Centre for Low Carbon Futures 2050

# Liquid Air in the energy and transport systems

## Opportunities for industry and innovation in the UK

### Summary Report and Recommendations

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## PUBLICATION DATE

9 May 2013
ISBN: 978-0-9575872-1-2

## REPORT NO.

020

## PUBLISHER

The Centre for Low Carbon Futures 2013.

For citation and reprints, please contact the Centre for Low Carbon Futures.


This report explores the technical, environmental and business potential of liquid air as a new energy vector.


THIS REPORT WAS SUPPORTED BY:

MESSER Gases for Life

ARUP

THE CENTRE FOR LOW CARBON FUTURES PARTNERSHIP

http://www.lowcarbonfutures.org

University of Hull

The University of York

The University Of Sheffield.

UNIVERSITY OF LEEDS

UNIVERSITY OF BIRMINGHAM

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# FOREWORD

Over the last two years I have noticed a marked increase in interest in energy storage, and a growing number of reports and research funding opportunities have contributed towards a better appreciation of its value. However, while understanding of both the role and need for energy storage is growing, there remain many areas of uncertainty. Our report 'Liquid Air in the energy and transport systems' is designed to help remove at least some of those uncertainties.

Many forms of energy storage are already employed around the world, ranging from large-scale pumped-hydro storage to many kinds of batteries across a broad range of applications. While these are probably the best known forms of energy storage, there remain a number of new technologies that are not yet fully understood or widely deployed.

Technologies alone are not enough. For science and technology innovation to move to production, there are a number of factors that impact the transition. For the private sector, the commercial viability of a new technology is clearly paramount, but mass deployment also requires a broader and deeper understanding of the application itself. In the case of energy storage technologies, this means understanding not only how technologies perform in specific circumstances, but how they will be deployed through a whole systems approach, with full consideration of the role they play in the electricity grid and mobile applications.

The Centre for Low Carbon Futures is a partnership of five UK research intensive universities comprising the University of Birmingham, the University of Hull, the University of Leeds, the University of Sheffield and the University of York, which are actively engaged in a broad range of energy systems research to support the transition to a low carbon future. Our work spans the UK, EU, Asia and Latin America. As part of a portfolio of activities we plan to produce a number of insights into various aspects of energy storage, and we have commissioned this report as our second[1] in that series. We see liquid air as one of the many technologies that could play a role as part of a whole systems approach, and will be featuring other technologies over the coming months in combination with a number of partners.

This report was commissioned by The Centre for Low Carbon Futures and supported by the Liquid Air Energy Network, Arup and Messer Group. We are again very grateful for the continued support of the Royal Academy of Engineering in London, which hosted a combined report launch and conference in London on 9th May 2013. We are also grateful to the individual authors who have worked with the editorial team to present their reflections on key topics, and to the University of Birmingham for its initiation of this report. We also acknowledge the community of university researchers worldwide, and those working with research councils and government departments, whose past and present research continues to bring greater awareness to the critical role that energy storage can play towards achieving a low carbon economy.

**Jon Price,**
**Director, The Centre for Low Carbon Futures**

1 First report 'Pathways for energy storage in the UK' The Centre for Low Carbon Futures 2012
ISBN 978-0-9575872-5-0

# PREFACE

The challenge of meeting our climate change targets is so great that capturing energy from renewable sources will be a critical component of any pathway. The priority for the last decade has been to improve generating technologies so they can provide energy at lower cost and with greater reliability. This is only part of the solution though; we also need to ensure that renewable generation operates effectively within a whole system that includes infrastructure and demand for energy. We also need to develop energy systems that increase our national energy security.

How energy is used has traditionally been overlooked, but the tide is now turning. Energy efficiency is becoming a mainstay of policy, and so is the management of energy systems. Greater emphasis is being placed on the use of technologies that can make best use of the renewable energy that is being produced. Turning the instantaneous power generated by a wind farm or solar array into energy vectors, which allow the use of that power at a different time or place, can increase the efficiency and reduce the costs of the whole energy system. It is the potential of a new energy vector – liquid air – that is the subject of this report.

Heat energy has also often been overlooked in the national debate, but this too is changing and particularly relevant to liquid air. The Government's recently published policy paper 'The Future of Heating' notes the potential of surplus industrial heat as a low or zero-carbon energy source, which could be used to generate electricity. Their report estimates 10–40 TWh of heat is currently lost from industrial sources in the UK.

We have an opportunity, and growing need, to scale up our investment in technologies that will ensure the energy from renewables is not wasted, and the opportunities for the UK industrial sector are not lost. We must pursue progress across the technology space, and throughout the innovation process, with policies and market frameworks to match. Liquid air is a prime example of a technology that has the potential to deliver a more efficient energy system and bring the benefits of green growth to the UK. Therefore we urge policy makers, the research community and private sector to consider this report, join in the evidence gathering and debate, and to build on the work already underway.

## THE CHALLENGES

If emissions and renewable energy targets for 2020 are to be met, it is clear our electricity system will have to change significantly. Figure A shows the scale of increase in renewable generation required in the UK, especially from wind and solar.

If the mid-points of the contributions from wind and photovoltaic (PV) were to be met, their installed capacity could supply over half the peak demand. This means we need to design an electricity system capable of managing high levels of renewable capacity, and one which does so at reasonable cost, without locking-in future emissions and without increasing the risk of the lights going out.

The end use of energy, and in particular electricity, will also change, as shown in Figure B. This is likely to occur over a longer timescale, to take advantage of the falling emissions from grid electricity and the development of new technologies.

Energy vectors, which can capture renewable power and use it elsewhere at another time, and even for a different application such as heat or transport, can reduce any waste when supply exceeds demand, help meet peak demand without resorting to carbon intensive thermal plant, and allow the remaining gas turbines to run more efficiently.

## THE OPTIONS

Governments, agencies and system operators are beginning to recognise that the energy system will need to become more flexible as we move from a situation in which predictability prevails to one of greater variability in supply and demand.

Such flexibility can come from technologies that allow us to shift energy from one place or time to another. These include transmission lines between neighbouring countries, a demand-side that can change its consumption patterns, and energy storage, which all sit alongside the conventional solution of flexing thermal plant in response to changes in supply or demand.

Energy storage offers the prospect of flexibility with no requirement for behavioural change by end-users, no reliance on availability of energy from other countries and no lock-in to future emissions.

Because of these advantages, energy storage has risen up the innovation and policy agenda in the last two years. Yet significant challenges remain before it can be considered a truly viable option for large-scale deployment. Technologies must improve their performance and cost, need to be tested operating in systems, and critically require a market framework that values their system-wide benefits. There is also a need to develop energy storage systems that can scale up but at a significantly lower price than existing options, and which consume fewer exotic materials and scarce resources.

There are myriad early stage technologies that offer a range of services, from second-by-second power quality management on the electricity grid, to heat stored in water underground across seasons. The most valuable area, however, is grid storage capable of storing electricity for several hours at a scale of 10s – 100s MW – which corresponds to the daily variations of intermittent generation and demand. Liquid air as a storage medium has the potential to occupy this space.

New vectors may also bring additional benefits by translating renewable electricity into other markets. Hydrogen and hot water (through district heating) have been the most studied vectors so far. Liquid air should now be considered too, since it can serve as a transport fuel and effectively capture waste heat energy from both vehicles and industrial processes. The ability to exploit waste heat is an especially important and distinctive feature of the system.

### THE OPPORTUNITY – LIQUID AIR

Despite their considerable industrial heritage, cryogenic liquids are a relative newcomer to the debate around energy vectors, as we explore in the papers that make up the Full Report. But it is this application of established technology to new challenges that makes liquid air such an attractive proposition, especially to a mature industrial nation such as the UK. As a country we have a manufacturing capability that is well suited to producing the components of a liquid air energy system.

Gases have been liquefied and stored for a variety of uses for many decades, and are now used routinely in almost every country. The transport of cryogens is expanding with the growth of liquefied natural gas (LNG), although LNG is course combustible rather than inert. To bring these components together in an integrated system is achievable and is already happening at a pilot scale. To unlock its full potential, the system must be optimised for the purpose and scale required, and reflect the needs of the country in which it is deployed. In practice, the technology might look very different in the UK compared to South America or the Middle East.

In the papers that make up the Full Report, we bring together the views of leading researchers and analysts to present an introduction to where and how cryogenic systems may help address the energy challenge. The analysis presented is an exposition of current thinking, covering the application of the technology in the energy and transport systems.

The deployment of grid-scale liquid air storage will require a combination of large-scale technical demonstration, a market framework that values the services storage can provide, and a willingness in the energy sector to embrace innovative solutions. In the Summary Report and Recommendations, we propose some changes to energy and transport policy that we believe would enable liquid air to compete alongside other options.

More immediately, liquid air can prove its worth in specific sectors, including providing the cooling in refrigerated lorries, serving as the primary fuel for vehicles where zero-emissions are critical such as warehouses or mines, and exploiting sources of waste heat or coolth found in industrial processes or LNG terminals.

It is also clear that realising the potential of liquid air requires investment. Initially this will need to come from the public sector to de-risk the technology to a level at which the private sector can see a commercial opportunity. Policy-makers and regulators also need to ensure the environment in general is conducive to innovation that may deliver long-term system benefits.

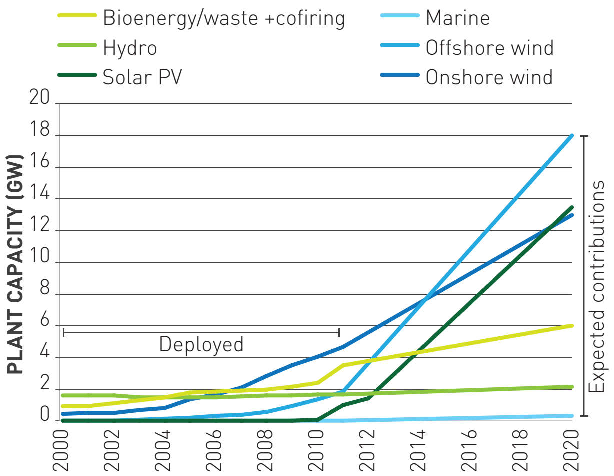


**Figure A:** Growth of renewable generation technologies required to meet 2020 target[2]

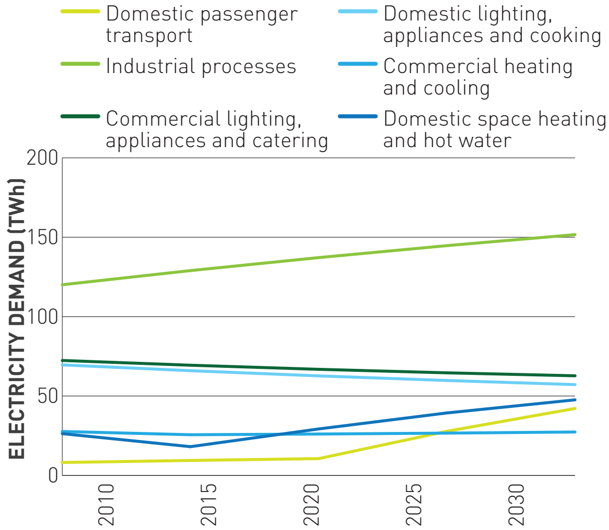


**Figure B:** Changing demand for electricity in the DECC Pathway, 'Renewables, higher electric'

2 Sources: DUKES (DECC, 2012), UK Renewable Energy Roadmap (DECC, 2009) and 2012 update, UK National Renewable Energy Action Plan (2009)

Figure C shows a possible timeline for the development of liquid air to full deployment as an energy storage medium and transport energy vector that the authors of this report believe to be attainable.

While there can never be a guarantee that any technology will go on to deliver, the UK may risk losing a significant opportunity if we do not invest now in a technology such as cryogenic energy storage. As this report shows, liquid air is a serious contender to take a place in the UK's energy system, and to deliver benefits to UK businesses that excel in the relevant manufacturing techniques.

