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# Liquid Air on the Highway

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

Liquid Air
Energy
Network

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# 1 SUMMARY AND RECOMMENDATIONS

This report explores the potential benefits and implications of introducing liquid air engines on commercial vehicles in Britain over the next decade. A number of engine concepts are being developed, but we focus on the two closest to commercial deployment: the zero-emissions 'power and cooling' engine for truck and trailer refrigeration; and the diesel-liquid air 'heat hybrid' engine for buses, lorries and other commercial vehicles. The Dearman Engine Company is developing both applications, and its refrigeration engine begins on-vehicle testing this year and scheduled for commercial production from 2016.

There is a strong financial, air-quality, energy security and carbon reduction case for developing liquid air-equipped commercial vehicles.

We have investigated the business, economic and environmental case for both refrigeration and heat hybrid liquid air engines, and assessed the capacity of the industrial gas industry to produce and distribute the necessary 'fuel' over the next decade. After extensive analysis based on modelling of data gathered from technology developers, industrial gas experts, transport consultancies and fleet operators, we have found:

## Main conclusions

- **There is 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 $CO_2e$ (well-to-wheel) and £113 million net of investment costs. Annual net savings in 2025 would reach £37 million and 404,000t$CO_2$e.

- **Promising first applications include refrigerated trucks and trailers and heat hybrid buses and lorries.** These could produce major reductions in diesel consumption, local air pollution, well-to-wheel carbon emissions, noise and cost. The strongest would repay their investment within months, and the rest in a range of two to four years.

- **Liquid air vehicles could achieve significant cuts in local air pollution.** A fleet of just 13,000 refrigerated trailers would reduce annual emissions of nitrogen oxides (NOx) by over 1,800 tonnes, equivalent to taking almost 80,000 Euro 6 lorries or 1.2 million Euro 6 diesel cars off the road. Annual emissions of particulate matter (PM) would fall by 180 tonnes, equal to removing 367,000 such lorries from service – more than three times the entire UK articulated lorry fleet today – or 2.2 million Euro 6 diesel cars.

- **The roll-out of liquid air vehicles could be fuelled entirely from existing spare capacity until at least 2019.** Great Britain has a mature and extensive industrial gas industry with substantial spare liquid nitrogen production capacity, which in principle could fuel 6,600 diesel-liquid air heat hybrid buses, or a third of the British urban bus fleet.

- **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 new jobs. On more ambitious assumptions, it would manufacture 173,000, generating net revenues of £713 million and more than 2,100 new jobs – similar to the job creation projected for fuel cells and hydrogen. Cumulative production to 2025 would total 930,000 engines with revenues of over £4.2 billion.

- **There is effectively no constraint on liquid nitrogen supply in any British city that would prevent a pilot scheme or early deployment of liquid air vehicles.** All of Britain's major cities are within commercial delivery distance of the existing industrial gas distribution network, and refuelling equipment for fleet vehicles could be easily installed at operators' existing depots.

- **There is a major opportunity for the industrial gas producers.** By 2025, new demand for liquid nitrogen or liquid air for transport applications could total 10,000 tonnes per day, more than doubling current the current nitrogen demand of 8,000tpd.

# 1 SUMMARY AND RECOMMENDATIONS

13,000 liquid air trailers would cut PM emissions as much as taking 367,000 Euro 6 lorries off the road.

## Key findings

In addition, our detailed modelling has shown that:

- Promising liquid air applications include:
  - Liquid air 'cooling and power' refrigerated trailers, which could repay their investment in as little as three *months*. Assuming these trailers capture 30% of annual sales by the early 2020s, the projected fleet would reach 13,000 vehicles by 2025 and generate cumulative net savings of £76 million and 880,000t$CO_2$e. This fleet would reduce *annual* emissions of nitrogen oxides (NOx) by over 1,800 tonnes, and particulate matter (PM) by 180 tonnes. That is the PM equivalent of removing 367,000 Euro 6 lorries from service – more than three times the entire UK articulated lorry fleet.
  - Liquid air 'cooling and power' rigid refrigerated lorries, which would repay their investment in under three years. Assuming these lorries capture 15% of annual sales by the early 2020s, the projected fleet would reach 6,000 vehicles by 2025, and generate cumulative net savings of almost £7 million and more than 50,000t$CO_2$e.
  - Urban heat hybrid buses, which would repay their investment in under two years. Assuming these buses capture 30% of annual sales by the early 2020s, the projected fleet would reach 4,100 in 2025 and produce cumulative net savings of £31 million and 162,000t$CO_2$e. The government could commission eleven times more heat hybrid buses than electric hybrid buses for the same level of subsidy.
  - Heat hybrid urban delivery trucks, which would repay their investment in around 4 years. Assuming these trucks capture 7.5% of annual sales by the early 2020s, the projected fleet would reach almost 13,000 by 2025, when it would generate annual net savings of £9 million and around 100,000t$CO_2$e.
- Businesses and cities could achieve major reductions in cost, carbon and air pollution by taking up liquid air:
  - If Leeds were to convert its bus and bin lorry fleets to diesel-liquid air heat hybrids, by 2025 it would make cumulative net savings of £14.5 million and 66,000t$CO_2$e.
  - If London converted just 30% of its buses, by 2025 the cumulative net savings would be £29 million and 112,000t$CO_2$e.
  - If the supermarket sector adopted a range of liquid air vehicles such as delivery trucks and refrigerated trailers at the same rate as the market as a whole (see above), by 2025 the sector would achieve cumulative net savings of £19 million and more than 250,000t$CO_2$e.
  - Supermarkets could also achieve dramatic reductions in local air pollution. Assuming they adopt liquid air refrigerated trailers at the same rate as the market as a whole (see above), their fleet would reach 3,200 by 2025. This would cut NOx emissions by 450 tonnes, equal to taking 19,000 Euro 6 lorries off the road, and reduce PM emissions by almost 45 tonnes, equal to removing 93,000 such lorries from service. Some supermarkets have already trialled vehicle refrigeration based on the simple evaporation of liquid nitrogen, but the liquid air 'cooling and power' approach would be more efficient and cost-effective.
  - Cities and businesses adopting liquid air vehicles could immediately report reductions in 'Scope 1' carbon emissions – those made directly by the organisation (see Box 1 on page 7).
- Vehicles carrying a tank of cryogenic fuel in insulated tanks at approximately -200°C could then exploit its cooling potential to further raise fuel economy – for example, by improving the efficiency of processes such as internal combustion engine charge cooling, knock-limit improvement and exhaust gas recycling.
- The cities with the best liquid nitrogen supply include Bath, York, Oxford, Portsmouth, Southampton, Hereford and Hull, and among the five largest, Sheffield and Leeds. In the event of widespread take-up, new liquid air or nitrogen capacity would be required soonest in east London and the West Midlands.

# 1 SUMMARY AND RECOMMENDATIONS

- All but two of Britain's 30 largest cities – Plymouth and Aberdeen – have liquid nitrogen supply within 100 miles. Even London, with the lowest per capita supply of any city, could convert a third of its bus fleet to liquid air before needing new production capacity.

