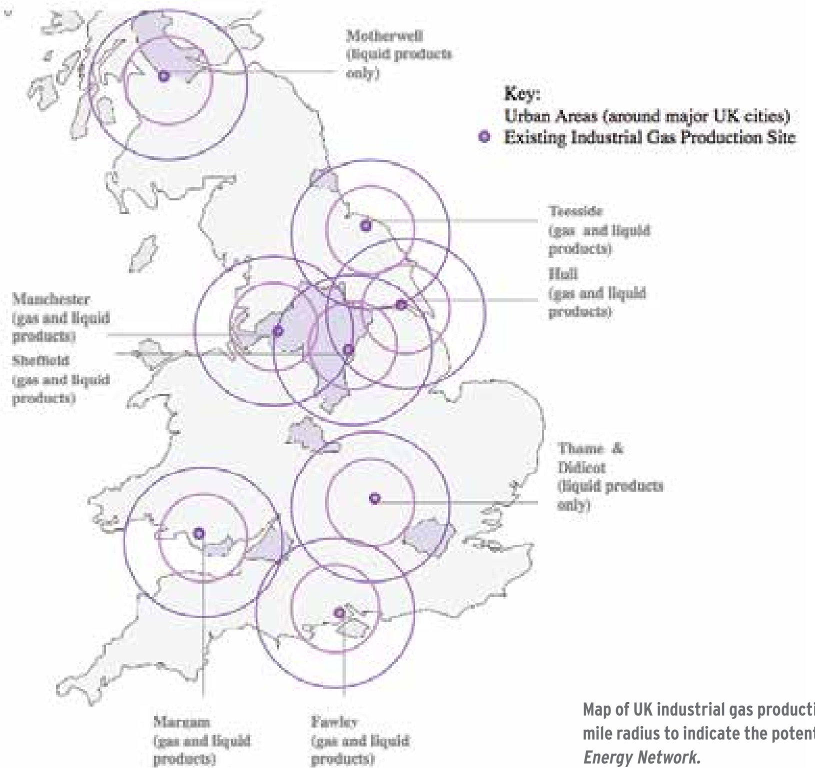
It would be a nitrogen rather than liquid air economy at first, simply because the industrial gas companies have substantial spare nitrogen production capacity and a nationwide tanker distribution network – a major advantage over some other potential low carbon energy vectors such as hydrogen. Liquid air and nitrogen have similar thermo-physical properties, and in Britain the existing spare capacity would be ample to support the early deployment of liquid air technologies (see Introduction). So a promising place to start to integrate liquid air technologies would be the eleven industrial gas production sites across Great Britain.

Industrial gas producers

The industrial gas producers are already closely involved in the management of the electricity grid. Air separation is an energy intensive business that consumes about 3% of the UK electricity supply, and producers are acutely attuned to wholesale power prices. Typically they operate liquefiers only at night, when electricity is cheaper, and avoid peak times – so helping to balance overall supply and demand. It would not be a huge leap for operators to install generating equipment and use their excess nitrogen to export power to the grid at peak times. In effect Air Separation Units would become LAES plants – liquefying at night, generating at peak times – while continuing to supply their traditional customers with cryogenic gases.

The industrial gas industry in Britain has significant spare production capacity in both liquid and gaseous nitrogen, and either could be used in place of liquid air to support early deployment.

According to the CLCF report, spare gaseous nitrogen production capacity could amount to as much as 8,500 tonnes per day, although making use of it on the grid would require investment in additional liquefiers and generating equipment. On this basis, the industrial gas industry collectively could



Map of UK industrial gas production sites. Each site is marked with a 50 and 100 mile radius to indicate the potential delivery catchment area. *Source: Liquid Air Energy Network.*

generate 800MW – the equivalent of a decent sized power station – for about 3½ hours per day. This could be used to supply lower carbon energy at peak times, when emissions are usually highest. At least some of the industrial gas production sites are likely to be in areas of grid congestion where additional storage capacity would be valuable. Those in Motherwell, Teesside and Hull might help manage flows between Scotland and England – increasingly important as wind capacity grows north of the border.

Spare liquid nitrogen production capacity is available immediately without further investment, and its potential in transport will be assessed in our forthcoming report, *Liquid Air on the Highway.*

Fleet operators and manufacturing

Much of the industrial gas suppliers' business involves distributing cryogenic gases by road tankers that reload with both product and diesel at a single site. This presents an obvious opportunity to introduce the Dearman engine 'heat hybrid' concept, with no need for any public refuelling infrastructure. If industrial gas tankers were fitted with ICE-DE hybrids, they could also refuel with liquid nitrogen at base, saving up to 25% on the fleet's diesel bill.