## THE FUTURE ROLE FOR CLCF

The Centre for Low Carbon Futures has been pleased to support this work within the scope of our programme on energy storage. Alongside the Liquid Air Energy Network we intend to be closely involved in the follow-up activities seeded by this report. The priority must be to accelerate implementation of the applications of liquid air in the UK and internationally. This is not only a job for government; businesses and the wider research community must also get behind this and other technologies if the potential benefits are to be achieved.

Our energy storage programme will develop over coming months with the creation of an 'energy storage observatory' to chart innovation in the field. The CLCF member universities will work together, drawing on the expertise of our research community and others to cover technology development, demonstration activities, and market and policy analysis. We will host meetings and conferences to cover both the technology research, and importantly the business models that can allow deployment to become a viable commercial proposition.

This is vital work since, as David Willetts MP, Minister for Universities and Science, points out in his paper 'Eight Great Technologies'[3], the UK has lost previous opportunities in energy storage to other countries because of the gap between our basic science and our manufacturing techniques. It was that gap which "gave the Japanese their chance" in battery technologies, he argues, and "we must not repeat that mistake". The Government is indeed investing to give academic and business communities the chance to lead the world and develop new technologies and industries that can benefit the UK. Liquid air should be part of that effort.

**Dr. Jonathan Radcliffe, Programme Director, CLCF Energy Storage Centre and Senior Research Fellow, University of Birmingham**

**Prof. Richard A. Williams, OBE FREng FTSE, University of Birmingham**

3 Eight Great Technologies, David Willetts MP, Policy Exchange, 2013, http://www.policyexchange.org.uk/images/publications/eight%20great%20technologies.pdf

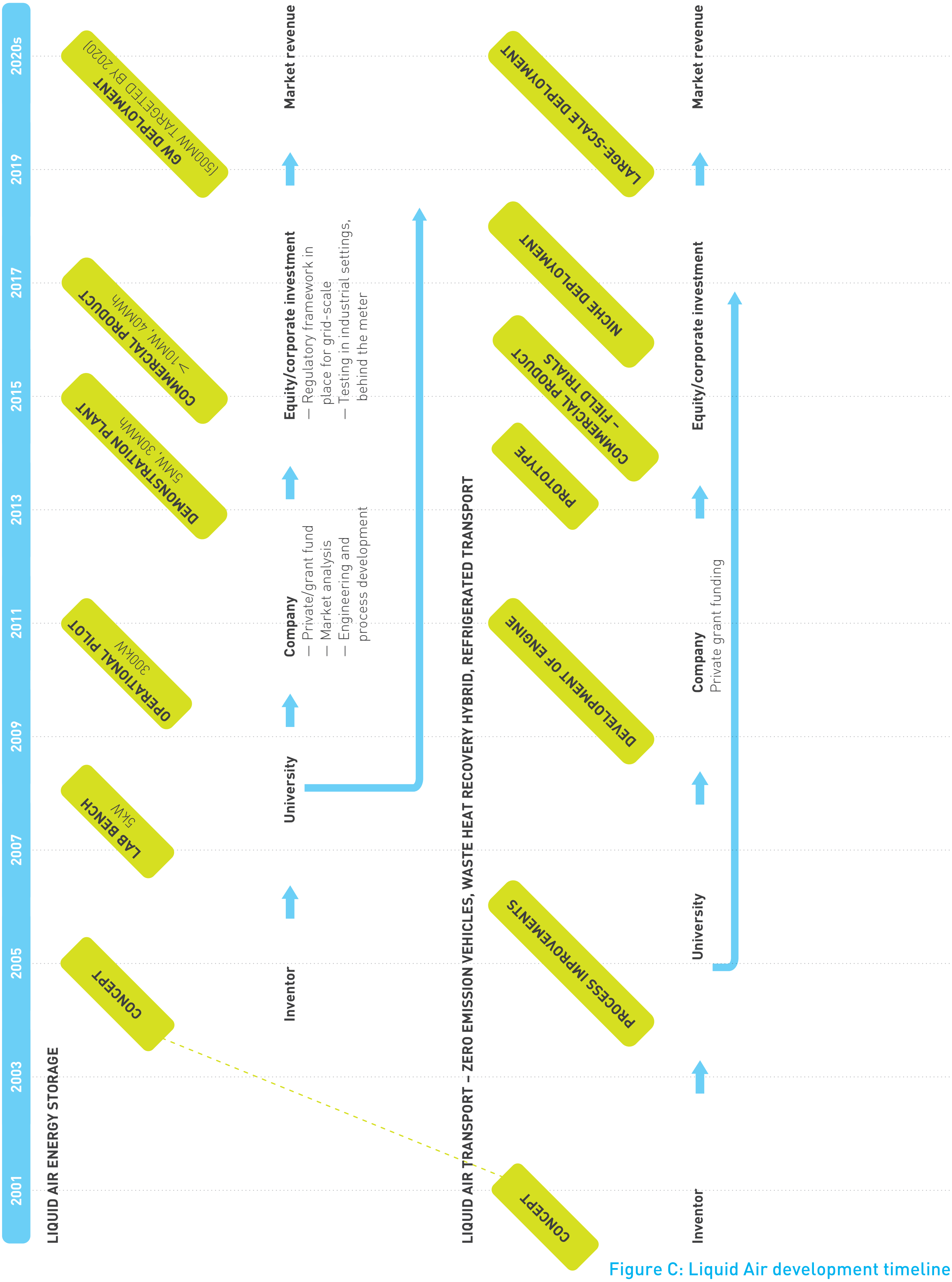


Figure C: Liquid Air development timeline

# KEY CONCLUSIONS

**THIS SUMMARY REPORT SHOULD BE READ IN CONJUNCTION WITH THE FULL REPORT, WHICH CAN BE FOUND AT WWW.LIQUIDAIR.ORG.UK.**

- Liquid air is a novel energy concept that could help solve some of our toughest energy challenges:
  - — balancing an electricity grid increasingly dominated by intermittent renewables
  - — reducing greenhouse gas emissions from transport
  - — exploiting waste heat.
- Liquid air could help cut $CO_2$ emissions from grid electricity by capturing 'wrong time' energy (such as excess renewable energy produced at night when there is too little demand) and using it to displace carbon intensive peak generation, and by allowing fossil plants to operate more efficiently. In a 'high wind' scenario, 15GW of liquid air energy storage would reduce grid emissions by 4.5%, while 30GW would cut them by 20%.
- Liquid air could act as a transport fuel capable of fast refuelling, zero emissions at the point of use, and ultra-low $CO_2$ emissions: a liquid air vehicle would have lower lifecycle emissions than one powered by electricity or hydrogen by 2030, based on projected overnight grid carbon intensity; a liquid air lorry refrigeration unit would deliver 80% emissions cuts based on current grid electricity.
- Liquid air could enhance UK energy security by reducing our reliance on imported oil and gas, and providing strategic energy storage: a single gasometer-style tank could store sufficient energy as liquid air to make good the loss of 5GW of wind power for three hours.
- Industrial gas companies produce 8,500 tonnes per day of excess nitrogen (the main component of liquid air) which currently goes to waste and could instead be liquefied to fuel 6.5 million car kilometres daily.
- Liquid air could be produced for less than four pence per litre delivered, and fuel costs per-kilometre could be half those of a petrol car on the basis of current electricity prices.

- Liquid air can help transform large resources of waste heat and waste cold into power and fuel:
  - — Exploiting waste cold from LNG re-gasification at UK import terminals would cut the electricity required for air liquefaction by almost 60% and costs by half.
  - — Liquid air electricity generation can turn waste heat into power at high levels of efficiency. UK industry loses up to 40TWh of waste heat each year – enough to heat 2.4 million homes.
  - — In transport, liquid air engines could be combined with conventional internal combustion engines (ICEs) to create highly efficient 'heat hybrids'. One novel ICE design incorporates liquid nitrogen to capture its own exhaust heat and raise fuel efficiency to 60%.
- Liquid air technologies are based on standard components and mature supply chains, and there is an extensive cryogenic liquids distribution network in all industrialised countries.
- The economic value of liquid air storage on the electricity grid could be £1 billion per year by 2050 and support 20,000 jobs. This excludes its potential impact in industry and transport.
- While liquid air appears to offer major benefits in emissions reduction, energy security and cost – quite apart from the economic potential of an entire new industry to UK PLC – those benefits may never be realised without appropriate policy support.

**ABOUT LIQUID AIR ENERGY NETWORK (LAEN)**

LAEN is a newly created forum to explore and promote the use of liquid air as an energy vector, with applications in grid electricity, transport and waste heat recovery. Building on the findings of the Centre for Low Carbon Future's report, LAEN will serve as the global hub where new ideas are demonstrated and shared, and promote liquid air as a potential energy solution among researchers, technology developers, manufacturers, energy producers and consumers, and government. Its membership will be drawn from the same groups. LAEN contact: Toby Peters (Founder), www.liquidair.org.uk.

# EXECUTIVE SUMMARY

## WHY DO WE NEED ANOTHER ENERGY VECTOR?

Energy policy in Britain and Europe rests on three pillars: decarbonisation, energy security and affordability. In order to reduce emissions and keep the lights on at an acceptable cost, much of the policy debate has centred on how to generate sufficient low carbon energy. However, the fundamental problem is not the adequacy of low carbon energy resources – wind, solar, nuclear etc are in principle sufficient to meet our needs many times over – but how to package that energy into useful forms. The imperative to decarbonise is forcing us to rethink the way energy has been transformed, transported and consumed for decades, and many of the trickiest problems relate to the mismatch between the forms in which low carbon energy is produced and the forms in which we need to consume it. Arguably one of our biggest challenges is to develop new energy vectors.

A vector is not a source of energy but a means of transporting it from one time and place to another. Unlike primary fuels – coal, gas and oil – vectors are man-made, resulting from the transformation of one source of energy into another more useful form – such as steam, electricity, hydrogen or biofuels. An ideal vector should be able to transport energy in both time and space, so that consumption can be decoupled from production, and the vector can serve as a transport fuel. However, existing vectors all suffer significant drawbacks and are not progressing as quickly as promised or required.

The need for new vectors is becoming more acute because of rapid changes in the energy system brought on by decarbonisation. Until recently our energy was almost exclusively derived from primary fuels such as coal, oil and gas that are easy to store and transport, and which can deliver power or heat whenever necessary. Today we are shifting rapidly to renewable forms of generation such as wind and solar, which, because they are intermittent, produce *energy* rather than *despatchable* power that is available on demand. This energy comes in the form of electricity, which is easy to move but harder and more expensive to store, making it particularly unwieldy as a transport fuel. It is the widening disconnect between energy and despatchable power that creates the need for new vectors.

It is widely accepted that cutting carbon dioxide emissions will mean a much larger role for electricity. Analysis by the Committee on Climate Change, the Government's independent advisor, has shown that decarbonising the electricity supply is vital to achieving the country's overall climate targets. This is because power sector emissions account for almost 30% of total emissions; cutting emissions is generally cheaper in electricity generation than in other sectors; and low carbon electricity can then be used to help decarbonise heat and transport.

However, because electricity is difficult and expensive to store, a strategy of decarbonisation that relies on electrification presents two major challenges: 1) balancing supply and demand on a grid increasingly dominated by intermittent renewable generation, and 2) transforming low carbon electricity into a form suitable for use in transport. Both challenges might be amenable to a new low carbon energy vector such as liquid air.

## WHAT IS LIQUID AIR?

Air can be turned into a liquid by cooling it to around -196C using standard industrial equipment. 700 litres of ambient air becomes about 1 litre of liquid air, which can then be stored in an unpressurised insulated vessel. When heat is reintroduced to liquid air it boils and turns back into a gas, expanding 700 times in volume. This expansion can be used to drive a piston engine or turbine to do useful work. The main potential applications are in electricity storage, transport and the recovery of waste heat.