## Recommendations

### 1. Regulate emissions from vehicle refrigeration

One of the striking findings of this report is the disproportionate impact of vehicle refrigeration on greenhouse gas emissions and local air pollution. In particular, trailer refrigeration units (TRUs) powered by auxiliary diesel engines can emit many times more NOx and PM than the lorry's main drive engine or a diesel car because they are currently unregulated. Proposals to strengthen the regulations are expected to be adopted by the European Commission (EC) this year, and may come into force by 2019-2021, but will make essentially no difference to the emissions of NOx and PM from TRUs.[1] It could be argued that for auxiliary engines operating in cities this approach is completely inadequate and a decade too late.

The Supreme Court has ruled the UK in breach of the EU Air Quality Directive, exposing Britain to fines of potentially more than £100 million, and most large British cities continue to break local air pollution limits. Regulating emissions from vehicle refrigeration would be a timely and cost-effective way of reducing pollution that causes 29,000 premature deaths in Britain each year.[2] We suggest the arrival of liquid air as a cost-effective solution means the emissions limit for vehicle refrigeration could quickly be reduced to zero.

### 2. Recognise liquid air

Research and development in liquid air grid and transport technologies has been awarded UK grant funding of some £20 million to date, from sources including DECC, the Technology Strategy Board and the EPSRC. The potential of liquid air has clearly been recognised by grant funding bodies, but because the technology has emerged relatively recently it has not yet been integrated into transport policy. Most low carbon transport roadmaps, for example, are still overwhelmingly geared towards supporting electric and fuel cell vehicles. Liquid air has now been recognised as a potential road transport energy vector by the European Road Transport Advisory Council (ERTRAC)[3]; it ought to be similarly recognised in UK transport policy.

### 3. Review eligibility criteria for green transport funding

Unlike some other low carbon technologies, liquid air engines would be cheap to build, and would generally pay back their investment quickly without subsidy. However, the progress of some applications, such as heat hybrid buses, could be held back by the subsidies awarded to competing technologies with high capital costs. The government's general position, rightly, is that taxpayer support for green technologies should be even-handed or 'technology neutral', yet policy could inadvertently end up 'picking winners'.

The Green Bus Fund, for example, now provides subsidies of up to 50% on the additional capital cost of any vehicle that reduces emissions by 30%. This discriminates in favour of technologies with high capital costs such as electric hybrids, and against those like liquid air heat hybrids, which would cost little more than a conventional diesel to buy but which do have some additional operating costs. To be fair, the Green Bus Fund was devised at a time when known options tended to be capital intensive, but the arrival of liquid air technology now requires the funding criteria be re-assessed. Our analysis (Box 4, page 35) suggests the Treasury could achieve the same level of emissions reduction at far lower cost to the public purse by making the Green Bus Fund properly technology neutral, by finding a way to put operating costs on an equal footing with capital costs. If so, it could procure eleven times more low carbon buses for the same public expenditure.

The Green Bus Fund is not the only funding channel that risks inadvertently picking winners. We urge the government to review its green transport funding mechanisms to ensure they do not inadvertently discriminate against emerging technologies that might reduce emissions at less cost to the taxpayer.

Regulating emissions from vehicle refrigeration would be a timely and cost-effective way of reducing pollution that causes 29,000 premature deaths in Britain each year.

With liquid air, the government could procure 11 times more low carbon buses for the same public expenditure.

### 4. Review green levies on liquid air and liquid nitrogen used as transport fuel

Transport is widely recognised as one of the most difficult sectors to decarbonise, because it requires new energy storage technologies to allow renewable energy to displace diesel. Liquid air or nitrogen is being demonstrated as one such 'vector'. Liquid nitrogen, however, is an established industrial product which is energy intensive to produce, and the tax treatment could affect its ability to compete as an energy vector.

The Chancellor announced several measures to reduce the costs of energy intensive industries in this year's budget, but these may be of limited help to the industrial gas industry (chapter 5). Industrial gas producers are already excluded from the EU ETS compensation package by decision of the European Commission (EC), which could also veto the Chancellor's new proposals. The Carbon Price Floor is to be frozen at £18 per tonne from 2017, but our modelling suggests the impact of this measure alone on liquid air or nitrogen prices will be modest.

We suggest that even if industrial gas production in general is eventually excluded from the new compensation schemes, that production of liquid nitrogen for use *as an energy vector* should be shielded from green levies if at all possible. To impose these levies on liquid air would mean – perversely – that taxes intended to encourage decarbonisation would inhibit the development of a new energy vector capable of delivering major reductions in heavy duty and refrigerated transport emissions. If the aim of policy is to encourage the use of intermittent renewable electricity to displace diesel in transport, and coal and gas on the grid, then the means of storing that energy and delivering it on demand should not be penalised but supported.

The Chancellor has exempted electricity produced by Combined Heat and Power from the Carbon Price Floor altogether, in part because it reduces greenhouse gas emissions. The same argument can be made for use of liquid nitrogen in transport applications, some of which would also deliver striking reductions in local air pollution (see point 1). We urge the government to review the imposition of green levies on electricity used in the production of energy vectors such as liquid air or nitrogen.

# 2 INTRODUCTION

Liquid air was first demonstrated as a transport fuel or energy vector as long ago as the early 20th century. But in those days the engine technology was cumbersome and inefficient, and soon eclipsed by the internal combustion engine (ICE). Since the start of this century, however, there has been an increasingly urgent need for new technologies to reduce diesel consumption, and three breakthroughs have transformed the prospects for liquid air.

Britain has enough spare liquid nitrogen capacity to fuel 6,600 buses, or a third of the urban fleet.

First, the British inventor Peter Dearman patented a novel liquid air engine that was far more efficient than previous designs, which the Dearman Engine Company is developing with the help of government funding into a range of engines for bus, lorry and refrigerated transport fleets. Second, engineers at Ricardo invented a split cycle ICE that incorporates liquid nitrogen to raise the fuel efficiency of heavy commercial vehicles. Third, liquid nitrogen evaporation is beginning to be taken up as a quiet and zero-emissions form of vehicle refrigeration.

The Dearman and Ricardo engines are expected to reduce diesel consumption by 15-30% as hybrid applications or integrated ICE designs, and 100% in stand-alone applications such as Dearman engine vehicle refrigeration. They are also expected to produce large savings in cost, carbon and local air pollutants, and to be in commercial production by the end of this decade. The Dearman Engine Company plans initial trials this year and fleet trials in 2015. Other highly innovative liquid air engines such as the EpiQair rotary engine are at an earlier stage of development.[4] Liquid air has now been recognised as a potential road transport energy vector by the European Road Transport Advisory Council (ERTRAC).[5]

At the same time, the fuel and refuelling infrastructure required to support liquid air vehicles is already widely available – a major advantage over some other alternative transport energy vectors. Liquid air is not yet produced commercially, but liquid nitrogen, which can be used in the same way, is produced throughout the industrialised world. Indeed, the industrial gas companies have large amounts of *spare* nitrogen production capacity, for the simple reason there is far more nitrogen than oxygen in the atmosphere but proportionately less commercial demand.

