

LIQUID AIR ON THE HIGHWAY | A SHORT GUIDE

The environmental and business case for liquid air commercial vehicles in the UK

The Dearman Engine Company

June 2014

LIQUID AIR ON THE HIGHWAY

With a liquid air transport refrigeration application going into on-vehicle demonstration this summer, Liquid Air on the Highway is a new report from that explores the economic and environmental benefits of introducing liquid air engines on commercial vehicles in Britain.

We find a strong financial, air-quality, energy security and carbon reduction case for developing liquid air-equipped commercial vehicles. A projected British fleet that grows to 36,000 vehicles by 2025 could save more than 1 billion litres of diesel, 1.4 million tonnes of CO2e (well-to-wheel) and £113 million net of investment costs. Promising first applications include liquid air refrigerated trucks and trailers and diesel-liquid air 'heat hybrid' buses and trucks.

Liquid air vehicles could achieve significant reductions in emissions of fatal air pollutants such as nitrogen oxides (NOx) and particulate matter (PM). A projected fleet of just 13,000 liquid air refrigerated trailers would reduce NOx emissions by the same amount as taking 80,000 Euro 6 trucks or 1.2 million Euro 6 diesel cars off the road. It would be the PM equivalent of removing 367,000 such trucks from service – more than three times the entire UK articulated truck fleet today – or 2.2 million Euro 6 diesel cars.

The development of liquid air vehicles would produce substantial economic, industrial and employment benefits to UK plc. On cautious assumptions, by 2025 Britain could be making 51,000 liquid air engines per year, generating net revenues of £276 million and almost 1,100 jobs. On more ambitious assumptions, it would manufacture 173,000, generating net revenues of £713 million and more than 2,100 jobs.

Infrastructure is not a barrier to entry. The roll-out of liquid air vehicles could be fuelled entirely from spare liquid nitrogen production capacity until at least 2019. By 2025, new transport demand for liquid nitrogen or air could more than double the size of the market.

The Liquid Air on the Highway report is published by the Liquid Air Energy Network, Centre for Low Carbon Futures and University of Birmingham.

"Transport solutions for lower carbon and better air quality tend to come at a cost – extra capital – which may take many years to pay back. The beauty of liquid air is that the devices using it, like our Dearman Engine, are not so costly. In many cases the operator can get a payback in a matter of a few months – a few years at most."

Nick Owen |
CTO, Dearman Engine Company

Centre for Low Carbon Futures 2050

Liquid Air Energy Network

UNIVERSITY OF BIRMINGHAM

WHAT IS LIQUID AIR?

Liquid air is about storing cold and power produced by renewables to use in a vehicle. This cuts diesel consumption, emissions and cost. The only exhaust is cold air.

Key to renewables replacing fossil fuels in transport is how to 'pack' and store the energy that is produced so that we can use it when it is needed in transport applications e.g. batteries or hydrogen.

Liquefying air is the cornerstone of the industrial gas industry (liquid nitrogen, oxygen, etc) – but it has only recently been seen as a pioneering solution to the problem of energy storage; capturing 'wrong time' or surplus renewable energy to use on demand in grid or transport applications.

Air turns into a liquid when cooled to around -196C using standard industrial equipment. This process can be driven by renewable or wrong-time/off-peak energy. 710 litres of ambient air becomes about 1 litre of liquid air, which can be stored in an unpressurised, insulated vessel.



710 litres of air | 1litre liquid air stored at atmospheric pressure | 710 litres of air + lots of cold

When ambient or low grade waste heat is reintroduced to liquid air it boils and turns back into a gas, expanding 710 times in volume. This can be used to drive an engine. It also exhausts lots of cold, making it highly relevant for processes which require power and cooling.

Liquid air is now recognised as a potentially powerful new energy vector, and has received some £20 million in government grants.
These grants include:

- £9 million support to develop Liquid Air Energy Storage for storing grid electricity;
- £6 million for the new Centre for Cryogenic Energy Storage at Birmingham University; and
- £5 million to develop liquid air vehicle engines.