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 +100C), which other technologies would find difficult to exploit and which significantly improves the energy return. There are myriad sources of low grade waste heat throughout the economy from power stations to factories to vehicle engines.

The industrial gases industry has been producing liquid nitrogen and liquid oxygen – the main components of liquid air – for over a century. Cryogenic gases have a wide range of applications including steel-making, food processing, medicine and superconducting technologies. The thermo-physical properties of liquid nitrogen and liquid air are similar, so a cryogenic energy vector could be provided by either.

The industry has a glut of gaseous nitrogen that could be made available for liquefaction, because there is four times as much nitrogen as oxygen in the atmosphere but much less demand for it commercially. Currently an estimated 8,500 tonnes per day of waste gaseous nitrogen is vented back to the atmosphere, which, if liquefied and used as transport fuel, would be enough to power the equivalent of 6.5 million car kilometres daily.

There have been several attempts to exploit liquid air or liquid nitrogen as an energy vector over the past century without commercial success. However, technological advances and market evolution in the early years of this century appear to have made it a practical and economic possibility worth considering again. Emerging liquid air technologies include:

- a novel piston engine that runs on liquid air or nitrogen, which could be used either as a prime mover (main engine) or as a secondary unit to recover waste heat from an internal combustion engine (ICE) or hydrogen fuel cell and so raise efficiency;
- a novel split cycle ICE engine design that incorporates liquid nitrogen to increase efficiency by capturing its own exhaust heat; and
- the Liquid Air Energy Storage (LAES) system, a plant which generates liquid air using cheaper, off-peak electricity, stores it for some hours or days, and then expands it through a turbine to deliver power back to the grid at times of peak demand.

Liquid air technologies can also be used to recover waste heat from industrial sources and in hybrid combinations with internal combustion engines and even hydrogen fuel cells.

## GRID ELECTRICITY

Under any likely scenario, balancing supply and demand on the electricity grid will become more challenging over the coming decades. About 19GW of firm generating capacity will close by the early 2020s, while large amounts of intermittent renewable and inflexible nuclear generation are expected to be added. National Grid estimates that back-up (or 'balancing') capacity needs to rise from 3.5GW today to some 8-13GW by 2020.

The debate around grid balancing is usually presented in terms of the need for additional gas fired plant to run when the wind drops. However, we find a powerful case for additional grid *storage*, in which liquid air could play a major part. Gas plant may be a reliable source of firm power, but it is a source of substantial greenhouse gas emissions, and critically, unlike storage, it cannot absorb 'wrong time' energy.

Much has been made of the potential impact on a wind-dependent grid of a high-pressure weather system in winter, bringing cold but windless weather with high demand and low renewable output. However, as wind capacity increases, the reverse problem will also exist: periods when wind output exceeds demand, either locally or across the entire grid, and wind generation has to be 'constrained' (switched off) and yet still paid for. This is already beginning to happen in Britain, where constraint payments have risen dramatically, from just £180,000 in the year to April 2011 to £34 million the following year. So far constraint payments have largely been caused by local bottlenecks in transmission lines, but if wind capacity grows as forecast, it is easy to foresee a situation in which off-peak wind generation could often exceed total demand, even if all grid bottlenecks were solved.

In this respect storage has a major advantage over gas and other forms of balancing capacity, and will become increasingly valuable to the grid by preventing the waste of 'wrong time' energy, and by allowing fossil power plants to run more efficiently at full load rather than 'ramping' up and down to compensate for variable wind output.

In this context, Liquid Air Energy Storage could play a major role. In particular – as we explore in chapter 3 of the Full Report – LAES could:

- provide network operators and other market participants a cost effective and scalable means of time-shifting large amounts of energy to help balance the grid, deliver investment savings by allowing upgrades of transmission and distribution networks to be deferred, and eliminating grid bottlenecks;
- provide strategic levels of electricity storage: a single gasometer-style tank of the capacity currently used in the LNG industry (190,000m$^3$) could store sufficient energy as liquid air to compensate the loss of 5GW of wind power for three hours;
- reduce $CO_2$ emissions from grid electricity by 1) capturing excess off-peak ('wrong time') renewable energy and using it to displace high-emitting peaking generators, and 2) allowing fossil power plants to run more efficiently at full load rather than ramping up and down to compensate for variable wind output;
- exploit the cold given off by the re-gasification of liquefied natural gas (LNG) at UK import terminals to help produce enough liquid air to fuel 16 billion car kilometres, more than 4% of the annual mileage of cars in Great Britain; and
- compete in a potential storage market of 14GW by 2050, with a value to the grid of some £10 billion per year, assuming a level playing field regulatory framework.

## TRANSPORT

Transport of people and goods is generally considered as a distinct category within the wider energy debate. Not only is it a significant, identifiable economic bloc responsible for over a third of all energy consumed in the UK, it also places unique demands on the energy vectors deployed. Imposing the additional requirement to reduce greenhouse gas emissions increases the difficulty of satisfying all those demands within a single vector, and this is reflected in the fact that progress on biofuels, electric vehicles

(EVs) and hydrogen fuel cell vehicles (FCVs) is proving far slower than expected or required by policymakers.

The self-evident but fundamentally defining fact about vehicles is that they are mobile, and usually need to be able to operate while disconnected from their source of energy. This in turn means they must carry 'batches' of energy on board and stop periodically to refuel. Most vehicles must also be able to cope with 'mission variation', since each trip may vary by destination, route, duration, speed and payload. This defines a series of factors against which transport energy vectors and technologies must be judged: energy density; power density; refuelling rate; and refuelling infrastructure. The relative importance of these factors varies between transport modes, and our detailed analysis reveals that liquid air could provide an attractive low carbon energy vector in several vehicle types and functions:

- Prime mover: a cryogenic engine such as the Dearman engine produces zero emissions at the point of use; has low greenhouse gas emissions provided the liquid air or nitrogen is produced from low carbon electricity; has energy and power density on a level with battery electric technology; and has the potential for rapid refuelling. This makes it potentially attractive as a 'prime mover' (main engine) for use in small cars and vans for short range urban use, scooters, short range marine craft, forklift trucks and mining equipment.
- Heat hybrid: a cryogenic engine such as the Dearman engine could also be used as a 'heat hybrid' in combination with an internal combustion engine or hydrogen fuel cell (see next section), to convert waste heat into additional shaft power at high levels of efficiency, reducing both fuel consumption and emissions. This approach would be viable in passenger ferries, commuter trains, heavy duty trucks and urban buses, and could also deliver 'free' cooling for passengers or goods.
- High efficiency internal combustion engine: heat recovery could also be achieved using the Ricardo split cycle engine, a novel internal combustion engine design that incorporates liquid nitrogen to capture exhaust heat and increase fuel efficiency. Detailed modelling of this approach undertaken through the Technology Strategy Board-funded 'CoolR' project has suggested that efficiencies of more than 60% are possible, compared to around 40% for modern diesel engines. Nitrogen could be supplied from a modest-sized onboard tank or an onboard liquefier driven by the engine and boosted by regenerative braking. This approach would be suitable for heavy duty trucks and container ships, and potentially rail locomotives, other commercial vehicles and even larger passenger cars.
- Refrigerated food transport: some food delivery vehicles already use liquid nitrogen as a heat sink to provide refrigeration, which cuts noise, complexity and carbon dioxide emissions substantially compared to conventional diesel-powered refrigeration. However, current systems fail to capture any additional shaft power from the nitrogen evaporation process. We calculate that a vehicle food refrigeration system using liquid nitrogen or liquid air to provide both additional shaft power and cooling would cut emissions from 47 tonnes per lorry per year (diesel refrigeration) to 10 tonnes, a reduction of almost 80% on the basis of current grid average electricity (chapter 10 of the Full Report). The same approach could also provide refrigeration or air conditioning for passenger ferries, cruise ships, freight trains and buses, with greatest benefits in hot climates.

## WASTE HEAT

Liquid air is inherently capable of converting waste heat into power because of its low starting temperature. The liquid air cycle works between -196C and ambient temperatures, meaning the addition of even low grade waste of less than 100C, which is otherwise difficult to exploit, can increase the work output significantly. Sources of waste heat that could be exploited by liquid air technologies include conventional and novel internal combustion engines (see previous section), power generation, industrial processes, and in future potentially hydrogen fuel cells.

In the UK, industrial processes provide myriad sources of waste heat, which total up to 40TWh per year – enough to heat 2.4 million British homes. Industrial demand for heat, at around 180TWh, is easily large enough to absorb this waste, but this takes no account of the obvious fact that sources of waste heat are rarely co-located and coincident with demand. Our analysis shows that even if all opportunities to make use of waste heat as *heat* were exploited, there would still be a very substantial waste heat resource available from manufacturing and process industries, and the best way to access this is to generate electricity. Our analysis suggests that if the ratio of peak to off-peak electricity prices is 2.5 or greater, liquid air could represent an economically attractive proposition to process plant operators with a waste heat source to exploit.

In countries with inadequate primary generating capacity, such as South Africa and Thailand, peak electricity prices can be as much as 8 times higher than off-peak prices, even today. In countries or regions with rising renewable generating capacity such as Germany, Texas and Great Britain, power prices can already turn negative in periods of high wind and low demand, and the effects of weather and renewable intermittency are expected to increase price volatility in the coming decades. By some forecasts the peak to off-peak ratio in such countries could be substantially higher than 2.5 within the next two decades.

In transport, PEM (Proton Exchange Membrane) hydrogen fuel cells operate at around 80C, not dissimilar to the coolant temperatures of internal combustion engines, meaning they too could be combined into heat hybrids with a Dearman engine or similar. This could improve the economics of hydrogen vehicles by allowing the PEMFC to be downsized.

Other advantages of such an arrangement include:

- Fuel cells are less efficient when running under dynamic conditions than at steady state, and a hybrid FC-liquid air engine may allow for greater efficiencies and component lifetime by load levelling.
- Manufacturers are constantly trying to reduce the amount of platinum used in fuel cells to cut costs, but this may increase heat generation, meaning thermal management could be increasingly important.

The markets where a PEMFC-liquid air hybrid would offer most immediate benefit and greatest chance of success have been identified as buses, taxis and forklift trucks.

### LIQUID AIR PRODUCTION AND COST

Liquid air is not produced commercially today since demand is for the individual components of air: oxygen, nitrogen and argon. The industrial gases industry in the UK sells 9,000 tonnes per day (tpd) of oxygen (gas and liquid) and 8,000tpd of nitrogen.

However, Air Separation Units (ASUs) inevitably produce excess gaseous nitrogen, because there is four times as much nitrogen as oxygen in the atmosphere but much less demand for it commercially. Spiritus Consulting estimates conservatively that excess gaseous nitrogen production capacity in the UK amounts to at least 8,500tpd, and the glut would be even larger but for the fact that producers adopt various measures to optimise the oxygen output of their ASUs. This surplus gas is currently vented harmlessly to the atmosphere.

The thermo-physical properties of air and nitrogen are similar, and either could serve as a cryogenic energy vector. In the early stages of a liquid air economy, therefore, waste nitrogen gas could be liquefied to use in place of liquid air. If the entire estimated daily nitrogen surplus were used for this purpose, it could potentially fuel the equivalent of 6.5 million car kilometres daily.

Producing liquid air directly would be simpler and cheaper than producing liquid oxygen and nitrogen, since the gases need not be separated. Air liquefaction can be achieved with less equipment than required to separate oxygen and nitrogen, and consumes about a fifth less energy.

We calculate that the production costs of liquid air are between 3 and 4.5 pence per kilogramme, or 2.5 to 3.6 pence per litre on the basis of current electricity prices. There is potential to reduce these costs by almost half through measures such as co-locating production with LNG terminals to exploit waste cold. The delivered cost, after distribution by road tanker, would be roughly double, but local production at refueling stations could eliminate this cost.