In Great Britain, we estimate there is enough spare *liquid* nitrogen production capacity to fuel 6,600 buses, or a third of the urban bus fleet, as diesel-liquid air 'heat hybrids'. There is even greater spare capacity in *gaseous* nitrogen, although making use of this would require investment in additional liquefiers. What's more, the industrial gas producers distribute liquid nitrogen through a nationwide tanker network, and most of the population is within commercial delivery distance of one of their 11 production sites. So the early deployment of liquid air, unlike hydrogen, presents no 'chicken and egg' infrastructure dilemma.

If the scene seems set for a rapid expansion of liquid air on Britain's roads, many questions remain, which this report sets out to answer. Britain may have substantial spare nitrogen capacity in aggregate, but it is not evenly distributed between production sites. Nor was it clear until now how much potential liquid nitrogen demand was represented by each of the applications currently in development. The principal aims of this study are to model vehicle performance and take-up, and map the existing liquid nitrogen supply, to understand:

- What are the potential fuel, financial and carbon savings, and the likely cryogen demand, in selected cities and companies, and Britain as a whole;
- How much of the projected growth in liquid air transport applications could be supported by existing spare capacity;
- Which cities are best placed for early adoption of liquid air technologies, and where is additional liquid air production capacity likely to be needed soonest;
- How much will liquid air cost in future, how will it compare with diesel, and what are the policy implications;
- What is the business case for individual liquid air vehicle applications based on investment costs, fuel savings, emissions reductions and other benefits such as local air quality improvement and noise reduction;
- What is the economic value or 'national business case' of liquid air vehicles to UK plc;
- What is the scale of the opportunity for the industrial gas producers;
- What are the R&D priorities for liquid air in transport applications.

# 2 INTRODUCTION

This report was co-funded by the Technology Strategy Board, and produced with the help of industry experts.

This report investigates only the vehicles that look most promising for liquid air applications in the short term, which is to say commercial vehicles including buses, delivery lorries, and refrigerated lorries and trailers. These tend to be intensively used, meaning the potential fuel and emissions savings are large, and usually refuel at a single depot, meaning they could be easily serviced by the existing liquid nitrogen distribution network. Smaller vehicles and cars will be the subject of a future report.

This report, co-funded by the Technology Strategy Board, is based on several months of detailed analysis by the Liquid Air Energy Network. LAEN's modelling combined its own market research with inputs from the Dearman Engine Company, Ricardo Strategic Consulting, E4tech and Spiritus Consulting, and fleet data from a range of commercial and public sector transport operators. This collaboration has produced the first detailed picture of the potential environmental and economic benefits to Britain of liquid air on the highway.

The report is structured first to present a general introduction to liquid air vehicle technologies and their progress to market (chapter 3); second to establish the likely availability, price and carbon intensity of the liquid air or nitrogen required to fuel them (chapters 4-6); and third to combine these building blocks with other inputs to produce the business case analysis (chapters 7 and 8). In chapter 9 we analyse the large reductions in local air pollution that could be achieved by liquid air transport refrigeration, and in 10 we identify areas for further research and development to support the development of liquid air on the highway.

The business case analysis incorporates modelling of individual vehicle applications by the sustainable energy consultancy E4tech. LAEN combined E4tech's conclusions about the capital costs, liquid air consumption and diesel savings of individual applications with our own analysis of the likely price and carbon intensity of liquid air, and with real-world fleet data from bus, municipal and logistics operators. This produced the case studies presented in chapter 8, which in turn support the national analysis presented in chapter 7.

We should stress that E4tech's capital cost forecasts are those that would be achieved once engines are produced in volume, which our projected roll-out, starting in 2015, may well pre-empt. The results of our analysis should be taken as what could be achieved if technology development and roll-out were well supported by government and industry.

For their generous sharing of data and insights we are indebted to: Air Products; Arriva Yorkshire; Go-Ahead; EYMS; Forkway Group; Clugston Distribution Services; Iceland Foods Ltd, John Lewis Partnership and Sainsbury's; Leeds City Council, Yorkshire Passenger Transport Executive (Metro), Leeds City Region; Hull City Council; and Birmingham City Council. Other companies have provided information but asked to remain anonymous.

For more information about the modelling supporting this report please contact the Liquid Air Energy Network at info@liquidair.org.uk

Liquid air is not yet produced in commercial quantities, but liquid nitrogen is in plentiful supply throughout the industrialised world.

### BOX 1: Defining our terms

In this report the word **'savings'** means net unless otherwise qualified. **Financial savings** or **net benefit** are the remaining operational savings after investment costs have been repaid. **Savings in greenhouse gas emissions** are well-to-wheel, not simply tailpipe, on the basis of the grid electricity emissions reduction trajectory required to meet the Committee on Climate Change target of 50g/kWh by 2030. **'Zero-emissions'** refers to tailpipe emissions only.

**Investment costs and benefits** are all incremental – ie the *additional* amounts required or produced compared to those of the incumbent technology, rather than the total amounts required to buy a vehicle or produced by that investment.

A **'heat hybrid'** consists of a diesel engine and a liquid air engine integrated so that waste heat and cold are exchanged between the engines to increase the efficiency of both and reduce diesel consumption.

A **'cooling and power'** engine is a stand-alone, zero-emissions liquid air engine used principally for refrigeration, in which the liquid air or nitrogen provides cooling both from its evaporation in a heat exchanger, and also by its expansion in a piston engine to produce power, which can then be used to drive a conventional refrigeration cycle (see chapter 3).

**Scope 1 emissions** are those emitted directly by a company through burning fossil fuels. **Scope 2** emissions are those emitted by the company's energy suppliers – eg electricity generators – and **Scope 3** emissions are those emitted by the company's supply chain. All UK companies listed of the London Stock Exchange must report their Scope 1 and 2 emissions by law.[6]

### BOX 2: Liquid air and liquid nitrogen

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 the atmosphere. The temperatures at which air and nitrogen liquefy are similar (-196°C for nitrogen, -194°C for air), and both expand about 700-fold when they re-gasify.

Liquid air is not yet produced in any quantity, but liquid nitrogen is produced throughout the industrialised world for use in food processing, fire suppression and superconducting technologies. The industrial gas companies have large amounts of spare nitrogen production capacity for the simple reason there is far more nitrogen than oxygen in the atmosphere but proportionately less commercial demand.

In this report, we assume that spare liquid nitrogen capacity would be used to fuel the deployment of 'liquid air' vehicles until supply constraints or rising LIN prices prompt the construction of new liquid air plants. 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 analysis suggests the spare liquid nitrogen capacity could support the deployment of liquid air vehicles until at least 2019.