In any event, the industrial gas production sites are well spaced around the country, and could deliver liquid nitrogen economically to the most likely centres of new transport demand (see map). Hauliers and supermarket chains could be early adopters of Dearman engine heat hybrid and refrigeration concepts because of the potential fuel and carbon savings. With a liquid nitrogen tank installed at a logistics hub or supermarket distribution centre, it might also make sense to install a Cryogenset for emergency power and to reduce the company's exposure to peak electricity prices, and generate revenue in the capacity markets.

In industries that already consume large amounts of liquid nitrogen, such as food processing, expanding the existing on-site storage capacity would allow the company to increase the number of functions it performs with liquid nitrogen, including back-up power, waste heat recovery, on-site vehicles such as forklift trucks, and off-site transport refrigeration. Over a thousand companies store large amounts (>15 tonnes) of nitrogen as a liquid but use it as a gas, who could install a cryogenic engine to generate electricity during vaporisation. Even industries that do not currently make use of liquid nitrogen could find a compelling case to integrate emergency power, heat recovery, refrigeration and transport around a single tank of cold.

A liquid air economy could help solve some of our toughest energy challenges.

LNG terminals

Britain's three LNG import terminals offer large scale integration opportunities. All three terminals – one at Isle of Grain in Kent and two at Milford Haven in South Wales – could provide prodigious amounts of cold to increase the efficiency of air liquefaction at a co-located LAES plant. If all the cold from projected UK LNG imports in 2030 were used in this way, it would produce 8.1 million tonnes of liquid air. This could then be used to deliver 0.81TWh back to the grid at peak times – which equates to 0.2% of total UK electricity demand in 2012. Alternatively, that much liquid air could in principle fuel 9.3 billion car kilometres, equivalent to almost 2% of the distance driven by cars in Great Britain in 2011, or 111,000 heat hybrid buses – more than 2.5 times the existing UK bus fleet.[6] If an LNG-LAES plant were used to bolster energy security, a single LNG-size storage tank filled with liquid air could make good the loss of 5GW of generating capacity for 3 hours. This could be increasingly valuable towards the middle of this decade, when Ofgem predicts the risk of power cuts will rise sharply.

If the waste cold at LNG terminals were used to produce liquid air for transport fuel, Isle of Grain in particular would help fill one of the few gaps in the industrial gas distribution network, the east side of London, and could easily supply the capital's bus depots. Bus operators have a strong incentive to adopt the Dearman engine heat hybrid because it would cut fuel costs and carbon emissions by displacing diesel with liquid nitrogen; enable stop-start technology, delivering *further* savings in cost and carbon; and provide 'free' air conditioning. A heat hybrid bus would consume around 200kg of liquid nitrogen per day, meaning the capital's largest bus depot (196 buses) could be supplied by 2 tanker deliveries, and the average depot (100 buses) by one delivery. The capital's entire fleet of around 7,600 buses would need less than 555,000 tonnes per year[7], less than a sixth of

[6] 8.1 million tonnes of liquid air / 365 / 200kg per bus per day = 110,958 buses

[7] 7,600 buses x 200kg per day x 365 = 554,800 tonnes of liquid air per year

In a liquid air economy, a wide range of energy needs could be serviced from a single tank of cold.

Grain's potential liquid air production capacity. Again, a bus depot with sufficient space could also install a Cryogenset to generate revenue by providing reserve capacity to the local grid.

New liquefiers: 'a tank of cold'

Much of the integration discussed so far could be achieved by exploiting the existing nitrogen glut. Once that is exhausted, to expand further we would need to build new liquid air production plants, and that would create the opportunity to create a fully 'joined up' system. Instead of integrating liquid air technologies somewhat piecemeal, we could start to plan a variety of energy services around a strategically placed 'tank of cold', in locations as diverse as industrial parks, bus depots and town centres. As wind capacity continues to rise, liquid air would allow lower carbon overnight electricity to be deployed in peak power generation, transport, refrigeration and cooling – all from a single plant. So what might a liquid air economy look like in 2030?

A new liquefier or LAES plant sited at an industrial park, for example, might supply a range of neighbouring businesses for different purposes. A datacentre might need liquid air for cooling and for its backup Cryogenset, while a logistics company might want fuel for its ZEV forklift trucks and heat hybrid lorries. A biomass power station or gas fired CHP plant could be integrated directly with the LAES unit, or if too distant, could install a Cryogenset and tank, to be refilled periodically by deliveries from the central liquefier. With sufficient regional demand for liquid air, the liquefier could be sized to support a tanker distribution network.