These costs translate to competitive per-kilometre fuel costs compared to incumbent technologies. Figure 2.1 shows that in all but one scenario the per-kilometre fuel costs are lower for a Dearman engine car than for a petrol car of average UK fuel economy (including duty and tax). The running costs of an EV are lower still, but these should be seen in the context of much higher capital costs; the Nissan Leaf costs £26,000 even after a government grant of £5,000, around twice the price of an equivalent sized

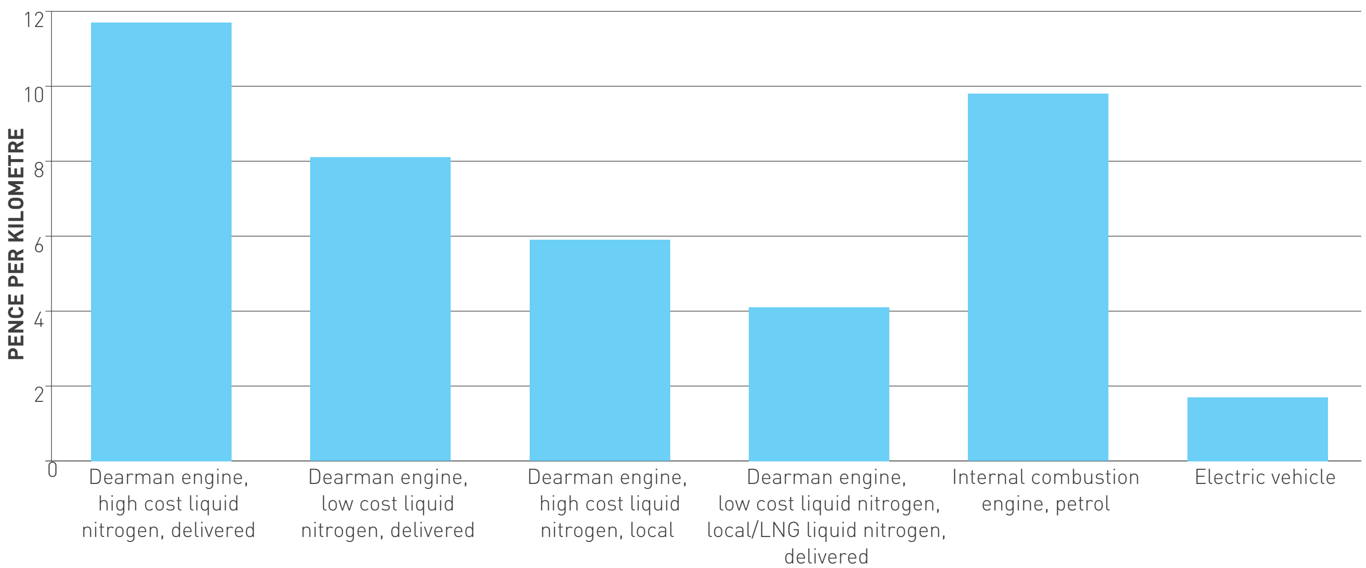


**Figure 2.1:** Fuel costs per kilometre of Dearman engine car compared to internal combusion engine and electric vehicles

ICE. A Dearman car would have similar capital costs to an ICE in the early stages of production. On balance we conclude the likely costs of liquid air mean it is likely be competitive – and perhaps highly competitive – with fossil fuels in a range of transport and other applications.

## INFRASTRUCTURE

The emergence of a liquid air or nitrogen economy, in which cryogenic liquids are widely used as an energy vector in transport and small-scale electricity generation, would require an extensive distribution network (chapter 7 of the Full Report). It is one of the strengths of liquid air compared to some other potential energy vectors that this requirement is already broadly satisfied; thousands of tonnes of liquid oxygen and nitrogen are already distributed across the country every day.

Figure 2.2 shows the location of existing industrial gas production sites; potential new production sites at LNG import terminals; urban conurbations; and the depots and distribution centres of some significant hauliers and supermarket chains, who may be early users of long-haul liquid air applications. Each production site is marked with a radius of 50 and 100 miles to show its potential delivery catchment area. It is clear that most of the UK is covered by existing or potential liquid air distribution.

From our analysis we also conclude that:

- there already exists a well-established distribution network for cryogenic fluids in the UK and across the industrialised world;
- surplus production capacity in liquid nitrogen and the existing distribution network are more than adequate to supply the short to medium term fuel needs of an emerging 'nitrogen economy' (chapter 6 of the Full Report);
- specifically, the existing distribution infrastructure is more than adequate to supply the early development of on-site, return to base and some long-haul transport applications; and

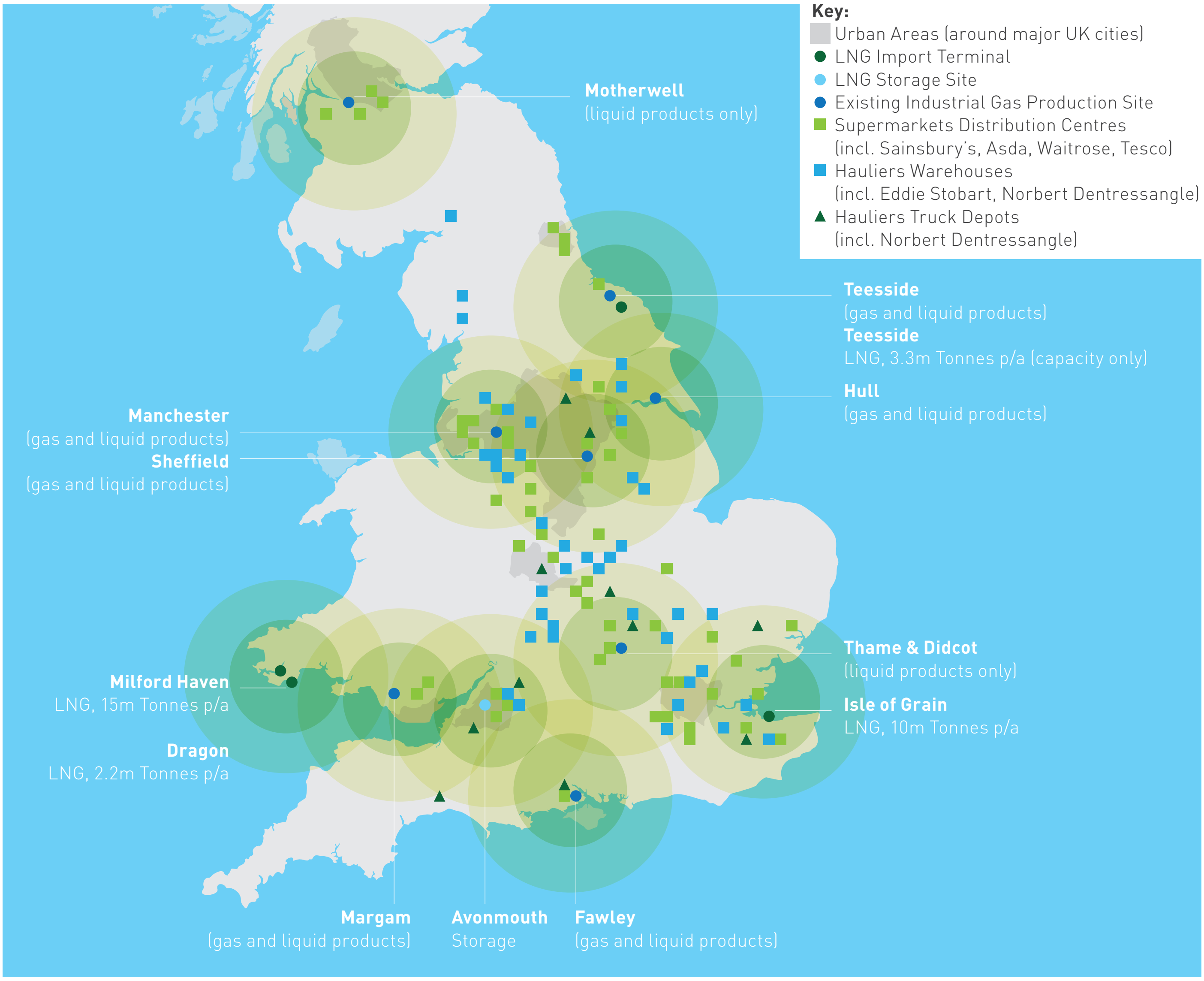


**Figure 2.2:** Potential liquid air suppliers and users

- in the longer term, a mix of local production of liquid air and nitrogen, and centralised production combined with distribution by cryogenic tanker, is likely be able to satisfy any foreseeable demand.

## MANUFACTURING AND PATHWAYS TO DEPLOYMENT

If liquid air as an energy vector benefits from a pre-existing 'fuel' distribution network (chapter 7 of the Full Report), it may gain further advantage from the characteristics of the equipment that would run on it (chapter 8 of the Full Report). Liquid air devices can generally be made substantially from existing components drawn from mature supply chains with few bottlenecks to hamper expansion. And unlike many other low carbon technologies – such as EVs – liquid air technologies require negligible rare earth metals and other scarce resources.

The **Liquid Air Energy Storage** system is made entirely from existing components drawn from the industrial gases and power generation industries. Key components such as compressors, cold boxes, heat exchangers, expansion turbines and generators are all available at scale from the global supply chain. A substantial proportion of a LAES plant could be also sourced from UK suppliers. A round table discussion of industry experts held at the Institution of Mechanical Engineers in March 2013 concluded that that if design, civil engineering and construction work were added to domestically produced components, around 50-60% of the value of a LAES installation could originate in the UK.

The round table also concluded there is no reason why the international supply chain should not deliver a target of 500MW of LAES capacity in the UK by 2020, or supply a potential UK market of 14GW by 2050. To achieve the earlier target, orders would need to start to be placed this year, but the current international supply chain is capable of delivering these levels of capacity without creating a bottleneck.

**In transport**, the Dearman engine is a reciprocating (piston) engine that operates at near ambient temperatures, and as a result it is unlikely to offer many unfamiliar challenges to vehicle engine manufacturers. The most unfamiliar part of the system is likely to be the part exposed to cryogenic working fluid – liquid air or nitrogen. However, cryogenic technologies are mature and have been used in the industrial gas and LNG industries for decades.

There is a wide variety of materials suitable for use in cryogenic systems, including stainless steel, aluminium alloys, PTFE and polyethylene, which are plentiful and relatively low cost. This contrasts favourably with some of the materials required for other low carbon vehicle technologies, such as platinum in hydrogen fuel cells and lithium and neodymium in battery electric vehicles.

In the short term it is expected that the Dearman engine would have similar capital costs and embedded carbon to a conventional ICE, and significantly lower than EVs or FCVs.

The New Automotive Innovation and Growth Team (NAIGT) technology roadmap foresees the introduction of zero emissions vehicles in the 2020s, and we find liquid air vehicles could be developed in this timeframe. We also conclude that since the Dearman engine could be used in heat hybrids, liquid air could extend the time before it becomes necessary to replace the ICE altogether by raising its efficiency and reducing emissions.

## SAFETY

Cryogenic liquids present significant hazards because of their intense cold and substantial gas production when warmed. However, these hazards are well understood and amenable to established safety management protocols. Some hazards are common to both liquid air and liquid nitrogen, while others are more specific to one or other cryogen, but the issues are fundamentally identical in grid and transport applications. The most likely problems relating to the use of liquid air or nitrogen as an energy vector are:

- Cold burn or frostbite (both liquid air and liquid nitrogen)
- Materials structure and integrity (both)
- Pressure build-up (both)
- Oxygen deficiency (mainly liquid nitrogen)
- Oxygen enrichment (mainly liquid air)

For the purposes of this brief summary (please see chapter 9 for full review of safety issues), cold hazards are easily solved by the use of materials suited to low temperature service, and appropriately insulated systems. Pressure build-up in storage or fuel tanks is also easily solved with pressure relief valves and burst discs. However, oxygen deficiency and enrichment deserve further discussion.