# 3 LIQUID AIR VEHICLE TECHNOLOGIES

The point of liquid air is to store 'wrong time' low carbon energy to displace fossil fuels in electricity generation and transport.

## What is liquid air?

Air turns to liquid when refrigerated to around -194°C at ambient pressure, and can be conveniently stored in insulated but unpressurised vessels. Exposure to heat – even at ambient temperatures – causes rapid re-gasification and a 700-fold expansion in volume, which can be used to drive a turbine or piston engine to do useful work. The main potential applications are in electricity storage and transport, and in both, liquid air can provide the additional benefit of waste heat recovery and/or cooling.

Since the boiling point of liquid air 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 (generally defined as temperatures up to +150°C), which other technologies would find difficult to exploit and which significantly improves the overall efficiency. Liquid air can also exploit the waste cold from LNG re-gasification to improve the efficiency of liquefaction and reduce costs.

The purpose of liquid air – as with batteries or hydrogen – is to store 'wrong time' low or zero carbon electricity, which can then be used to displace high carbon coal or gas in electricity generation and petrol or diesel in vehicles. The carbon intensity of liquid air depends on the source of electricity used to make it, and most industrial liquefiers operate at night when the greenhouse gas emissions of grid electricity are lower than average. New liquefiers could be integrated with renewable generation such as wind to produce effectively zero carbon liquid air from wrong time energy which might otherwise be wasted. Liquid air and nitrogen are in any case zero-emission fuels at their point of use, offering the same potential for dramatic local air quality improvement as electricity or hydrogen.

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

## Liquid air vehicle technologies

Three liquid air vehicle engines are now in development. The Dearman engine is a novel piston engine powered only by the phase-change expansion of liquid air or liquid nitrogen, which can be used in a number of configurations, including waste heat recovery from an internal combustion engine or fuel cell ('heat hybrid'), and as a zero-emissions 'power and cooling' engine for refrigeration. The Ricardo split cycle engine is a novel internal combustion engine that incorporates liquid nitrogen to raise its efficiency. The EpiQair rotary liquid air engine is another novel design, but at an earlier stage of development. Both the Dearman and Ricardo engines are suitable for heavy commercial vehicles such as lorries and buses, where modelling suggests they could deliver diesel savings of 25-30%.

### The Dearman engine

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

In the Dearman engine cycle, warm or even ambient temperature HEF is injected into the cylinder, followed by liquid air or nitrogen that has passed through a vaporiser. Then, as the fluids mix, direct heat transfer causes the gas to expand, so pushing the piston down. The HEF continues to provide heat throughout the power stroke, leading to efficient 'isothermal' expansion. Afterwards the cryogenic gas exhausts harmlessly to the atmosphere while the HEF is re-heated and re-cycled. In a variant of the engine, the vaporiser is dispensed with entirely, and liquid air is injected directly into the cylinder, where the warmth of the HEF drives internal vaporisation for yet higher efficiency.

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

The inventor Peter Dearman has already demonstrated his engine in a modified car, and the Dearman Engine Company (DEC) is building a transport refrigeration prototype, to begin on-vehicle field trials with the engineering consultancy MIRA in 2014, with Technology Strategy Board grant funding.

*Dearman engine ZEV*

Used on its own, the Dearman engine is a zero-emissions engine whose exhaust consists only of clean, cold air or nitrogen. It is also capable of low carbon emissions depending on the carbon intensity of the electricity used to produce the cryogen. On the basis of the projected carbon intensity of grid electricity in 2030, a Dearman engine car would have lower lifecycle carbon emissions than both electric (EV) and fuel-cell (FCV) vehicles.[7]

Liquid air or nitrogen has a similar energy density to that of an EV battery but is far quicker to refuel – taking minutes not hours. A source of heat is required to drive vaporisation, and a reasonably efficient engine requires around twice as much heat as the power it produces, and has to harvest that heat from the environment. So as a ZEV the Dearman engine lends itself to vehicles that are shorter range, have a lower power requirement or operate on a single site. At the same time, the need for heat to drive vaporisation means warmer environments are preferred, and also benefit because heat harvesting provides a source of cooling or air conditioning at no extra cost. Modelling by E4tech suggests potential markets include fork-lift trucks, specialist mining and airport vehicles, inland waterway craft, 3-wheel taxis or 'tuk tuks' for emerging markets and, in future, city cars.

*Dearman engine 'heat hybrid': waste heat recovery and cooling*

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

An ICE loses roughly two thirds of the energy contained in its fuel as waste heat – about one third each through the radiator and exhaust. The heat lost through the radiator is low grade (~100°C) which conventional technologies find difficult to harvest. However, since the DE bottom temperature is -196°C, even low grade waste heat can be converted into shaft power at practical conversion efficiencies of up to 50%. The cooling loop of a diesel engine contains a mixture of water and glycol – just like the heat exchange fluid in a Dearman engine. This means the ICE waste heat could be transferred either directly, combining radiator fluid and HEF in a single circuit, or indirectly, via two separate circuits connected

**Liquid air turns an engine's waste heat into extra power, and provides efficient zero-emission refrigeration.**

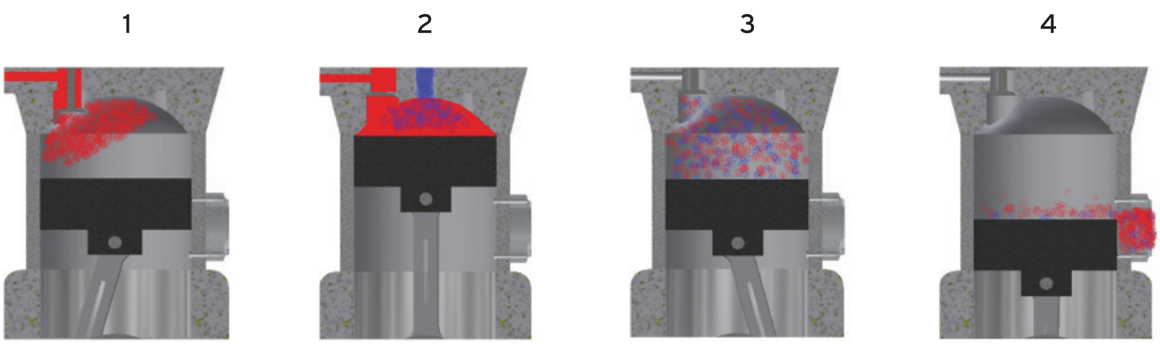



Figure 1: The Dearman engine power cycle: (1) Return Stroke, warm heat exchange fluid (HEF) enters the cylinder; (2) Top Dead Centre, high pressure nitrogen is injected into the cylinder and heat transfer with the HEF causes rapid temperature rise and expansion; (3) Power Stroke, the nitrogen expands pushing the piston down, direct contact heat transfer continues allowing near isothermal 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.

A liquid air 'heat hybrid' bus or lorry could cut diesel consumption by 25%.

by a heat exchanger. There is nothing to stop an ICE-DE 'heat hybrid' incorporating other technologies to harvest higher grade waste heat from the ICE exhaust.