A supermarket distribution hub, on the other hand, might install a large liquid air tank, to be regularly refilled from the nearest liquefier, which could support its Dearman engine truck refrigeration units, forklift trucks and a Cryogenset for emergency power. A metropolitan bus depot could adopt a similar approach, with a large tank to support both its heat hybrid bus fleet, and a Cryogenset for grid balancing. In the longer term, it might also support refuelling for private vehicles.

Further afield, a mine operation could gain particular benefits from organising its operations around a tank of cold. If underground vehicles were designed to run on Dearman engines as ZEVs, their exhaust of cold air would provide much needed cooling and reduce the load on ventilation systems. Above ground, heavy duty off-highway vehicles such as dumper trucks could be designed as heat hybrids to save large amounts of diesel. The liquid air could also provide back-up against power cuts - particularly valuable in countries where the electricity grid is unreliable, such as South Africa – and cooling for mine buildings. Since mines would need large volumes of liquid air, and are often remote, it is likely they would install their own liquefier to operate off-peak.

The potential of the nitrogen or liquid air economy is only beginning to become apparent, and it seems likely that further opportunities will emerge as our understanding improves. The Liquid Air Energy Network has been formed to investigate the possibilities, and will publish its findings in a series of reports over the coming year. These will include *Liquid Air on the Highway; Liquid Air – Mapping the UK Opportunity; and Cleantech Leapfrog – a tank of cold.* For more information, please visit www.liquidair.org.uk

BOX 3: Integrating liquid air into power generation

Liquid air could integrate with a wide range of generating plant to help balance the grid, which will become increasingly challenging as the proportion of intermittent renewable capacity continues to rise. The same could be also said for other forms of bulk electricity storage such as pumped hydro or compressed air (CAES), but liquid air has several distinct advantages.

For example, wind farms could integrate energy storage to absorb excess power when demand is low and export it at peak times. This would 'firm' the wind output, making it more valuable to both the wind farm operator and the grid; reduce the likelihood of wasteful constraint payments; and cut carbon emissions. In principle these benefits could be provided by any form of bulk storage, but pumped hydro and CAES are geographically and geologically constrained, whereas liquid air plants are not. For example, the power from the 300MW Thanet Wind Farm off the Kent coast joins the grid at the Richborough electricity substation, where there are plans to build a 40MW diesel peaking plant for when the wind drops. This role could be served by a LAES plant or Cryogenset without resorting to fossil fuels, but in the flat Kent countryside pumped storage would be impossible.

Nuclear and other thermal power stations could also benefit by integrating storage to 'shape' their output in response to fluctuating demand, allowing them to run more efficiently. Energy storage could be charged during off-peak hours and used to generate additional power at peak times. The advantage of liquid air is that unlike other storage technologies it can make use of the power station's waste heat to produce additional power at high levels of efficiency. A fully integrated design proposed by Professor Yulong Ding of the University of Birmingham would raise the peak output of the nuclear plant to three times its rated capacity.

One conventional way of satisfying peak electricity demand is through Open Cycle Gas Turbine (OCGT) plants or diesel generators, which are inefficient and almost as carbon intensive as coal. However, another novel liquid air design from Professor Ding would eliminate the emissions of such plants through carbon capture, while generating peak power almost as cheaply as baseload (for more detail see the CLCF report cited on page 25). This might go some way towards reconciling the government's renewed interest in gas with its legally binding emissions reduction targets. No other storage technology is capable of this.

Liquid air could be integrated with all sorts of generating capacity – wind, gas, nuclear – to increase efficiency and cut carbon.

BOX 4: Scotland

Scotland could be an early adopter of liquid air technologies. The Scottish government has set a target of generating the equivalent of its total electricity consumption from renewables, and exporting as much electricity again, by 2020, and has recognised the importance of grid storage. It intends to publish a comprehensive energy strategy within the next two years, based not only on the principles of decarbonisation, security of supply and lowest possible cost, but also of economic opportunity to Scottish industry.