Cryogenic liquids can be stored for substantial periods in insulated vessels, at atmospheric or slightly above atmospheric pressure. However, all cryogenic liquids will boil off in time, as ambient heat gradually penetrates the insulation. Pressure will rise in the vessel, and gas will then be released through a relief valve. Boil off generally occurs at a rate of around 1% per day in small tanks, and at 0.2% or lower for larger tanks, where the greater ratio of volume to surface area favours cold retention.

If the cryogen is liquid nitrogen, and if the tank or vehicle is housed in an enclosed space with inadequate ventilation, and if it is left unmonitored for an extended period, then there is a risk that the vented nitrogen will displace the original air and render the atmosphere unbreathable. Anyone entering such a space would be at risk of asphyxiation. However, this hazard could be eliminated by mandating appropriate passive ventilation standards for any building containing such equipment, oxygen monitoring or both. Health and safety procedures for the amount of ventilation required for an environment with cryogenic inert gases are well established, and oxygen monitoring equipment is routinely used at industrial gas production sites.

If the cryogen is liquid air, a different hazard predominates. The asphyxiation risk is lower since both nitrogen and oxygen boil off. However, nitrogen boils off preferentially to oxygen, since it has a higher partial vapour pressure at the same temperature and this factor drives evaporation. As a result, a tank of liquid air left unmonitored for extended periods may see the proportion of oxygen in the mix rise above 21%, the proportion that occurs naturally in the atmosphere. Any concentration above 23.5% is considered dangerous, since oxygen is highly reactive if it comes into contact with hydrocarbons or other organic material.

The risk of oxygen enrichment is clearly linked to the size of the storage vessel and the length of time liquid air is held in storage. Larger tanks retain cold better, and grid-scale applications such as Liquid Air Energy Storage that cycle frequently would store liquid air too briefly for enrichment to take place. Smaller tanks holding liquid air for longer periods would be at greater risk of oxygen enrichment. We suggest for safety reasons that in circumstances where liquid air may be stored for long periods it should be handled according to liquid oxygen handling procedures.

More generally, there is good reason to believe the hazards associated with the use of liquid air and liquid nitrogen as transport fuel can be managed to acceptable levels, because:

- the industrial gas industry transports thousands of tonnes of cryogenic liquids by road tanker daily (chapters 6 and 7 of the Full Report);
- LNG and LPG are increasingly used as lorry fuel, and the hazards of transporting liquid air are expected to be much lower than for these or for liquid oxygen, which is also commonly transported by road;
- early applications of liquid air in transport are likely to involve commercial vehicles with fully trained operators;
- hazardous fuels such as petrol and diesel are routinely used by public, and the hazards have been managed to acceptable levels; and
- any use of liquid air or liquid nitrogen by members of the public would require it to be as safe or safer than using petrol or diesel, and all relevant technologies would need to be designed and engineered to ensure this.

There is no insuperable safety reason why liquid air and/or liquid nitrogen should not be widely deployed as an energy vector in both grid and transport applications.

## CLIMATE CHANGE

The ability of liquid air to reduce carbon dioxide emissions depends largely on the carbon intensity of the electricity used to produce it. However, the scale of emissions reductions is also application specific: some liquid air concepts such as refrigerated food transport would reduce carbon dioxide emissions even based on current grid average carbon intensity; others would start to deliver emissions reductions only on the basis of lower carbon electricity.

The carbon intensity of the grid is projected to fall significantly over the next two decades as coal fired power stations close and more wind generation continues to be added. This will reduce grid emissions overall, but will have an even more pronounced impact on off-peak or overnight carbon intensity, when demand is lower and nuclear and wind capacity will on average deliver a bigger proportion of the necessary power.

This is important because at present liquid nitrogen is invariably produced at night to take advantage of lower cost electricity. This coincidence of lower cost and lower carbon overnight electricity means emissions from liquid air technologies will fall faster than if they were charged at the grid average. It means, for example, that a diesel-cryogenic hybrid bus running on overnight liquid air would start to emit less $CO_2$ than a standard diesel from 2015, and emissions would continue to improve thereafter.

### Grid average emissions reductions

Liquid Air Energy Storage can help reduce average emissions from grid electricity by:

- capturing excess wind or other lower carbon overnight power that would otherwise be 'constrained' (wasted) and using it to displace fossil fuel generators at peak times; and
- allowing fossil plant to run more efficiently at full load, while storage devices assume their 'load following' role – raising or reducing output to match demand.

These two factors have the effect of lowering average emissions from grid electricity beyond any reductions achieved by simply changing the primary generating mix.

In terms of reduced wind constraint, we estimate that in a 'high wind' scenario with 40GW of wind capacity, around 17TWh would be constrained each year, the energy equivalent of around 3,000 x 2MW wind turbines. Liquid air storage could reduce some of this constraint and in turn displace high emitting plant, saving up to 8 million tonnes of $CO_2$ ($MtCO_2$) or around 6.5%.

In terms of total grid emissions savings under the same scenario – including reduced wind constraint and increased fossil plant efficiency –the emissions savings depend heavily on the duration of the assumed storage capacity. Higher capacities of storage with longer durations, such as those achievable by LAES devices, can displace larger shares of peaking capacity and thereby increase the $CO_2$ reductions.

Figure 2.3 shows that one hour storage, even with large scale deployment, produces maximum $CO_2$ savings of around 7–8%. However, this reduction can be achieved with around half the capacity if storage durations exceed three hours. At six hours' storage duration – easily achieved by LAES – 15GW of storage capacity would save 5.6Mt$CO_2$, while 20GW would save 14Mt. A far more ambitious scenario of 30GW would save 24Mt, or almost a fifth (19.4%) of total grid emissions of 125Mt$CO_2$ in this scenario.

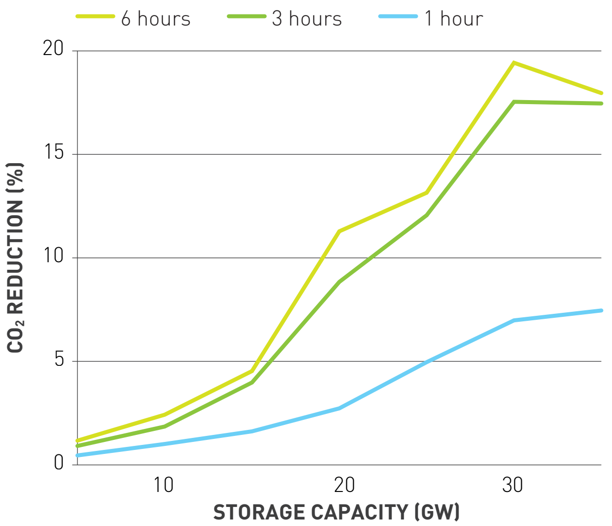


**Figure 2.3:** The impact of storage on $CO_2$ emissions with 40GW wind capacity

### Overnight grid emissions reductions

Since liquid nitrogen is invariably produced overnight when power prices are lowest, it is important to understand the likely evolution of the off-peak carbon intensity of grid electricity. Our analysis, based on scenarios from DECC's 2050 pathways, shows that overnight emissions intensity falls faster than grid average, as the share of zero carbon generation during these low demand periods doubles to as much as 80% by 2030. Figure 2.4 shows that by 2030 the emissions factor during low demand periods could be as low as 53g$CO_2$/kWh for a system that on average still emits 93g$CO_2$/kWh.

### Emissions reductions in transport

In conventional vehicles, the dominant source of greenhouse gas emissions is the combustion of fossil fuels in the vehicles themselves. Lifecycle studies have shown that for a passenger car about 80% of total emissions come from fuel use – overwhelmingly from the exhaust pipe, with a much smaller fraction caused by oil production and refining – and 20% from 'embedded' emissions due to manufacturing and disposal of the vehicle. In commercial vehicles, which are used more intensively, fuel use accounts an even higher share of lifecycle emissions – typically 90% or more.

For alternative technologies such as EVs, FCVs and future vehicles powered by liquid air engines such as the Dearman engine (DE), emissions are dominated by the carbon intensity of the electricity used to make the 'fuel' and the efficiency of the powertrain. This makes the lifecycle emissions of all three technologies sensitive to the pace of decarbonisation of the electricity grid. On a 'well-to-wheels' basis, which considers emissions from fuel use only, emissions from a DE vehicle would be twice those of an ICE based on today's grid average electricity, but fall to less than a third of the ICE's based on the projected carbon intensity of overnight electricity in 2030.

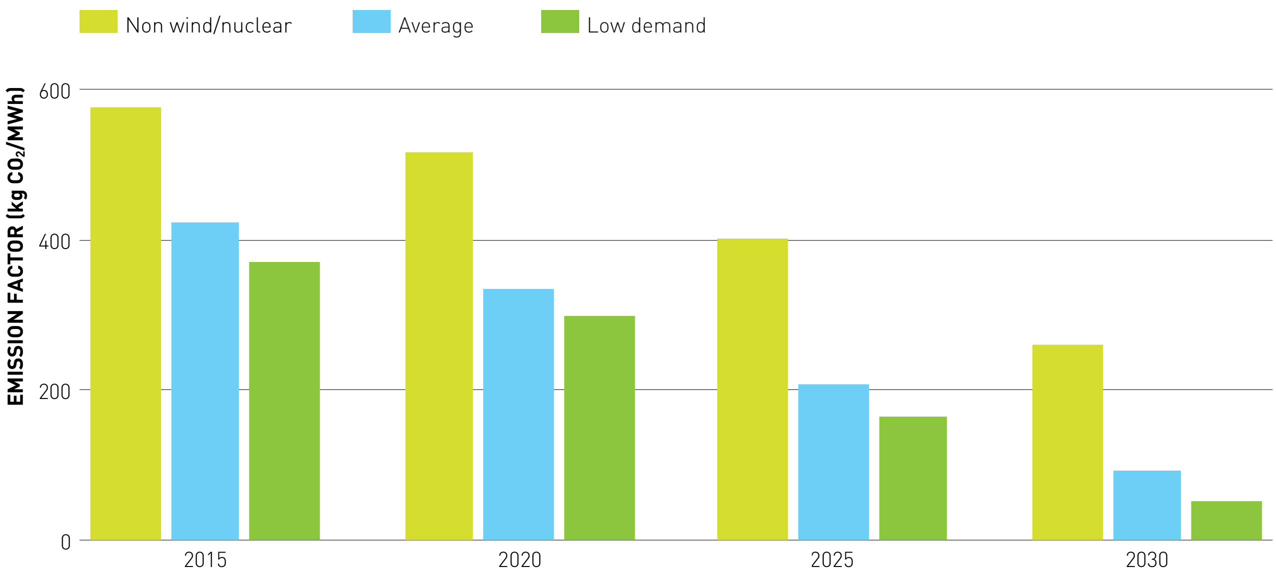


**Figure 2.4:** Fossil, average and overnight grid emission factors to 2030

Another significant factor is embedded emissions. EVs and FCVs have higher embedded emissions than ICE vehicles because of the lithium and platinum needed to make batteries and fuel cells. However, DE vehicles are likely to have embedded emissions similar to ICE vehicles in the early years of production, and this becomes increasingly important as the well-to-wheels emissions of all alternative powertrains decline over time. This means estimated DE lifecycle emissions are lower than those of current EVs and FCVs by 2030.

Cryogenic engines such as the Dearman engine could be combined with conventional ICEs as highly efficient 'heat hybrids'. Detailed modelling by the Dearman Engine Company and E4tech shows such ICE-DE hybrids could produce carbon savings from 2015.

One liquid air application, food transport refrigeration, could achieve major $CO_2$ reductions even on the basis of the current grid average carbon intensity. We calculate a large refrigerated lorry fitted with an auxiliary Dearman engine to provide both shaft power and cooling could save 38 tonnes of $CO_2$ per year, a reduction of 80% against conventional diesel-powered refrigeration unit. On the basis of projected overnight carbon intensity in 2030, the savings would be 98%.