A heat hybrid would convert waste heat from the ICE into extra shaft power through the Dearman engine. This could be used to supply temporary peaks in load such as pulling away, acceleration or going uphill ('peak lopping'), and would allow the ICE to be downsized and run more efficiently. The DE also has the advantage of displacing a material portion of transport related emissions into an energy vector – liquid air or nitrogen – that can be produced from low or zero carbon sources. These characteristics mean the ICE-DE heat hybrid lends itself to use in buses, coaches, lorries and urban delivery vehicles. An ICE-DE heat hybrid could consume up to 25% less diesel – so reducing the overall fuel bill – and deliver progressively larger $CO_2$ savings as the carbon intensity of grid electricity falls.

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

### *Dearman engine refrigeration – 'power and cooling'*

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

At present, transport refrigeration is overwhelmingly powered by diesel – either through a compressor driven by the vehicle's main engine, or a separate TRU – and refrigeration alone can consume as much as 20% of a lorry's fuel.[8] Diesel TRUs also emit high levels of nitrogen oxides (NOx) and particulate matter (PM) and are noisy, which can stop them being allowed to make urban or night-time deliveries. Any technology that can significantly reduce fuel costs, emissions and noise should present a strong business, environmental and social case.

Vehicle manufacturers and industrial gas producers have begun to offer vehicle refrigeration based on liquid nitrogen evaporation, under trade names including natureFridge and FROSTCRUISE. The cold logistics company Gist operates FROSTCRUISE trailers for Marks & Spencer and Starbucks, while Nisa-Today's is trialling natureFridge. Such systems are zero-emission at the point of use and quieter, so useful for making deliveries at night. Liquid nitrogen is either sprayed directly into the trailer (natureFridge) where it evaporates and displaces warmer air with inert cryogenic gas, or it is passed through a heat exchanger (FROSTCRUISE) that cools the air in the compartment indirectly. The direct approach is about 30% more efficient than the indirect alternative, but requires additional safety measures to prevent the driver entering the compartment until excess nitrogen is vented. Neither approach, however, extracts any power from the evaporation process.

The refrigeration unit currently being developed by the Dearman Engine Company is a significant advance on existing technologies, since it uses liquid air or nitrogen to produce both cooling and shaft power. First the cryogen is vaporised in a heat exchanger in the refrigeration compartment, so cooling it down; then the high pressure gas is used to drive the Dearman engine, whose shaft power can be used to drive a conventional refrigeration compressor or for auxiliary power. This would produce even greater 'well-to-wheels' emissions savings than simple evaporation of liquid nitrogen compared to a diesel TRU.

## The Ricardo split cycle liquid nitrogen engine

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

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

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

Ricardo believes the engine will initially be deployed on heavy duty vehicles – rail, marine, lorries and off-road applications – which are big enough to accommodate an extra tank for liquid nitrogen, and where the diesel savings would be sufficient to offset some additional infrastructure cost. A standard heavy duty vehicle with a diesel tank of 240 litres would be able to reduce this to 170 litres with the split cycle engine, but would also require a nitrogen tank of 1.1m$^3$ – roughly the same size as would be needed to convert the vehicle to compressed natural gas (CNG). Diesel consumption would fall by almost 30%, and depending on cost assumptions for fuel and nitrogen, financial savings could be as much as 20%. The Automotive Council roadmap shows the Ricardo split cycle engine in volume production by 2020.

The new split cycle engine could be 60% efficient, compared to 40% for a modern diesel.

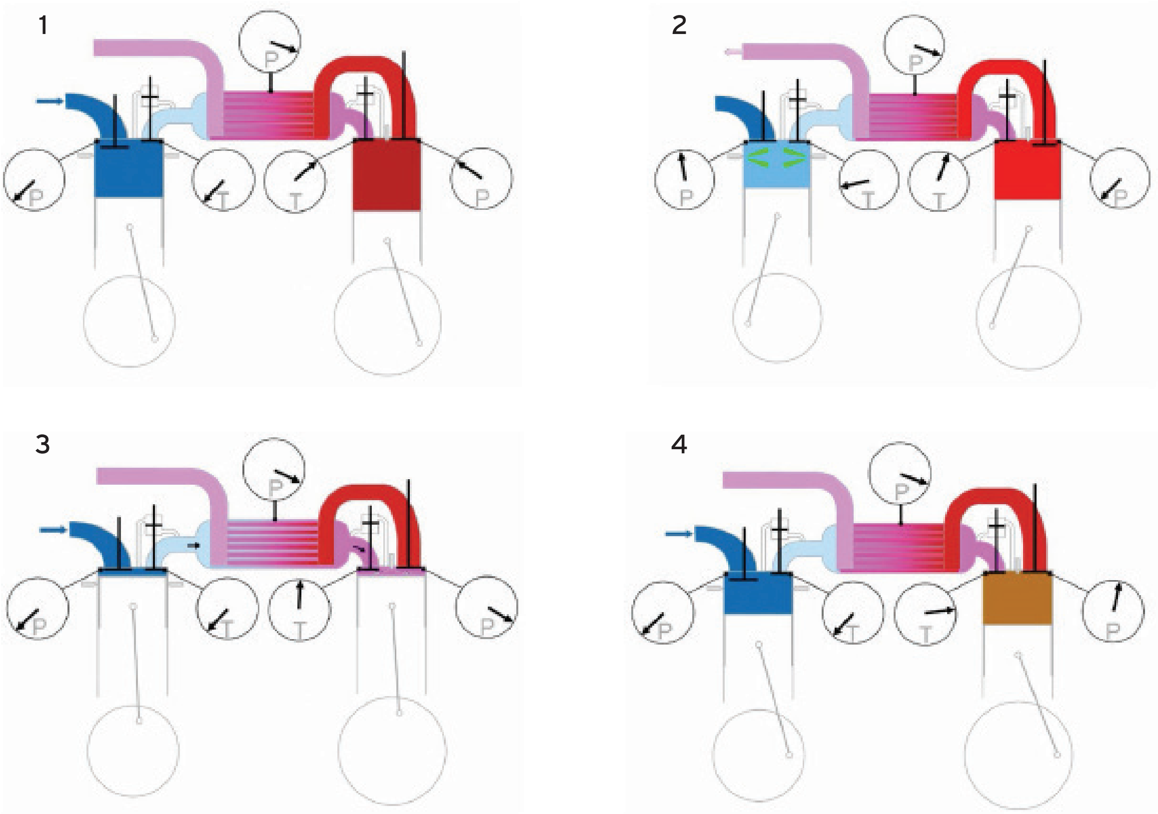



Figure 2: The Ricardo split cycle liquid nitrogen engine. The left hand cylinder is the compressor, the right hand is the combustor; T = temperature and P = pressure. From top left: (1) air flows into the compressor and the hot air in the combustor expands providing drive; (2) exhaust opens warming the recuperator, while liquid nitrogen is simultaneously injected to achieve isothermal compression; (3) pressurised, cool air is transferred from compressor to combustor warming en route; (4) fuel is added to the combustor, and combustion heats and pressurises the charge.