Liquid air has also been recognised in the technology roadmaps of both the Automotive Council and the European Road Transport Research Advisory Council (ERTRAC).



"Utilisation of liquid nitrogen for both refrigeration and power is an exciting concept, especially for transport applications. The technology can provide not only potential savings in fuel consumption and emissions, but also better cold chain temperature control and stability. At Air Products we are very pleased to be in collaboration with Dearman on these projects, it's an exciting development for new liquid nitrogen applications technology."

Jon Trembley |
COE Lead Cryogenic Applications,
Air Products

LIQUID NITROGEN SUPPLY

Liquid air is not yet produced commercially, but liquid nitrogen, which can be used in the same way, is produced throughout the industrialised world.

Liquid air and liquid nitrogen (LIN) can both serve as a cryogenic energy vector or transport 'fuel'. They are not identical but do share many properties, since nitrogen makes up four fifths of air. The temperatures at which air and nitrogen liquefy are similar (-196C for nitrogen, -194C for air), and both expand about 700-fold when they re-gasify.

Industrial gas companies have large amounts of spare nitrogen production capacity for the simple reason there is far more nitrogen than oxygen in the atmosphere but proportionately less commercial demand. This surplus could be used in place of liquid air to support early deployment.

Liquid nitrogen is produced at plants known as Air Separation Units (ASUs) and routinely delivered by road tanker to industrial customers.

- As the map shows, all of Britain's major cities are within delivery distance of one of the ten ASUs with spare liquid nitrogen capacity.
- In total, Britain's spare capacity would be enough to fuel a third of the urban bus fleet as liquid air 'heat hybrids'. It is also enough to support the projected deployment of all types of liquid air vehicles until at least 2019.
- Liquid air would be cheaper to produce than liquid nitrogen, because there is no need to separate the nitrogen and oxygen, meaning liquefaction requires less equipment and consumes around a fifth less energy.
- Our modelling shows that on the basis of estimated average off-peak power prices in 2013, liquid air could be supplied for 5p/kg excluding VAT at distances up to 100 miles. At this level most of the liquid air vehicles we modelled deliver substantial cost savings and short payback times.



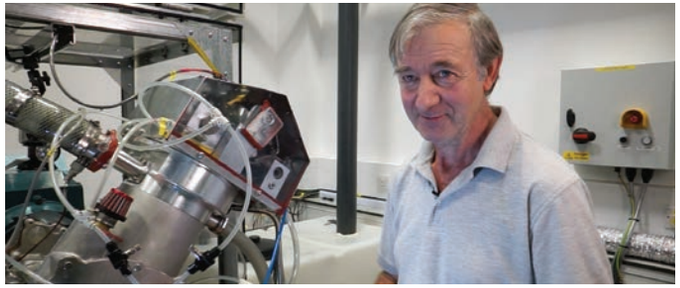
Map of GB industrial gas production sites. Please note, the distribution radius shown for each production site of 60 miles as-the-crow-flies is an indicative approximation of the 100-miles-by-road used in our analysis.

THE DEARMAN LIQUID AIR ENGINE – THE BASICS

There are different liquid air vehicle engines now in development. The closest to market is the Dearman engine – a novel piston engine powered by the phase-change expansion of liquid air or liquid nitrogen. The only exhaust is cold air.

The Dearman engine was invented by Peter Dearman, a classic British 'garden shed' inventor. Peter has already demonstrated his engine on a modified car, and it is now being developed by the Dearman Engine Company.

The novelty lies in the use of a heat exchange fluid (HEF – water or water and glycol mix) that promotes extremely rapid rates of heat transfer inside the engine, allowing a small, single-stage Dearman engine to achieve levels of thermal efficiency that would otherwise require more costly, multi-stage expansion with re-heating. In this way the Dearman engine also reduces the size of bulky and inefficient external heat exchanger that handicapped earlier cryogenic engine designs.