## ENERGY SECURITY

Energy security is a widely used but poorly defined term. Even the Government has no categorical definition, despite having published an energy security strategy in November 2012. More generally the phrase is taken to mean the lights will stay on, homes remain warm and vehicles keep moving in all but the most exceptional circumstances. Although the Government has not precisely defined energy security, a report for DECC by the late Malcolm Wicks MP in 2009 identified three different aspects:

**geopolitical security:** avoiding undue reliance on specific nations so as to maintain maximum degrees of freedom in foreign policy;

- **price security:** avoiding unnecessary price spikes due to supply/demand imbalances or poor market operation; and
- **physical security:** avoiding involuntary physical interruptions to consumption of energy.

Liquid air could help improve energy security under all three headings by:

- reducing gas imports by storing excess off-peak wind power to displace gas fired peaking plant;
- reducing imports of oil, petrol and diesel by converting low carbon electricity into a transport energy vector/fuel;
- improving the physical energy security of the electricity grid by mitigating intermittency of renewable generation, reducing the risk of power cuts;
- providing strategic electricity storage – a single cryogenic storage tank of the type used to store LNG could store enough energy as liquid air to make good the loss of 5GW of wind power for three hours; and
- improving price security by reducing the need to invest in flexible generation and grid reinforcement, and reducing wind wastage. A study for the Carbon Trust found the total benefits of grid storage could amount to £10 billion per year by 2050.

## POLICY

This report opened with the observation that British energy policy rests on three pillars: decarbonisation, energy security and affordability. We have demonstrated that liquid air could provide huge benefits under all three headings – quite apart from the economic potential of an entire new industry to UK PLC. However, the projected benefits may never be realised without appropriate policy support.

### Grid electricity

The Government's support for low carbon technologies is already extensive, yet there remains a gap. While policy supports renewable electricity generation on the one hand, and EVs and heat pumps on the other – all of which will put increasing strain on electricity networks as their capacity grows – the same level of support is not available to energy vectors such as liquid air, which could help resolve those problems. Grid storage can help balance intermittent wind generation and peak demand, for example, while liquid air transport fuel would inevitably be produced overnight, so capturing surplus wind generation and smoothing peak demand. Yet policy is currently geared to maximising the development of intermittent renewables and promoting demand-side technologies that could exacerbate the daily peaks.

In this sense, the current system is quite dysfunctional. In the UK we pay millions of pounds in 'constraint payments' to wind farms to switch off when the wind is blowing but their power cannot be used; we then pay again for high emitting diesel or open cycle gas generators to remain on standby to manage demand peaks, and to run coal or gas fired power stations inefficiently as spinning reserve. Critically no explicit value is attributed to firming the output of intermittent renewables, nor to reducing the carbon cost of providing the reserve. The value of storage is therefore largely unrecognised in the current system.

The eventual consequences of failing to value the system flexibility that storage can bring are already beginning to unfold in Germany, where the rapid expansion of wind and solar power combined with the early closure of the nuclear fleet is starting to threaten the integrity of the electricity grid. The problem in Britain is not yet as severe, but wind constraint payments are rising fast (chapter 1 of the Full Report), and Ofgem has warned of extremely tight capacity margins by the middle of the decade, coinciding with a squeeze on global gas supplies (chapter 11 of the Full Report).

We would never argue for special treatment for liquid air, but the case for supporting any technology that can absorb excess renewable energy and warehouse it to displace high carbon generation is strong. These technologies could be the key to making the rest of the system work at lowest cost, and have the potential to deliver huge value in the coming decades. But like all early stage technologies they need support until they can stand on their own two feet – and a level playing field.

For reasons explored in in the Policy Review below, the Government's proposed Capacity Mechanism fails to recognise the full benefits of storage, and looks likely overwhelmingly to favour new gas fired plant. Therefore there is a strong case for supporting storage through a bespoke mechanism that specifically rewards the ability to absorb 'wrong time' energy and deliver it back at times of high demand or for use as low carbon transport fuel. Storage technologies also need the revision or repeal of a number of specific regulations that hamper their development.

| | | EFFICIENCY ASSUMPTION | LIFETIME ENERGY kWh* | TOTAL $CO_2$ EMISSIONS (INC. MANUFACTURE AND DISPOSAL | | | |
|---|---|---|---|---|---|---|---|
| | | | | 2015 | 2020 | 2025 | 2030 |
| **Grid avge.** | EV | 77% | 25,194 | 19.87 | 17.63 | 14.4 | 11.55 |
| | FCV | 26% | 73,734 | 40.42 | 33.88 | 24.41 | 16.08 |
| | DE** | 25% | 78,000 | 38.93 | 32.01 | 21.99 | 13.18 |
| **Overnight** | EV | 77% | 25,194 | 18.5 | 16.7 | 13.36 | 10.54 |
| | FCV | 26% | 73,734 | 36.43 | 31.16 | 21.38 | 13.11 |
| | DE** | 25% | 78,000 | 34.7 | 29.13 | 18.79 | 10.04 |

*Shaft energy required (19,500kWh) x efficiency **at ambient = lowest carbon emissions

**Table 2.1:** Lifecycle emissions of various power trains compared

| | ENERGY SECURITY TYPE | | |
|---|---|---|---|
| **liquid air benefit** | **Geopolitical** | **Price** | **Physical** |
| Reduce gas imports | ● | ● | |
| Reduce oil imports | ● | ● | |
| Mitigate renewables intermittency | | ● | ● |
| Strategic energy storage | ● | ● | ● |
| Reduce investment in flexible generation and grid infrastructure | | ● | |
| Reduce wind curtailment | | ● | |
| Increase autogeneration | | ● | ● |

**Table 2.2:** Potential energy security benefits of liquid air

In summary, the following changes to energy policy should be considered:

1. **Electricity storage should be given at least equal support to other low carbon grid technologies through a specifically targeted mechanism such as one modelled on the Non Fossil Fuels Obligation (NFFO).**
2. **The support mechanism should reward a storage plant according to its ability to both absorb and discharge energy, flexibility, speed of response, power rating, energy storage capacity and location.**
3. **Transmission and distribution licences should explicitly allow operators to own and operate electricity storage and receive capacity payments for these services.**
4. **Imposing electricity network charges on storage devices when both charging and discharging is disproportionate and should be halved.**
5. **Energy storage devices should be able to integrate with other renewable and low carbon generation solutions – including biomass, energy from waste and waste heat – without compromising their subsidies.**
6. **The Renewable Heat Incentive (RHI) should be amended to include devices that generate power using waste heat from non-renewable sources, such as commercial and industrial process heat, if it can be shown the electricity would displace fossil generation.**
7. **Initial capital grants should be extended to large-scale commercial demonstrators where appropriate, as planned for CCS**

### Transport

In transport, where liquid air technologies are not yet as mature, the issues are different.

It has long been recognised that high levels of decarbonisation will be harder to achieve in transport than other sectors such as electricity generation. At the same time, it is increasingly clear (chapter 1 of the Full Report) that existing technology approaches to cutting transport emissions are not delivering quickly enough, and do not adequately address the needs of the heavy duty sector. Lorries account for 60% of global diesel demand, and the IEA has forecast that 40% of the growth in global oil demand to 2035 will come from road freight alone. Since batteries cannot currently provide the energy density required for heavy goods vehicles, alternative approaches are required to raise their efficiency and cut emissions.

We have shown in this paper that liquid air could help achieve major fuel and emissions savings through a variety of approaches – especially in heavy vehicles and refrigeration (chapters 4 and 10 of the Full Report). These approaches are complementary to other medium-term measures such as use of natural gas as a haulage fuel.

Yet policy support for early stage transport technologies such as liquid air remains somewhat insensitive to the potential of real disruptors and the needs of the small companies that typically develop them. In this context, the following changes to transport technology policy should be considered:

1. **Grant funding calls should offer appropriate opportunities for disruptive technologies, and make allowance in their structure for a less widespread level of understanding of those technologies; objectives should be set but the means should be technology agnostic where possible.**
2. **New technologies should be supported by a process of 'pre-clearance', to establish their basic scientific feasibility. This pre-clearance should then be publicly available, so that fund assessors can quickly verify the unfamiliar technology's credibility. The costs of 'pre-clearance' should be grant funded, perhaps by adapting the SMART award 'proof of market/concept' scheme.**
3. **A rigorous review should be undertaken periodically of existing visions for longer term $CO_2$ abatement, to quantify progress against targets and identify emerging roles for disruptors. In the context of liquid air or nitrogen, this would need to embrace not only its role as a main or supplementary 'fuel' in some applications, but also its energy-chain interaction with electricity grid buffering and with bulk LNG evaporation.**
4. **Support mechanisms such as research and infrastructure grants should evolve to embrace the increasingly complex interaction of energy systems – for example, some of the liquid air vehicle-fuel systems described could involve vehicles, refrigeration, grid buffering, the industrial gas industry, and bulk LNG supply within a single concept. This opportunity may not be realised if initiatives do not 'join up'.**
5. **A specific programme should be developed to support the field trial and deployment of technologies that replace or reduce diesel use in refrigerated food transport, which would be equally open to batteries and hydrogen fuel cells.**

# POLICY REVIEW

This report opened with the observation that British energy policy rests on three pillars: decarbonisation, energy security and affordability. We have demonstrated here and in our Full Report that liquid air could provide huge benefits under all three headings – quite apart from the economic potential of an entire new industry to UK PLC. However, the projected benefits may never be realised without appropriate policy support. In this chapter we explore what is required from government to enable the beginnings of a potential 'nitrogen economy'.

The case for government support for new low carbon technologies is widely accepted. In its Energy Technology Perspectives 2012, the International Energy Agency argues that governments "must play a key role in turning low-carbon technologies from aspiration into commercial reality", and that "Targeted policies, from the creation of national energy strategies to support for research, development, demonstration and deployment, will lead to a more secure, sustainable and affordable energy system; help stabilise the global climate; and underpin sustainable long-term economic growth".[4]

The means of government support are also well established: from grants in the earliest stages to support R&D, demonstration and early deployment; to market support mechanisms in the later stages to help newly commercial technologies compete against mature incumbents. Later, as the new technologies gain market share and economies of scale, costs come down and the level of support can be reduced.

It is important to stress the need for continuity of government support through all stages of development if the full economic benefits of low carbon technology innovation are to be realised. If early grants are not followed up by a market support mechanism, for example, promising home-grown technologies will either die in the cradle or be developed abroad. On the other hand, if market support mechanisms exist but grants are inadequate, then the technologies that gain are likely to be imported. Either way, the economic benefits of technology development and manufacturing are likely to be lost to the UK.

UK energy policy today includes measures to support a wide range of low carbon technologies from cradle to maturity. A variety of grants exists for early stage technologies, from batteries to wave power, while market support mechanisms include Renewable Obligation Certificates (ROCs) or Contracts for Difference (CfDs) for wind, Feed-in Tariffs (FiTs) for solar and other forms of micro-generation, and more recently the Renewable Heat Incentive. EVs are supported through a £5,000 per car purchase subsidy, and another £1,000 to help install a charging point at the buyer's home. The Green Deal provides support for installing energy efficiency technologies in homes.

The Government's support for low carbon technologies is therefore extensive. Yet there remains a gap. While policy supports renewable electricity generation on the one hand, and EVs and heat pumps on the other – all of which will put increasing strain on electricity networks as their capacity grows – the same level of support is not available to energy vectors such as liquid air which could help resolve those problems. Grid storage can help balance intermittent wind generation and peak demand, for example, while liquid air transport fuel

4 Energy Technology Perspectives 2012, IEA, http://www.iea.org/Textbase/nppdf/stud/12/ETP2012.pdf

would inevitably be produced overnight, so capturing surplus wind generation. Yet policy is currently geared to maximising the development of intermittent renewables and promoting demand-side technologies that could exacerbate the daily peaks.