Scotland's ambitious renewable generation target suggests a potentially large role for Liquid Air Energy Storage. A study by William Holt of Strathclyde University found the target implied a need for more than 3GW of storage by 2020, equivalent to 32 x 100MW LAES plants. A round table held by LAEN in Glasgow in June 2013 found that if 60% of the value of that plant were sourced in the UK, the value to the domestic economy could be some £2 billion. Much of that value could accrue to Scotland, since building LAES plants would play to its strength in the oil and gas sector and mechanical engineering more generally. For more information please see www.liquidair.org.uk.

5. CONCLUSIONS & RECOMMENDATIONS

From this brief review it is clear that:

- the liquid air cycle has a wide range of potential applications in transport and power which support Britain's strategic energy and environmental objectives;
- the ability of liquid air to recover energy from waste heat and cold at high levels of efficiency means there are many opportunities to integrate with existing technologies and even develop a 'liquid air economy';
- since they rely largely on existing components and supply chains, liquid air technologies could be quicker to market than other novel technologies at a nominally similar level of development;
- excess nitrogen production and distribution capacity could support extensive deployment of liquid air technologies before any new capacity need be built; there is no 'chicken and egg' dilemma.

While liquid air has many advantages, however, its early and widespread deployment is far from guaranteed. Like all novel technologies it must cross the 'valley of death' between demonstration and commercialisation - where most fail. On the other side of the valley lies the possibility of a joined-up 'liquid air economy', where liquid air is widely deployed to deliver major reductions in fuel consumption, cost, carbon emissions and local air pollution, as well as economic growth and new jobs.

To maximise liquid air's chances of success still requires research and development, and this effort needs to be co-ordinated to ensure researchers focus on the principal challenges and avoid duplication. This in turn requires the development of full-scale technology and product roadmaps which – unlike the indicative timeline presented on page 22 – should be developed with input from all relevant stakeholders.

The Liquid Air Energy Network was founded to catalyse this work, and we recommend liquid air stakeholders should collaborate to:

- develop and maintain technology and product roadmaps for both grid and transport applications. These roadmaps should be produced by consensus, aligned with broader government and industry roadmaps, and aimed to maximise the economic and environmental opportunity for UK plc;
- explore the global opportunities for liquid air across industry and transport, in both developed and developing economies, and quantify the market potential;
- map potential sources of liquid nitrogen supply and demand to determine where best to carry out field trials and early deployment;
- develop models to explore the potential benefits of integrating grid and transport applications through multi-purpose liquid air plants;
- work with government to ensure liquid air is recognised even better in the policy and funding framework;
- start to inform the public over the benefits and safety of liquid air technologies.

To achieve this, LAEN has established three working groups covering grid energy storage, transport, and integrated modelling, with members drawn from industry, universities technology developers and independent consultants. The grid and transport groups will each develop and maintain a mutually agreed technology roadmap and common research agenda to:

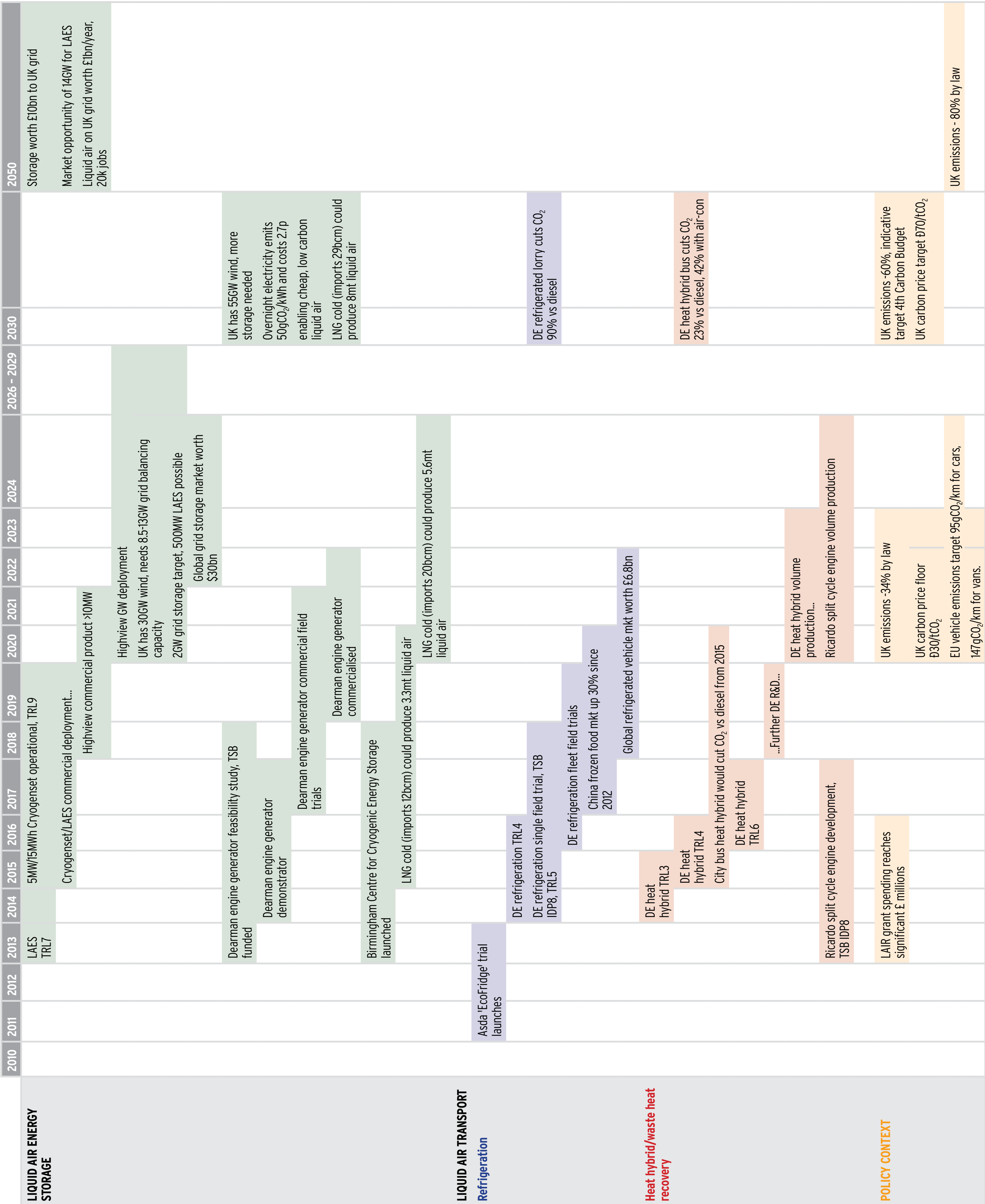
- guide fundamental research at universities and industrial research;

- set specific short term objectives to drive technology and manufacturing development towards the product road map;
- integrate liquid air with wider grid and transport roadmaps and research agendas developed by government, industry and other key groups;
- identify areas of existing UK capability and weakness, and potential areas for future development and UK benefit;
- make strategic recommendations to UK funding bodies such as the EPSRC and TSB to maximise the benefit to UK plc.

The Liquid Air Transport Technology Group has already started work, and the first iteration of the transport roadmap will be published as part of our next report, *Liquid Air on the Highway*, which is jointly funded by the TSB. The purpose is to identify the research needs of liquid air transport applications across passenger, commercial and off-road vehicles; key areas of UK technical capability or weakness; and development paths that maximise the benefit to UK plc. The roadmap will set specific short term objectives, and pay particular attention to areas prioritised by Automotive Council's industry-wide roadmap. More broadly, the *Highway* report will map potential sources of liquid nitrogen supply and demand to determine where best to carry out field trials and early deployment.

The grid and integrated modelling groups will begin work shortly, and their conclusions will be reflected in LAEN reports over the coming year, including *Liquid Air – Mapping the UK Opportunity, and Cleantech Leapfrog – a tank of cold*. For more information on the LAEN research programme and report launch events, please visit www.liquidair.org.uk.

TECHNOLOGY TIMELINE



Liquid air technology timeline. *Sources: Highview Power Storage; Dearman Engine Company; E4tech; Imperial College; Energy Storage Network; National Grid; DECC; Climate Change Committee; European Commission; Pike Research; Centre for Low Carbon Futures; Liquid Air Energy Network.*