Peter Dearman, inventor of the Dearman engine

The Dearman liquid air engine will be inexpensive to build. It will be low maintenance and have low environmental impact.

Running on a cryogenic fluid gives the Dearman engine two major advantages.

- First, the evaporation of liquid air or nitrogen gives off large amounts of valuable cold, which can provide 'free' refrigeration or air conditioning.

- Second, the low boiling point (-196C) means that low grade waste heat of around 100C, harvested from diesel engines or in future hydrogen fuel cells, can be used to boost the cryogen's expansion to produce additional power at practical conversion efficiencies approaching 50%. These features are the basis of the first two applications of the Dearman engine.

The Dearman engine may also be developed as a 'prime mover' or main propulsion engine for smaller vehicles such as forklift trucks, 3-wheeler taxis ('tuk tuks') for developing countries, and eventually city cars.

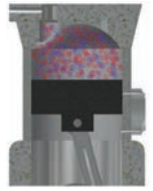
DEARMAN ENGINE STROKE DIAGRAM



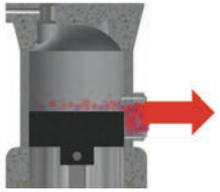
1. Return Stroke
Warm heat exchange fluid (HEF) enters the cylinder.



2. Top Dead Centre
Liquid air or nitrogen enters the cylinder where it mixes with the HEF, causing rapid temperature rise and expansion.



3. Power Stroke
The expanding gas pushes the piston down. Direct contact heat transfer continues, allowing a near constant temperature expansion.



4. Bottom Dead Centre
The exhaust mixture leaves the cylinder. The gas is returned to the atmosphere and the HEF is re-heated and re-used.

DEARMAN ENGINE REFRIGERATION

Vehicle refrigeration today is overwhelmingly powered by diesel, often using a highly polluting secondary engine to drive the Transport Refrigeration Unit.

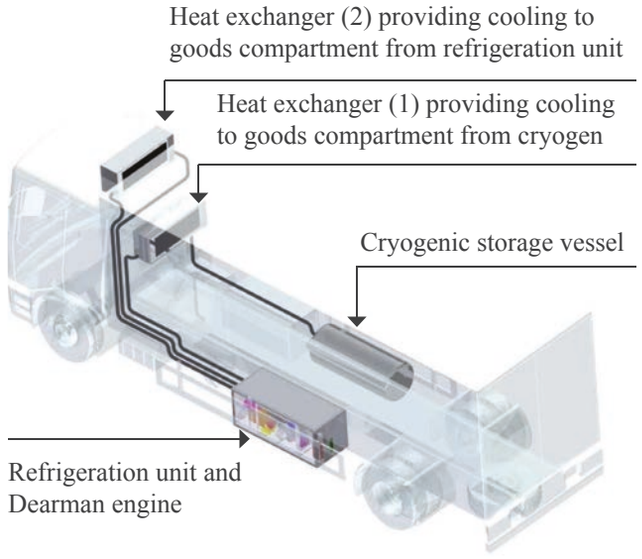
Diesel powered transport refrigeration units (TRUs) are inefficient and highly polluting. Refrigeration alone can consume as much as 20% of a truck's diesel, and a TRU emits up to six times as much NOx and 29 times as much PM as a modern Euro 6 truck propulsion engine.

UK case	Vs Diesel	Vs Evap'
CapEx	+£270	+£2,600
Yearly OpEx	-£1,200	-£3,100
Payback Time	~2 months	<1 year
10yr TCO*	-12k	-£28k
CO2now/2030+	-23%/-92%	-43%/-46%

A Dearman TRU for a 40' refrigerated trailer would produce even greater 'well-to-wheel' CO2 savings than a conventional nitrogen evaporation system, and would repay its investment within three months.