In this sense, the current system is quite dysfunctional. In the UK we pay millions of pounds in 'constraint payments' to wind farms to switch off when the wind is blowing but their power cannot be used; we then pay again for high emitting diesel or OCGT generators to remain on standby to manage demand peaks, and to run coal or gas fired power stations inefficiently as spinning reserve. Critically no explicit value is attributed to firming the output of intermittent renewables, nor to reducing the carbon cost of providing the reserve. The value of storage is therefore largely unrecognised in the current system.

The eventual consequences of failing to value the system flexibility that storage can bring are already beginning to unfold in Germany, where the rapid expansion of wind and solar power combined with the early closure of the nuclear fleet is starting to threaten the integrity of the electricity grid. Power prices regularly go negative in Germany during periods of high renewable generation and low demand, utilities are being forced to mothball gas-fired power stations whose operating hours have been dramatically reduced, and neighbouring countries such as Poland and the Czech Republic are installing equipment to cope with uncontrolled cross-border power flows. The problem in Britain is not yet as severe, but wind curtailment payments are rising fast (chapter 1 of the Full Report), and Ofgem has warned of extremely tight capacity margins by the middle of the decade, coinciding with a squeeze on global gas supplies (chapter 11 of the Full Report).

There is clearly a strong case for public support for energy storage technology development. We would never argue for special treatment for liquid air, but the case for supporting any technology that can absorb excess renewable energy and warehouse it to displace high carbon generation is strong. These technologies could be the key to making the rest of the system work at lowest cost, and have the potential to deliver huge value in the coming decades. But like all early stage technologies they need support until they can stand on their own two feet – and a level playing field.

The IEA recognises the importance of such enabling technologies in its Energy Technology Perspectives 2012, where it argues that future success "will critically depend on the overall functioning of the energy system, not just on individual technologies". The most important challenge for policy makers over the next decade, says the IEA, "will likely be the shift away from a supply-driven perspective, to one that recognises the need for systems integration... Enabling and encouraging technologies and behaviour that optimise the entire energy system, rather than only individual parts of it, can unlock tremendous economic benefits".

If this shift is to be achieved efficiently, government policy should provide support for energy storage. In the rest of this chapter we discuss specific policy ideas in the areas of grid, transport and waste heat.

## ELECTRICITY NETWORKS

This paper has shown that energy storage technologies such as LAES could deliver range of substantial benefits to the grid, including emissions reduction, energy security and major financial savings. However, the current structure of the UK electricity market does not support new investment in energy storage; pumped hydro plants such as Dinorwig were built decades ago under the (nationalised) CEGB. Today the opportunities for transmission and distribution companies to own and gain value from storage are limited by regulations and by the regulated rates of return on assets, which means that more expensive options such as storage do not compare favourably against other allowable expenditure. The benefits of grid storage concepts such as liquid air are therefore unlikely to be realised without substantial reform to energy policy and market structures.

### Grant funding

It is well established that public support can help rebalance the risk and reward for development and demonstration of world-beating technologies. UK government spending on research, development and demonstration (RD&D) in energy technologies fell steeply from the early 1980s to the turn of the century, but has since risen sharply to its highest level ever (Figure 3.1). The main delivery channels for this type of support are the Research Councils, government departments, the Energy Technologies Institute (ETI), the Technology Strategy Board (TSB) and potentially Ofgem's Low Carbon Network Fund (LCNF). Each of these sources has provided grant funding for energy storage in recent years. For example, Highview Power Storage secured £1.1 million in funding from DECC to help build its pilot plant in Slough, while Isentropic, another heat transfer storage developer, was granted £14 million by ETI in 2012.

Government direct spending on energy RD&D has almost quadrupled in recent years to over £500 million in 2010/11 (Table 3.1). However, it is interesting to note that whereas renewable energy secured more than a third of the five year total, and energy efficiency almost a quarter, energy storage secured no more than 4% (less, in fact, since the category is shared with 'other power technologies'). Hydrogen and fuel cells received 5%, more than all other storage technologies combined, without yet developing a commercially viable product.

Most grants to energy storage technologies so far have been small, reflecting their current level of development, but it important that larger grants are made available in due course, since it is vital to demonstrate grid storage at scale. Large-scale energy storage projects are needed to demonstrate improved efficiencies of the storage technologies, better management of the electricity network, reduced amounts of constrained wind and more efficient running of thermal plant, which would be hard to show with small scale pilots. The Government accepts the need to fund large demonstration projects, since it has committed £1 billion to a competition for a single 400MW CCS power station. Large-scale energy storage could probably be delivered sooner than CCS with the appropriate support, and a government prepared to fund CCS at £1 billion/400MW should be prepared to fund the right energy storage projects proportionately.

### Market mechanisms

Grid storage technologies such as LAES will also require a market mechanism to help them compete and bring costs down. The Energy Bill currently before parliament contains proposals to introduce a new Capacity Mechanism to ensure sufficient capacity exists to prevent power cuts as coal and nuclear plants close over the next decade and wind capacity continues to rise. 'Capacity' is generally taken to mean generating plant such as gas-fired power stations, but the Government plans to include transitional arrangements for Demand Side Management (DSM) and storage, which we welcome. However, we fear the scheme as currently conceived fails to recognise the real role and value of storage, and will never deliver as much storage capacity as the network needs.

Some measure such as the Capacity Mechanism certainly looks necessary, since around a fifth of the UK's firm generating capacity will close over the next decade and Ofgem has warned of extremely thin capacity margins by around 2015. The Government will decide whether or not the scheme should go ahead in 2014, but details of how it would operate remain sketchy even now; DECC plans to announce the arrangements for DSM and storage in May 2013,

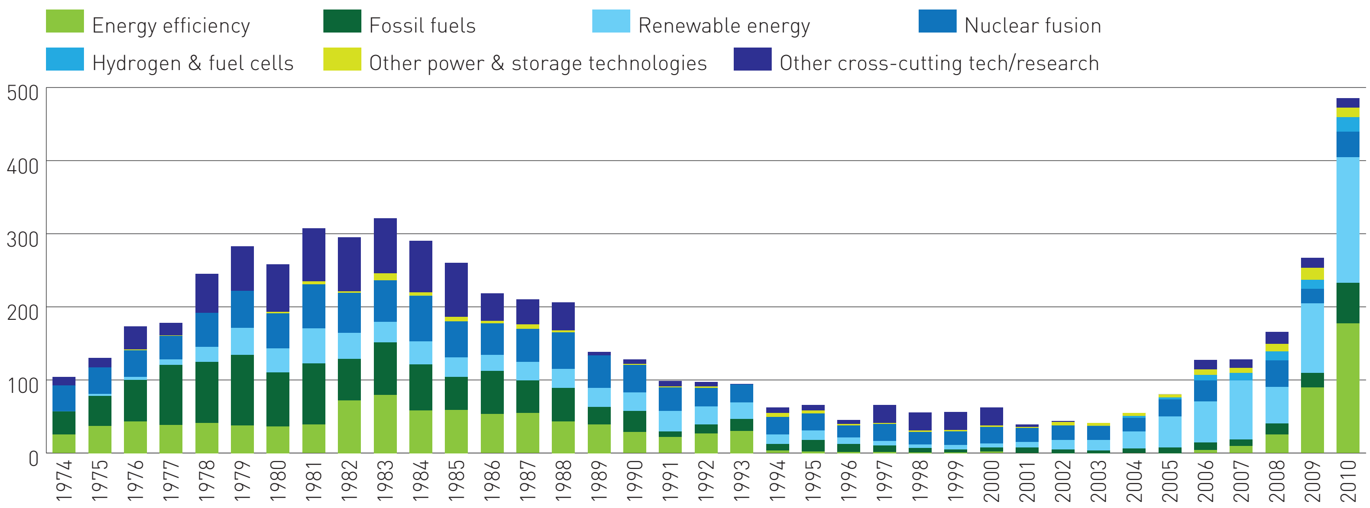


**Figure 3.1:** UK RD&D spending on energy since 1974. Source: DECC[5]

| FINANCIAL YEAR | 2006/7 | 2007/8 | 2008/9 | 2009/10 | 2010/11 | TOTAL | |
|---|---|---|---|---|---|---|---|
| ENERGY EFFICIENCY | 3.90 | 9.42 | 25.28 | 89.50 | 177.06 | 305.16 | 24% |
| FOSSIL FUELS | 10.55 | 8.94 | 15.03 | 20.31 | 56.06 | 110.89 | 9% |
| RENEWABLE ENERGY | 55.81 | 81.13 | 50.09 | 94.61 | 171.34 | 452.98 | 36% |
| NUCLEAR FUSION | 28.93 | 0.00 | 36.46 | 19.90 | 34.91 | 120.19 | 10% |
| HYDROGEN & FUEL CELLS | 8.08 | 10.03 | 11.77 | 12.82 | 20.26 | 62.95 | 5% |
| OTHER POWER & STORAGE FACILITIES | 7.37 | 6.68 | 10.27 | 15.74 | 12.87 | 52.93 | 4% |
| OTHER CROSS-CUTTING TECH/RESEARCH | 12.44 | 12.23 | 16.47 | 13.70 | 12.93 | 67.76 | 5% |
| NUCLEAR FISSION | 3.17 | 29.20 | 4.54 | 16.90 | 36.70 | 90.51 | 7% |
| **Total (£m)** | **130.23** | **157.63** | **169.90** | **283.48** | **522.13** | **1,263.37** | **100%** |

Table 3.1: UK spending on energy RD&D since 2006 in £m (2011 prices). Source: DECC[6]

5 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/85832/energy_innovation_spend_data.xls
6 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/85832/energy_innovation_spend_data.xls

and for the entire scheme in October 2013. However, it already seems clear that the Capacity Mechanism will not adequately support storage, precisely because it is designed to create new capacity – the ability to generate power or reduce demand – and will not reward the ability to absorb and store energy, with all the benefits described in chapters 3 and 10 of the Full Report. As a result it seems likely – in the absence of specific measures to prevent it – that gas generation will be the overwhelming beneficiary of the Capacity Mechanism.

Since the aim of the scheme is to ensure energy security at least cost, and since gas generation is a mature, reliable technology with low capital costs, this may seem a sensible outcome. However, this fails to recognise several fundamental points:

1. Gas addresses only one side of the balancing equation, whereas storage addresses both. Gas capacity can generate when wind output is low, but cannot absorb excess wind power when demand is low and deliver it back to the grid at peak times. Gas back-up capacity increases greenhouse gas emissions while storage reduces them.
2. While storage technologies cannot currently compete with unabated gas on capital cost, projected costs for grid-scale LAES are comparable to gas (chapter 3 of the Full Report), and these projections can be treated with some confidence since they are based on mature components.
3. Any large scale deployment of gas is probably incompatible with the UK's statutory emissions reductions targets, or alternatively could expose customers to funding expensive stranded assets.
4. Major studies for DECC and the Carbon Trust by researchers at Imperial College have shown potential financial benefits from storage of £10 billion per year by 2050. Without support now these benefits may never be realised.[7]
5. Without support now, manufacturers, researchers and developers in the UK will be denied opportunities to demonstrate their technology in the home market and drive costs down through innovation, meaning technology, manufacturing and jobs will be lost overseas.
6. Without support now, the UK could lose a head start on a global electricity storage market estimated at $20–25 billion annually by 2020.[8]

In light of these factors and the likely shortcomings of the Capacity Mechanism, there is a strong case for supporting storage through a bespoke mechanism that specifically rewards the ability to absorb 'wrong time' energy and deliver it back at times of high demand. The Electricity Storage Network (ESN) has proposed a mechanism based on the Non Fossil Fuels Obligation (NFFO), which supported the development of renewables in the early days of privatisation. Instead of doling out grants, this model involves a Dutch auction among developers to provide a desired amount of capacity. In other words, the Government would decide each year how much new storage capacity is needed, and developers would compete in a tender to provide it at the lowest cost. Suppliers would be paid the price they bid – not the clearing price – for the duration of a contract long enough to enable the project to be financed. The price would not need to cover the entire cost of the storage capacity, but only the difference between a project's revenue from other sources and that required to make it viable. The tenders could be subdivided according to characteristics such as response time and duration, to ensure that the full range of storage services is supported. The advantage of this general approach is that 1) it is technology agnostic, 2) competition drives innovation and squeezes out costs, and 3) unlike grant funding there is no doubt the capacity will get built.