A novel liquid air rotary engine design with low friction and variable displacement could be highly efficient.

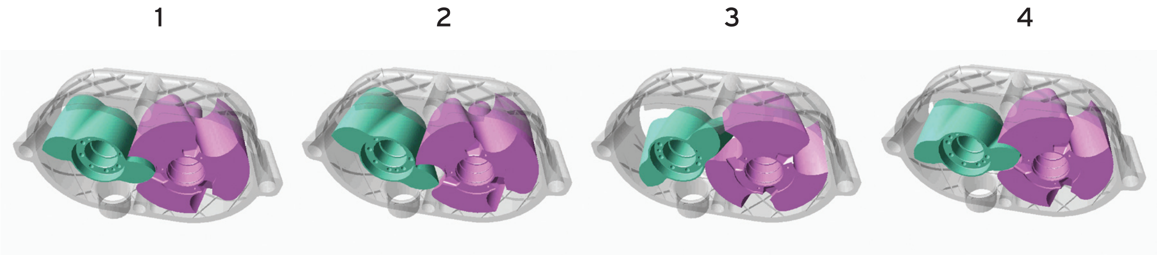



Figure 3: The EpiQair power cycle. See main text for description

## The EpiQair rotary liquid air engine

The 'EpiQair' rotary liquid air engine is a novel design, which came to light following the publication in May 2013 of the CLCF report *Liquid air in the energy and transport systems*. The developer, Epicam, had already invented a technology based on two interacting high-speed rotors that form transient chambers for expansion or compression. The technology was originally developed as an internal combustion engine, from which the expander was then developed separately as an exhaust heat recovery unit and the compressor as a supercharger. Following the report, however, Epicam increased the range of applications to include a liquid air engine for vehicle transport and distributed power generation, and a scalable air liquefier. The company claims the liquid air design is highly efficient because of two key features: the absence of friction, and variable displacement.

The EpiQair liquid air power cycle is illustrated in Figure 3. A two-lobed rotor turns anti-clockwise and interacts with a 3-pocketed rotor turning clockwise, forming transient expansion chambers. The rotors do not contact each other at any point, nor do they contact the engine casing, which eliminates friction apart from the shaft bearings. Pressure loss from the transient chambers is limited by the use of small clearances and the fact that each expansion takes place within a rotation of around 90° – much briefer than in a piston engine. The 700-fold expansion of the liquid air is extremely brief and happens twice per revolution of the lobed rotor, and the rotors can be designed to turn at 20-30,000 rpm. Epicam claims the engine will be around a tenth of the size of an equivalently powered internal combustion engine with a power density beyond the capability of any IC piston engine.

Liquid air is drawn from the fuel tank into a heat exchanger where its temperature rises from -196°C to almost ambient. Expansion is prevented by a high pressure pump at entry to the heat exchanger and by an electronically controlled injector at the exit. The air therefore becomes super-critical at about 350 bar with its density unchanged from that of liquid air. The injector delivers a charge of the super-critical fluid at the start of each new expansion cycle, when the volume of the transient chamber between the rotors is very small and equals the volume of fluid injected. Inside the chamber the charge expands, forcing the rotors to turn in opposite directions and delivering power on the lobe rotor shaft.

Although not shown in the diagram, the engine's containment wall can be mounted on a linear bearing, allowing it to move back and forth parallel to the axes of the rotors, so allowing the maximum volume of the transient chambers to be varied to match the changing demand for power as operating conditions vary. The charge mass is also varied to match the volume setting so that the engine can maintain its high expansion ratio of about 400:1, and the high efficiency of the engine at part-load.

The EpiQair engine can also work as an air liquefaction system. Renewable electricity could be used to power an electric motor to drive an EpiQair compressor – reversing the cycle described above. The compressed air passes through a heat exchanger to cool, and then into an EpiQair expander, so producing liquid air. Epicam says the high expansion and compression ratios of its technology could produce an efficient and scalable liquefier.

Epicam is also developing a supercharger based on its technology with a Tier 1 supplier, but seeks funding to develop its liquid air engine technology.

# 4 THE LIQUID AIR SUPPLY

Liquid air is not yet produced commercially, but liquid nitrogen (LIN), which can be used in the same way, is produced throughout the industrialised world. Indeed, the industrial gas companies often 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 spare nitrogen capacity could be used to fuel the initial deployment of liquid air vehicles. In this chapter we map this spare capacity to potential centres of demand, and in the next we analyse the likely future price of liquid air and its competitive position versus diesel.

Spare nitrogen capacity could be used to fuel the initial deployment of liquid air vehicles.

## Spare capacity

Industrial gases are produced at plants known as Air Separation Units (ASU) which separate the main elements of air by refrigeration, since each liquefies at a slightly different temperature: oxygen at -183°C, argon at -186°C and nitrogen at -196°C. This can lead to two different kinds of spare nitrogen capacity: *gaseous and liquid*.

Gaseous nitrogen (GAN) is an inevitable by-product of oxygen production; once oxygen has been separated out, cold nitrogen gas is basically what's left.[9] Since there is four times more nitrogen in the atmosphere than oxygen, but proportionally less commercial demand, many ASUs produce excess nitrogen. Some of the surplus is recycled to cool incoming air, so raising the energy efficiency of the ASU, but much is vented harmlessly to the atmosphere. A previous report from the Centre for Low Carbon Futures (CLCF) entitled *Liquid air in the energy and transport systems* estimated UK spare gaseous nitrogen capacity at 8,500 tonnes per day. To use this nitrogen as transport fuel would require investment in additional liquefiers.

There is also substantial spare liquid nitrogen production capacity, however, which is available immediately without additional investment. Air liquefaction is an energy intensive business and industrial gas producers typically operate liquefiers at night to take advantage of cheaper electricity. This means liquefiers are largely idle during the daytime, when they could be producing liquid nitrogen for transport fuel. To do so would mean running them on more expensive daytime electricity, but no additional equipment would be needed to support first deployment – a distinct advantage over other vectors such as hydrogen. In the short term, liquid nitrogen produced during the daytime would be marginally more carbon intensive than that produced at night, but as we show in chapters 6 and 7, this capacity could be exhausted by 2019, when cheaper and lower carbon liquid air plants would need to be built. Spiritus Consulting estimates total spare liquid nitrogen capacity in Great Britain at

| Region | Liquefier Spare Capacity (TPD) | Sites |
|---|---|---|
| Glasgow/M8 Corridor | 140 | BOC Motherwell, ML1 5LF |
| Teeside | 220 | BOC Teesside, TS6 7RT |
| ManchesterM6/M56/M62 Corridor (2 sites) | 140 | AP Carrington, M31 4TG |
| | 0 | AP Ellesmere Port, CH65 4EP |
| Sheffield M1/M62/M42/M69 network | 225 | BOC Brinsworth, S60 5NT |
| Humberside ( 3 sites) | 300 | BOC Scunthorpe, DN15 6XH |
| | 0 | AL Eggborough, DN14 0BS |
| | 120 | AP Hull, H12 8PP |
| West of London M4/M4 Corridor ( 2 sites ) | 180 | AP Didcot, OX11 7PL |
| | 180 | BOC Thame, OX9 3NX |
| South Wales/Swansea/M4 Corridor | 350 | BOC Port Talbot,SA13 2NS |
| Southampton/M3 Corridor | 350 | BOC Fawley, SO45 3NX |
| | | |
| **TOTAL** | **2205** | |

Table 1: Spare liquid nitrogen production capacity by production site. Source: Spiritus Consulting

Britain has ample spare nitrogen capacity to fuel early deployment of liquid air vehicles.