AUTOMOTIVE COUNCIL TECHNOLOGY READINESS LEVELS

1	■ Basic Principles have been observed and reported. ■ Scientific research undertaken. ■ Scientific research is beginning to be translated into applied research and development. ■ Paper studies and scientific experiments have taken place ■ Performance has been predicted.	6	■ A model or prototype of the technology system or subsystem has been demonstrated as part of a vehicle that can simulate and validate all system specifications within a test house, test track or similar operational environment. ■ Performance results validate the technology's viability for a specific vehicle class.
2	■ Speculative applications have been identified. ■ Exploration into key principles is ongoing. ■ Application specific simulations or experiments have been undertaken. ■ Performance predictions have been refined. ■ Performance has been predicted.	7	■ Multiple prototypes have been demonstrated in an operational, on-vehicle environment. ■ The technology performs as required. ■ Limit testing and ultimate performance characteristics are now determined. ■ The technology is suitable to be incorporated into specific vehicle platform development programmes.
3	■ Analytical and experimental assessments have identified critical functionality and/or characteristics. ■ Analytical and laboratory studies have physically validated predictions of separate elements of the technology or components that are not yet integrated or representative. ■ Performance investigation using analytical experimentation and/or simulations is underway.	8	■ Test and demonstration phases have been completed to customer's satisfaction. ■ The technology has been proven to work in its final form and under expected conditions. ■ Performance has been validated, and confirmed.
4	■ The technology component and/or basic subsystem have been validated in the laboratory or test house environment. ■ The basic concept has been observed in other industry sectors (e.g. Space, Aerospace). ■ Requirements and interactions with relevant vehicle systems have been determined.	9	■ The actual technology system has been qualified through operational experience. ■ The technology has been applied in its final form and under real-world conditions. ■ Real-world performance of the technology is a success. ■ The vehicle or product has been launched into the market place. ■ Scaled up/down technology is in development for other classes of vehicle.
5	■ The technology component and/or basic subsystem have been validated in relevant environment, potentially through a mule or adapted current production vehicle. ■ Basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested with equipment that can simulate and validate all system specifications within a laboratory, test house or test track setting with integrated components. ■ Design rules have been established. ■ Performance results demonstrate the viability of the technology and confidence to select it for new vehicle programme consideration.	10	■ The technology is successfully in service in multiple application forms, vehicle platforms and geographic regions. In-service and life-time warranty data is available, confirming actual market life, time performance and reliability.

6. GLOSSARY

APU	Auxiliary Power Unit
ASU	Air Separation Unit
BCCES	Birmingham Centre for Cryogenic Energy Storage
CAES	Compressed Air Energy Storage
CHP	Combined Heat and Power
CLCF	Centre for Low Carbon Futures
CNG	Compressed Natural Gas
DE	Dearman engine
DEC	Dearman Engine Company
DECC	Department of Energy and Climate Change
EPSRC	Engineering and Physical Sciences Research Council
EV	Electric vehicle
FCV	Fuel cell vehicle
HEF	Heat exchange fluid
ICE	Internal combustion engine
LAEN	Liquid Air Energy Network
LAES	Liquid Air Energy Storage
LATTG	Liquid Air Transport Technology Group
LNG	Liquefied Natural Gas
NOX	Nitrogen oxides
OCGT	Open Cycle Gas Turbine
ORC	Organic Rankine Cycle
PM	Particulate matter
STOR	Short Term Operating Reserve
TRL	Technology Readiness Level
TRU	Transport Refrigeration Unit
ZEV	Zero emissions vehicle

ABOUT THE CENTRE FOR LOW CARBON FUTURES

The Centre for Low Carbon Futures is a collaborative membership organisation that focuses on sustainability for competitive advantage. Formed by the University of Birmingham, University of Hull, University of Leeds, University of Sheffield and University of York, we work across the EU, Asia and Latin America. The Centre brings together engineers, natural scientists and social scientists to deliver highimpact research on our 2013/14 themes of Energy Systems, Green Growth and Smart Infrastructure.

CLCF is developing a series of Technology Insights, sponsored by and in conjunction with industry. These insights aim to reduce some of the uncertainties surrounding the vast array of technology options, and complement the evidence based research reports produced by CLCF, by providing a more practical guide to the potential uses of emerging technologies.

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ABOUT THE LIQUID AIR ENERGY NETWORK

Working with the Birmingham Centre for Cryogenic Energy Storage (BCCES) and the Centre for Low Carbon Futures (CLCF), the Liquid Air Energy Network (LAEN) was founded to explore the potential of liquid air as an energy vector, and to ensure Britain maintains its lead in this promising new technology and secures the full energy, environmental and economic benefits. Its research is conducted in collaboration with technology developers, industry, universities and partner organisations. This is the first report in a series of policy and technology guides. For more information please visit www.liquidair.org.uk.

SOURCES

The information and estimates in this briefing note have been drawn from a number of sources including the Centre for Low Carbon Futures report *Liquid Air in the energy and transport systems* (May 2013 add in ISBN number); consultants E4tech, Ricardo UK, and Spiritus Consulting; liquid air technology developers Highview Power Storage and the Dearman Engine Company; and the Liquid Air Energy Network (LAEN). Some sources, such as the modelling and forecasts by E4tech and Ricardo, are unpublished.

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