(*Total cost of ownership)

Some operators have begun to test vehicle refrigeration based on the simple evaporation of liquid nitrogen, which eliminates NOx and PM emissions, but does not extract any power from the expansion process. The Dearman refrigeration unit is a significant advance because produces both cooling and shaft power from a single unit of 'fuel'. It goes into on-vehicle demonstration this summer at MIRA (Motor Industry Research Association).



First the cryogen is vaporised in a heat exchanger in the refrigeration compartment, so cooling it down; then the high pressure gas is used to drive the Dearman engine, whose shaft power can be used to drive a conventional refrigeration compressor or for auxiliary power. This means it is extremely efficient and cost effective.

"Hubbard, after many years of refining design, has realised that near term future requirements cannot be achieved with existing available components and technologies. Hubbard has enthusiastically engaged with Dearman to jointly develop a transport refrigeration system that will be the paradigm shift to economic clean cold on the highway."

Pat Maughan |
MD, Hubbard Products Ltd

DEARMAN ENGINE HEAT HYBRID

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

An internal combustion engine loses roughly a third of the energy in its fuel through the radiator as low grade waste heat, which conventional technologies find difficult to harvest.

In a Dearman heat hybrid system, heat from the ICE cooling loop is used to 'boil' the liquid air or nitrogen and to warm the heat exchange fluid (HEF). The power produced by the Dearman engine is fed into the main gearbox, allowing the ICE to be downsized and operate more efficiently.

- A heat hybrid would be cheap to build and could reduce diesel consumption by up to 25%.
- Modelling suggests heat hybrid delivery trucks would repay their investment in around four years, while heat hybrid buses would pay for themselves in under three.
- Heat hybrid buses would cost significantly less than an electric hybrid to build; the government could commission eleven times more for the same level of subsidy.

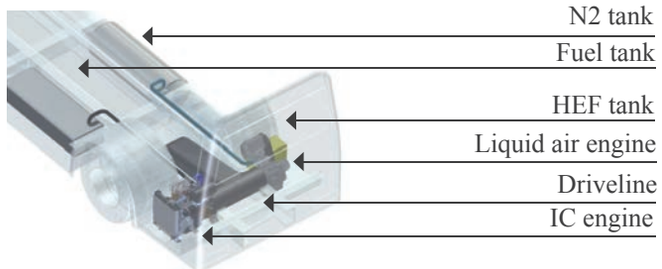
A consortium including the Dearman Engine Company, Air Products, MIRA, Cenex, TRL, The Manufacturing Technology Centre and Productiv has been awarded nearly £2 million by the Technology Strategy Board to demonstrate a heat hybrid system for urban commercial vehicles. An industry advisory board for this programme includes Alexander Dennis (the UK's leading bus manufacturer), John Lewis Partnership, Tata Motors, Leeds City Council and Yorkshire Passenger Transport Executive (Metro).

UK example	Bus no a/c	With a/c
CapEx	+£6,000	+£4,000
Yearly OpEx Saving	£1,200	£2,800
Payback Time	<3 years	<1.5 years
10yr TCO Saving	15k	£24k

If the vehicle also needs air conditioning, the case for the Dearman engine strengthens further as the engine extracts both power and cold from the same unit of liquid air.

"Waste heat recovery is central to low carbon transport technology roadmaps. Liquid air technologies provide a means of recovering the low grade waste heat in the radiator system and converting it into additional power – so cutting fuel consumption and emissions beyond most schemes which focus on the exhaust."

Professor Andrew Atkins | Chief Engineer (Technology), Ricardo



BUSINESS CASE

The business case for introducing liquid air equipped vehicles in Britain is compelling. The most promising early applications include refrigerated trucks and trailers, urban buses and delivery trucks.

These could produce major reductions in diesel consumption, local air pollution, well-to-wheel carbon emissions, noise and cost.

Unlike most green technologies, liquid air vehicles would need no subsidy; the strongest applications would repay their investment within months, and the rest in a range of two to four years.