2,200 tonnes per day. This capacity is 'spare' in the sense that the plant exists and is currently idle, but its owners are commercially driven and would naturally need a convincing economic case to bring it into production. A breakdown of the surplus by production site is shown in Table 1.

In this report we focus on the spare liquid nitrogen capacity, since it is available without additional investment to supply field trials and early deployment of liquid air vehicles. In aggregate the liquid nitrogen surplus is enough to fuel around 6,600 heat hybrid buses, equivalent to a third of the urban fleet in Great Britain. However, the surplus is not evenly distributed and delivery distances can affect the price of liquid nitrogen, so it is important to understand which centres of potential demand are well or poorly supplied, which we analyse below.

## Industrial geography

Great Britain has twelve industrial gas production sites, whose location reflects our industrial heritage. The significant users of oxygen and nitrogen are steel producers, chemical plants and general manufacturing, so ASUs have been built near the historical locations of these industries. Major industrial users may be supplied by gas pipeline, but other customers (the 'merchant trade') are supplied with liquefied gases by road tanker. Liquid air vehicles can therefore be supplied from an existing distribution network, a major advantage over some other potential low carbon energy vectors such as hydrogen. The operator would need to rent only a cryogenic tank and pump, and a 60 tonne tank (Figure 4) would hold enough liquid nitrogen to support 30 buses on two 22-tonne tanker deliveries per week.

Figure 5 shows the location of twelve industrial gas production sites, of which the ten with spare liquid nitrogen capacity are marked with an indicative delivery radius. At first glance, it is clear that most of the industrial and populous areas of the country are well within distribution range of one or more source of liquid nitrogen, while those that appear poorly supplied are generally rural: northern Scotland, Cumbria, East Anglia, and parts of Wales and the West Country. This suggests the earliest opportunities to deploy liquid air commercial vehicles are likely to be in urban areas, and that fuelling refrigerated

Figure 4: Highview's Liquid Air Energy Storage demonstration plant at Slough. The tank holds 60 tonnes of liquid air. Photo: Highview Power Storage

transport from farm gate to distributor – in East Anglia, for example – may represent a chance for industrial gas producers to expand.

It should be stressed, however, that cryogenic gases are routinely delivered throughout the country, even in areas that appear blank on this map – East London is supplied from Thame or Didcot, for example, Cornwall from Fawley and South Wales – but that transport costs will have an additional impact on the final price. Other things such as volume being equal, a food processor in Norfolk is likely to pay more than a superconductor manufacturer along the M4, but both will be supplied.

It is also clear that the spare LIN capacity of 2,200tpd is ample to provide fuel for demonstration projects and early deployment. However, this spare capacity is unevenly distributed between the 11 production plants (Table 1). We have developed a more detailed understanding of where LIN is most abundant and where less so, to answer some important questions about the development of liquid air vehicles in Britain:

- In which locations is LIN likely to be most abundant (and cheapest) to support field trials and early deployment;
- How much headroom is provided by existing spare capacity in each region to deploy liquid air vehicles before any new production capacity need be built;
- In the event of rapid deployment in any given location, what is the maximum amount of LIN that could reasonably be called upon;
- In the event of widespread deployment of liquid air vehicles, where is new liquid air capacity likely to be needed soonest.


Figure 5: Map of GB industrial gas production sites and assumed delivery catchment areas. 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.

All but two of Britain's 30 largest cities would be easily supplied from local spare capacity.

To answer these questions we have analysed the potential supply from spare LIN capacity to all cities with a population greater than 150,000, by quantity, distance and population (Table 2). Population was used as an initial proxy for future LIN demand in transport, and per capita supply as a measure of the adequacy of supply relative to potential demand (Figure 5). The results were used to identify which cities to study in more detail, and potential locations for field trials and early deployment. Again, we should stress that even cities that appear poorly supplied by these criteria would always be able to obtain supplies of liquid nitrogen; we simply sought to identify the places likely to benefit from the largest, nearest and cheapest supply.

For each location we measured the distance between the city centre and the two nearest LIN plants, and then summed the available supply in 20 mile increments. The number of sources of supply was limited to the two nearest to minimise LIN cost and competition for supply between cities, but a second pass included all liquefiers within 100 miles. This was intended to test the maximum supply that could be called upon should one city decide to develop liquid air rapidly. In each case, the results were divided by population to give a measure of supply adequacy. The results are shown in Table 2.