ESN proposes a minimum target of 2GW by 2020, which equates to 1 new Dinorwig pumped hydro station, and less than 10% of the projected increase in renewable capacity by that date. 2GW is also the scenario that provides the highest value from storage in 2020 as calculated by Strbac and colleagues.[9] The amount tendered each year should be consistent with achievable growth targets, starting at say 50MW in 2014, 400MW in 2018 and 750MW in 2020.

A market support mechanism is vital to nurture the development of grid storage technologies such as liquid air, but to flourish such technologies also need the repeal or revision of a number of specific regulations that hamper their development. For example, DNOs are forbidden from owning generating plant, and the definition of 'generating plant' currently includes storage devices. As a result some of the electricity market players that could benefit most from innovative storage concepts are prevented from deploying them. Storage devices must also pay grid access charges both while absorbing power and while generating, which raises their costs disproportionately and fails to reflect their role in the grid.

**A list of our policy recommendations for grid storage can be found on page 22.**

7 Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future, Report for the Carbon Trust, Strbac et al June 2012

8 Energy Storage on the Grid, Pike Research, July 2011

9 Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future, Report for the Carbon Trust, Strbac et al June 2012

## TRANSPORT

It has long been recognised that high levels of decarbonisation will be harder to achieve in transport than other sectors such as electricity generation, because of the need for low capital cost, energy dense fuel and convenient refueling. Recent progress on vehicle efficiency has been good, the result of many small incremental improvements, especially in the light duty sector. However, it could be argued that the 'low-hanging fruit' of this approach will be exhausted by around 2020.

At the same time, the drawbacks of some existing technology approaches to cutting transport emissions have become increasingly clear. The shortcomings of biofuels have been highlighted by recent work on the impact on Indirect Land Use Change (ILUC), and this has led to the scaling back of policy targets in both the EU and the US, as discussed in chapter 1 of the Full Report. In hydrogen, while the routes to meeting cost reduction targets for FCVs are becoming clearer, their commercialisation remains challenging with issues such as hydrogen purity and storage presenting significant hurdles. EVs do not yet offer the range or refueling speed of conventional vehicles, and suffer a significant cost premium.

It appears that the existing approach to preparing for a total transformation to near-zero emission road transport is not delivering quickly enough, and does not adequately address the needs of the heavy duty sector. Lorries account for 60% of global diesel demand, and the IEA has forecast that 40% of the growth in global oil demand to 2035 will come from road freight alone.[10] Since batteries cannot currently provide the energy density required for HGVs, alternative approaches are required to raise their efficiency and cut emissions.

We have shown in this paper that liquid air could help achieve major fuel and emissions savings through a variety of approaches – especially in heavy vehicles and refrigeration (chapters 4 and 10 of the Full Report). These approaches are complementary to other medium-term measures such as use of natural gas as a haulage fuel. We have also shown how liquid air addresses several research priorities established by the vehicle manufacturing industry's New Automotive Innovation and Growth Team (NAIGT) roadmap (Table 3.2 on page 28), in particular under the headings of propulsion, energy storage and efficiency (chapter 8 of the Full Report).

The NAIGT roadmap and research priorities are an extremely useful framework, but any such vision is inevitably an established view; disruptive technologies, by definition, do not appear on the technology roadmap until they are accepted into mainstream thinking. The risk here is that policy becomes focused on an accepted view – an approach which can have the advantage of focus in the short term, but creates the risk of missing disruptive opportunities. With existing technology approaches proving challenging to realise, it may be time may for an approach that takes a fresh look at disruptors.

The UK is well suited to disruptive innovation in terms of its culture and skills, and also enjoys successful innovation support schemes such as the Technology Strategy Board's collaborative R&D programme. This fund has incubated the UK's successful and world-leading flywheel-hybrid capability, which is clearly a disruptive challenge to the battery-hybrid, alongside a spectrum of more evolutionary but important research. The programme has run specific grant-funding calls for disruptive technology from time to time.

Nevertheless there are major challenges for the newly-arrived disruptor. Partnership with a larger manufacturer or supplier is often expected, and can be hard to secure without proof of concept and a degree of general acceptance. New technologies such as liquid air must be explained from first principles in every grant application whereas batteries and fuel cells benefit from a broad hinterland of assumed knowledge.

Policy support is often quite prescriptive when technologies are deployed too; once such support involves infrastructure, this is hard to avoid. The Office of Low Emission Vehicles (OLEV), a cross-departmental body comprising BIS, DfT and DECC, oversees programmes worth £400 million, most of which are directed to electric vehicles – for instance, the 'Plugged In' grants family. There are however notable exceptions such as the 'Green Bus' fund, which is technology agnostic.

**A list of our policy recommendations for transport technology can be found on page 22.**

10 World Energy Outlook 2012, IEA, http://www.worldenergyoutlook.org/publications/weo-2012/#d.en.26099

Common Research Agenda summary

| SHORT TERM<br>5–10 YEARS FROM PRODUCTION | MEDIUM TERM<br>7–15 YEARS FROM PRODUCTION | LONG TERM<br>10–20 YEARS FROM PRODUCTION |
|---|---|---|
| INDUSTRY | | UNIVERSITIES |
| PROPULSION | | |
| • IC engine optimisation<br>• Boost systems for downsizing<br>• Flexible valve/actuation for engines/transmissions | • Higher efficiency IC engines<br>• Capacitive boost systems<br>• AI electric actuation systems<br>• Optimised range extender engine<br>• Lower cost e-motor<br>• Heat energy recovery (e.g E-turbine) | • Super high efficiency motors (superconducting)<br>• New IC engines with 70%+ thermal efficiency<br>• Advanced heat energy recovery (e.g. thermoelectric)<br>• Motor/Fuel Cell materials |
| ENERGY STORAGE | | |
| • Improved quality/durability 200+Wh/kg & $800/kW.h cost battery systems<br>• Low cost power electronics | • Next gen batteries 300+ Wh/kg & $500/kW.h cost<br>• Flexible power elec. modules<br>• Other forms of energy recovery (mechanical/chemical etc.) | • 3rd gen batteries 400+ Wh/kg & $200/kW.h cost<br>• New low cost solid state power conversion systems<br>• Hydrogen storage technology |
| VEHICLE EFFICIENCY | | |
| • Lightweight structures and interiors<br>• Low rolling resistance tyres/ brakes | • New vehicle classes and configurations<br>• Combination of function to reduce weight/cost<br>• Minimised weight/losses | • Flexible re-configurable multi-utility vehicle concepts<br>• 50% weight reduction from 2008<br>• Advanced aerodynamics concepts |
| SYSTEM CONTROL | | |
| • Information enabled control (topology, V2V, V2I, traffic etc)<br>• Optimised vehicle energy management<br>• Intelligent thermal management | • Advanced information enabled control<br>• Intelligent P/T and HVAC management | • Autonomous P/T and vehicle control integrated with active safety |
| ENERGY & FUEL SUPPLY | | |
| • Optimised 1st gen biofuels processes<br>• New 2nd gen biofuel processes | • Intellgent energy/re-fuelling infrastructure (e.g. fast charge)<br>• Industrial scale demonstration of new 2nd gen biofuel processes | • 3rd gen biofuel processes<br>• 2nd gen industrial scale biofuel production infrastructure |
| PROCESSES & TOOLS | | |
| • Process & delivery tool development and connectivity | • Auto-optimisation methods using virtual systems | • Artificial intelligence to deliver complex multi-criteria system optimisation |

**Table 3.2:** NAIGT common research agenda summary. Source: NAIGT

# GLOSSARY

| | |
|---|---|
| ASU | Air Separation Unit |
| BIS | Department for Business, Innovation & Skills |
| CCS | Carbon Capture and Storage |
| CEGB | Central Electricity Generating Board |
| CFD | Contracts for Difference |
| $CO_2$ | Carbon Dioxide |
| DE | Dearman Engine |
| DECC | Department of Energy and Climate Change |
| DfT | Department for Transport |
| DNO | Distribution Network Operator |
| DSM | Demand Side Management |
| ESN | Electricity Storage Network |
| ETI | Energy Technologies Institute |
| EV | Electric Vehicle |
| FCV | Fuel Cell Vehicle |
| FiT | Feed-in Tariffs |
| GW | Gigawatt |
| ICE | Internal Combustion Engine |
| IEA | International Energy Agency |
| ILUC | Indirect Land Use Change |
| LAEN | Liquid Air Energy Network |
| LAES | Liquid Air Energy Storage |
| LNG | Liquefied Natural Gas |
| LPG | Liquefied Petroleum Gas |
| Mt | Million tonnes |
| $MtCO_2$ | Million tonnes of $CO_2$ |
| MW | Megawatt |
| MWh | Megawatt hour |
| NAIGT | New Automotive Innovation and Growth Team |
| NFFO | Non Fossil Fuels Obligation |
| OCGT | Open Cycle Gas Turbine |
| OLEV | Office for Low Emission Vehicles |
| PEM | Proton Exchange Membrane |
| PEMFC | Proton Exchange Membrane Fuel Cell |
| PTFE | Polytetrafluoroethylene |
| PV | Photovoltaics |
| RD&D | Research, development and demonstration |
| RHI | Renewable Heat Incentive |
| ROC | Renewable Obligation Certificates |
| TSB | Technology Strategy Board |
| TWh | Terawatt hour |
| ULCV | Ultra Low Carbon Vehicle Demonstration |
| ZEV | Zero Emissions Vehicle |

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## ACKNOWLEDGEMENTS

CLCF wishes to thank the many experts who generously contributed their time and expertise to the drafting of this report – and not only those listed at the front of this document. Many others also gave valuable advice or contributed through a series of round table discussions held at Institution of Mechanical Engineers, Arup and Messer during March and April 2013. In particular we would like to thank Neil Rowley of National Grid, Graeme Bathurst of TNEI and Mike Wilks of Pöyry for reviewing early drafts; Dr. Jonathan Radcliffe and Professor Richard Williams for invaluable insights; Sona Abaryan and Nicola Alexander of Dearman Engine Company for professional support; Ashleigh Dunn of CLCF; David Strahan for editing the report; and Toby Peters, founder of the Liquid Air Energy Network, for originating and overseeing the project. We are of course indebted to the Dearman Engine Company, Highview Power Storage, Arup and Messer Group for making it possible.



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CLCF is grateful for funding and support from ANA Peru, Accenture, Beijing Institute of Technology, Birmingham City Council, Brazilian Embassy to London, British Deputy High Commission of India, British Embassy of Beijing, British Embassy of Brasilia, British Embassy to Colombia, British Embassy to Peru, British Embassy to Tokyo, Centre for Sustainable Development Studies Columbia (CEID), China Beijing Environmental Exchange (CBEEx), Committee on Climate Change of the UK (CCC), Department of Business, Innovation and Skills (UK), Department of Energy and Climate Change UK (DECC), Energy Intensive Users Group, ICLEI- Local Governments for Sustainability (Tokyo), Indian Chamber of Commerce, Inter-American Development Bank (IADB), International Institute for Sustainable Development (IISD), Jadavpur University (India), Leeds City Council, Ministry of Environment, Peru (MINAM), National Physical Laboratory, OECD, Regional Development Agency, Royal Academy of Engineering, Trades Union Congress, Tecnológico de Monterrey (Mexico), Transport Research Laboratory, University College London, Worldwide Universities Network (WUN), University of Sheffield, University of Hull, University of Leeds, University of York, University of Birmingham

ISBN 978-0-9575872-1-2

9 780957 587212

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