For example, projected sales of some 670 heat hybrid buses in 2025 would require incremental investment (the additional cost compared to a normal diesel bus) of around £4 million, but would produce annual fuel savings of almost £15 million; a net financial benefit of almost £11 million.

If all applications grow as projected the entire liquid air fleet would grow to 36,000 vehicles by 2025, and would have saved

- more than 1 billion litres of diesel,
- 1.4 million tonnes of CO2e (well-to-wheel), and
- £113 million net of investment costs.

Annual net savings in 2025 would reach £37 million and 404,000tCO2e. The cumulative net financial benefit of a fleet that grows from zero to 4,100 buses during 2015-2025 would be £31 million, and each bus would repay its incremental investment in less than two years.

- If supermarkets adopted liquid air delivery trucks and refrigerated trailers at the same rate as the market as a whole, by 2025 they would make cumulative net savings of £19 million and more than 250,000tCO2e.

- If Leeds were to convert its bus and bin truck fleets to diesel-liquid air heat hybrids, by 2025 it would make cumulative net savings of £14.5 million and 66,000tCO2e.

"Our lifestyles demand cooling, but cold is a very energy intensive commodity to produce. Liquid air and the Dearman engine are about 'producing' and storing cold and power from renewables to use on a vehicle to reduce diesel consumption.

Liquid air is not a silver bullet, but the opportunity exists to deliver a new, sustainable approach – zero-emission power and cooling. Given the energy cost to provide cooling, this can deliver significant cost and emission savings in applications where cold is valuable."

Toby Peters |
CEO, Dearman Engine Company

AIR QUALITY

Liquid air vehicles could produce major reductions in local air pollution, particularly emissions of NOx and PM from refrigerated vehicles.

Vehicle refrigeration today is overwhelmingly powered by diesel, often using a secondary engine and compressor called a Transport Refrigeration Unit. TRUs are currently unregulated in the EU and are inefficient and highly polluting.

An analysis by the consultancy E4tech shows that a TRU emits six times as much NOx and 29 times as much PM as a Euro 6 truck engine annually. Compared with a Euro 6 diesel passenger car, the TRU emits almost 93 times as much NOx and 165 times as much PM.

	NOx	PM
TRU v Euro 6 diesel car	92.6	164.6
TRU v Euro 6 diesel truck engine	6.2	28.6

Annual emissions multiples – total yearly emissions from a 40ft auxiliary Transport Refrigeration Unit vs. other applications.

Source: E4tech

Liquid air transport refrigeration would eliminate these emissions.

- A projected fleet of 13,000 liquid air trailers in 2025 would save 1,800 tonnes of NOx and 180 tonnes of PM per year.
- This would be the NOx equivalent of removing either 80,000 Euro 6 trucks or 1.2 million Euro 6 diesel cars from the road.
- It would be the PM equivalent of retiring 367,000 Euro 6 trucks – more than three times the entire UK articulated truck fleet today – or 2.2 million Euro 6 diesel cars.

The introduction of national regulation of TRU emissions in the UK would be a timely and effective way to make large and early reductions in NOx and PM. The advent of liquid air transport refrigeration means the emissions limit could quickly be reduced to zero at no cost to the economy.

"Like most most other large cities in the UK, Leeds suffers the effects of poor air quality, due mainly to road traffic emissions. This has resulted in health based limits being breached, the imposition of Air Quality Management Areas, and the possibility of incurring EU Infraction Fines."

Dave Cherry | Environmental Assessment Manager, Leeds City Council

UK PLC

The development of liquid air vehicles in Britain would boost manufacturing, growth and jobs.

If liquid air vehicles develop as projected in Britain, it is likely they would also be sold abroad. Many countries would no doubt produce the vehicles domestically under licence, but since Britain is already a major engine exporter it is fair to assume a portion of global liquid air engine sales would be made in Britain. To calculate the potential benefits to UK plc, E4tech assessed two scenarios – cautious and ambitious - using a slightly modified version of the Department of Energy and Climate Change's Technology Innovation Needs Assessment (TINA) methodology.

Benefits in 2025	Engines made in UK (1000s)	UK Gross Revenues (£m)	UK net GVA (£m)	New jobs by 2025
UK sales to UK	5	£175	£18	675
UK sales to EU	46	£180	£29	410
UK sales to rest of world (RoW)	122	£474	£81	1,034
Total				
Conservative: UK + EU	51	£355	£47	1,085
Ambitious: UK + EU + RoW	173	£829	£129	2,119

The development and subsequent adoption of liquid air vehicles in the UK and abroad could deliver considerable growth to the UK's manufacturing industry, as well as creating jobs.

- **Cautious:** if Britain were to manufacture all liquid air vehicle systems sold in Britain and the EU only, the UK would **manufacture 51,000 liquid air engines in 2025**, bringing net revenues of £276 million and net Gross Value Added – a measure of economic value, equivalent to GDP after taxes and subsidies have been discounted – of £47 million, and **create or maintain almost 1,100 jobs.**

  Cumulative production to 2025 would be 333,000 engines with revenues of over £2 billion.

- **Ambitious:** if Britain were to capture all sales not only in the UK and the EU, but also North America, Russia, and Australia, it would **manufacture 173,000 engines** in 2025, bringing **net revenues of £713 million** and net GVA of £129 million, and **create or maintain over 2,100 jobs.**

  Cumulative production to 2025 would total 930,000 engines with revenues of over £4.2 billion.

For perspective, gross revenues from the manufacture of liquid air engines in 2025 of £860 million equates to almost 1.5% of the current turnover of the UK motor industry, while 2,100 jobs broadly matches the job creation forecast of the fuel cell and hydrogen industry.

Manufacturing liquid air vehicles in Britain would also play to the country's traditional strength in cryogenics, much of it concentrated in Oxfordshire, and represented by the British Cryogenics Cluster, whose members have a combined turnover of some £2 billion and employ 20,000 people. Most are SMEs likely to take on both graduates and apprentices.

LIQUID AIR ECONOMY

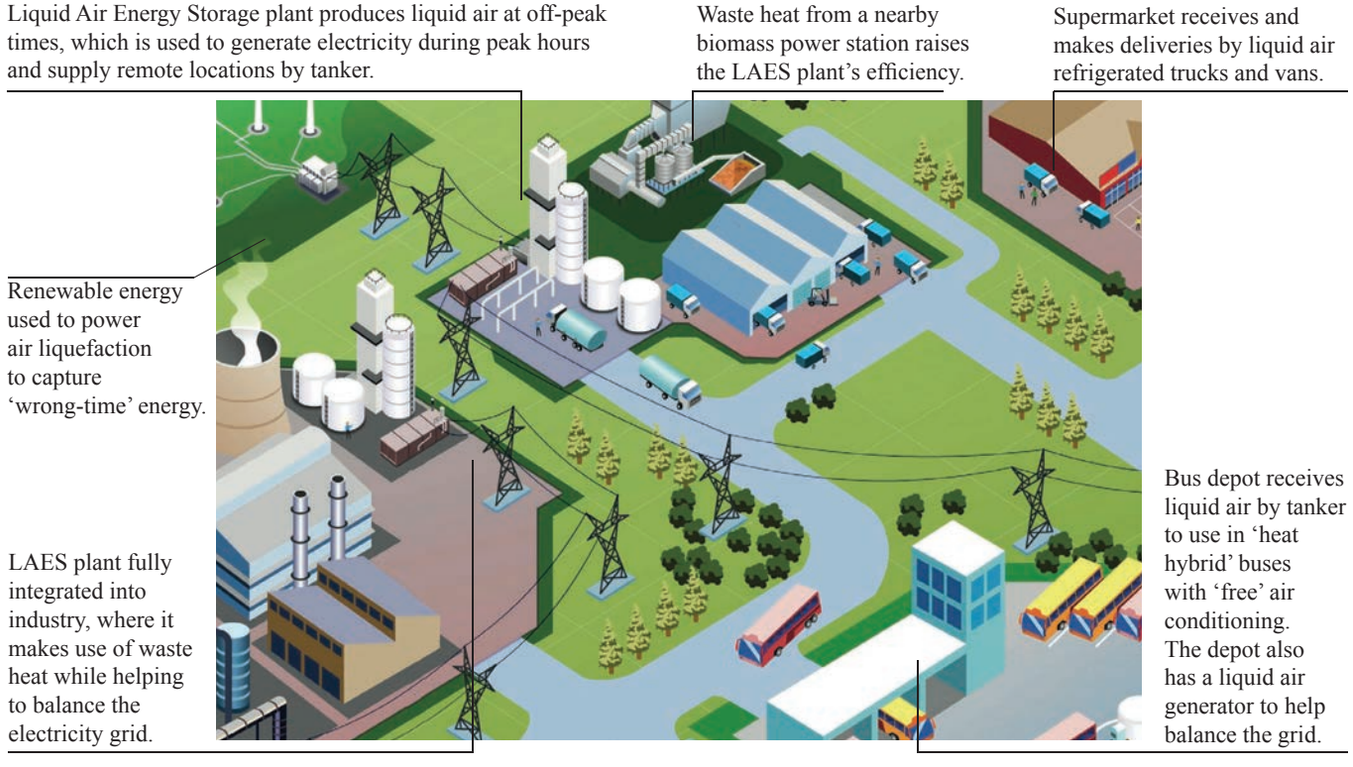
Our lifestyles demand cooling – air conditioning, industrial cooling, data cooling as well as a ‘cold chain’ of refrigerated vehicles from farm right through to single-drop home delivery.

As we plan our future energy mix, integrating renewables and energy storage, we need to manage not just power and heat demand, but power, cooling and heat. Unlike a battery which stores only ‘power’, liquid air stores power and ‘free’ cooling. In combining renewable energy with liquid air energy storage, the opportunity exists to instigate a new cleantech, zero-emission and sustainable approach to power and cooling – one which has significant economic gains over power only solutions.

Energy from waste cold: Along with integrating renewables to meet cooling demands, vast amounts of cold from processes such as LNG re-gasification go to waste. LNG is essentially gas packaged in cold (a significant energy cost), but we then discard the cold when we ‘unpack’ the gas. However, liquid air liquefaction plants can be integrated with LNG regasification plants to capture and harness the waste cold to use in transport or the built environment.

The cold given off by the National Grid Isle of Grain LNG terminal over the course of a year would be enough to fuel London’s entire 7,600 strong bus fleet as liquid air ‘heat hybrids’ more than six times over.

The joined-up cold economy: In our complete energy mix, perhaps a radically new approach is urgently needed – a joined-up ‘cold economy’, mediated by cold vectors like liquid air to harness not just renewables but also waste cold to sustainably and cost-effectively provide power and cooling on demand in transport, industry and the built environment.



LIQUID AIR IS NOW PART OF MAINSTREAM THINKING

There has been £20 million of UK public sector funding for liquid air technologies in the last 12 months, including:

- the development of the Birmingham Centre for Cryogenic Energy Storage (BCCES), a first-of-its-kind institution pursuing innovation in liquid air technologies and research into the liquid air economy;
- the Dearman engine's first application, power and cooling, which goes into on-vehicle demonstration this summer at MIRA (Motor Industry Research Association), funded by the TSB's IDP8 grant.



"Liquid air offers significant potential benefits as a future energy vector, both for use in light duty propulsion and as an enabler for other promising low-carbon power train innovations, particularly waste heat harvesting."

Professor Neville Jackson |
Chief Technology and Innovation Officer, Ricardo |
Vice Chairman, ERTRAC | Director, CENEX
(UK Centre of Excellence for Low Carbon Vehicles and Fuel Cells) |
Deputy Chair, UK Automotive Council

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The Dearman Engine Company