| | Accessible daily LIN supply at various distances from city<br>Supply from nearest two depots | | | | | | | | | | | | | Supply from all depots within 100 miles | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Tonnes per day | | | | | | | Grams/day/head | | | | | | TPD | | G/D/H |
| **Miles from city:** | **20** | **40** | **60** | **80** | **100** | **Populat'n (1,000s)** | | **20** | **40** | **60** | **80** | **100** | | **100** | | **100** |
| London | | | 360 | 360 | 360 | 8,174 | | | | 44 | 44 | 44 | | 710 | | 87 |
| Birmingham | | | | 140 | 140 | 1,073 | | | | | 130 | 130 | | 725 | | 676 |
| Leeds | | 225 | 225 | 225 | 225 | 751 | | | 299 | 299 | 299 | 299 | | 1005 | | 1337 |
| Glasgow | 140 | 140 | 140 | 140 | 140 | 593 | | 236 | 236 | 236 | 236 | 236 | | 140 | | 236 |
| Sheffield | 225 | 225 | 525 | 525 | 525 | 553 | | 407 | 407 | 950 | 950 | 950 | | 785 | | 1420 |
| Bradford | | | 225 | 225 | 225 | 522 | | | | 431 | 431 | 431 | | 1005 | | 1924 |
| Manchester | 140 | 140 | 140 | 140 | 140 | 503 | | 278 | 278 | 278 | 278 | 278 | | 665 | | 1322 |
| Edinburgh | | 140 | 140 | 140 | 140 | 477 | | | 294 | 294 | 294 | 294 | | 140 | | 294 |
| Liverpool | | 140 | 140 | 140 | 140 | 466 | | | 300 | 300 | 300 | 300 | | 365 | | 783 |
| Bristol | | | | 530 | 530 | 428 | | | | | 1238 | 1238 | | 880 | | 2055 |
| Cardiff | | 350 | 350 | 350 | 350 | 346 | | | 1011 | 1011 | 1011 | 1011 | | 350 | | 1011 |
| Leicester | | | | 225 | 525 | 330 | | | | | 682 | 1592 | | 1025 | | 3108 |
| Wakefield | | 225 | 225 | 225 | 225 | 326 | | | 691 | 691 | 691 | 691 | | 1005 | | 3084 |
| Coventry | | | | 360 | 360 | 317 | | | | | 1136 | 1136 | | 725 | | 2287 |
| Nottingham | | | 225 | 225 | 225 | 306 | | | | 736 | 736 | 736 | | 785 | | 2568 |
| Newcastle upon Tyne | | | 220 | 220 | 220 | 280 | | | | 785 | 785 | 785 | | 220 | | 785 |
| Sunderland | | 220 | 220 | 220 | 220 | 276 | | | 799 | 799 | 799 | 799 | | 220 | | 799 |
| Brighton | | | | | 530 | 273 | | | | | | 1939 | | 530 | | 1939 |
| Hull | 120 | 420 | 420 | 420 | 420 | 256 | | 468 | 1638 | 1638 | 1638 | 1638 | | 865 | | 3374 |
| Plymouth | | | | | | 256 | | | | | | | | | | |
| Wolverhampton | | | | 140 | 140 | 249 | | | | | 561 | 561 | | 545 | | 2185 |
| Stoke-on-Trent | | 140 | 140 | 140 | 140 | 249 | | | 562 | 562 | 562 | 562 | | 365 | | 1466 |
| Derby | | | 225 | 365 | 365 | 249 | | | | 905 | 1467 | 1467 | | 785 | | 3156 |
| Swansea | 350 | 350 | 350 | 350 | 350 | 239 | | 1464 | 1464 | 1464 | 1464 | 1464 | | 350 | | 1464 |
| Southampton | 350 | 350 | 530 | 530 | 530 | 237 | | 1478 | 1478 | 2237 | 2237 | 2237 | | 710 | | 2997 |
| Salford | 140 | 140 | 140 | 140 | 140 | 234 | | 598 | 598 | 598 | 598 | 598 | | 665 | | 2843 |
| Aberdeen | | | | | | 223 | | | | | | | | | | |
| Portsmouth | | 350 | 350 | 530 | 530 | 205 | | | 1707 | 1707 | 2585 | 2585 | | 710 | | 3462 |
| York | | | 120 | 120 | 120 | 198 | | | | 606 | 606 | 606 | | 1005 | | 5074 |
| Peterborough | | | | | 525 | 184 | | | | | | 2859 | | 525 | | 2859 |
| Hereford | | | | | 530 | 183 | | | | | | 2889 | | 710 | | 3870 |
| Bath | | | | 530 | 530 | 176 | | | | | 3010 | 3010 | | 1060 | | 6021 |
| Oxford | 360 | 360 | 360 | 360 | 360 | 152 | | 2370 | 2370 | 2370 | 2370 | 2370 | | 710 | | 4674 |
| Dundee | | | | 140 | 140 | 146 | | | | | 961 | 961 | | 140 | | 961 |

Table 2: Liquid nitrogen supply by road distance from source. The columns to the left show the amount of spare liquid nitrogen capacity available to each city from its nearest two liquefiers in tonnes per day, assessed in 20 mile increments. The columns to the right of the population column express that supply per capita, in grammes per head per day. The two right-most columns show the spare capacity available from *all* liquefiers within 100 miles as tonnes per day and grams per head per day respectively. The relative per capita supply for each city is shown graphically in Figure 5.

From Table 2 it is clear that:

- All but two of Great Britain's 33 largest cities have substantial LIN supply within 100 miles to support vehicle trials and early deployment.
- Of Britain's two largest cities, London has no LIN supply within 40 miles, and Birmingham none below 60 miles.
- Bath, York and Oxford, small cities which each have several liquefiers nearby, have by far the highest per capita supply. They are followed by a broadly equal cluster of well supplied cities including Salford, Wakefield, Hull, Derby, Nottingham, Leicester, Peterborough, Hereford, Southampton and Portsmouth.
- Of the larger cities, Sheffield is well supplied at any distance, and more generously at over 60 miles. Glasgow has some supply close to hand, but spare capacity at Motherwell is modest relative to population, and per capita supply is at the lower end of the range.
- Leeds, Britain's third largest city, is better supplied than London or Birmingham, but per capita supply is relatively low when supply is restricted to the two closest ASUs. If all liquefiers within 100 miles are included, however, supply increases five-fold, and per capita supply is robust.
- Only five cities have no supply within 80 miles, and only two would require deliveries over distances greater than 100 miles: Plymouth and Aberdeen.
- All other cities have substantial supplies within 100 miles, although per capita supplies are noticeably weaker for London, Glasgow and Edinburgh.
- Supply is generally good at 100 road-miles even when restricted to the two nearest liquefiers, and often very much higher when expanded to increase all liquefiers within that distance. This shows how much LIN could reasonably be called upon should one city decide to expand liquid air transport rapidly. However, in the event of widespread uptake of liquid air, in each case this additional supply would be competed for by a larger number of cities.

These conclusions were tested and are supported by the case studies presented in chapter 8. On this basis we conclude:

- There is effectively no constraint on LIN supply anywhere in the country that would prevent a pilot scheme or early deployment of liquid air technologies;
- The best supplied cities for early deployment include Oxford, Portsmouth, Southampton, Swansea, Cardiff, and Hull;
- Among the five largest cities, Sheffield and Leeds are best supplied;
- In the event of widespread take-up, new liquid air or nitrogen capacity would be required soonest in east London and the West Midlands, as shown in Figure 5;
- Even in the less well supplied cities, substantial supplies of LIN are likely to be available.

There is effectively no constraint on nitrogen supply anywhere that would prevent a pilot scheme or early deployment of liquid air technologies.

# 5 THE PRICE OF LIQUID AIR

New transport demand could double the nitrogen market by 2025.

The prices paid for liquid nitrogen are typically commercially confidential, and governed by contracts negotiated with each customer individually. We understand bulk LIN is currently available at around 5-6p/kg, but prices do vary considerably to reflect sales volumes, delivery distance, the time sensitivity of deliveries, the amount of spare capacity and other variables.

The future price of liquid air is likely to be influenced by some additional factors, including market size, energy inputs and tax treatment. A previous report by CLCF, *Liquid air in the energy and transport systems*, gives the size of the UK nitrogen market as 8,000 tonnes per day, but the deployment of liquid air vehicles projected in chapter 7 implies new transport demand for liquid nitrogen or air of 10,000 tonnes per day in 2025 – more than doubling the current market.

Production at such volumes alone ought to moderate prices, but other factors could also help. New production plant would be required, and if liquid air were chosen over liquid nitrogen, the energy requirement per tonne of cryogen would be a fifth lower than at present. At the same time, rising wind capacity is likely to increase the incidence of negative overnight power prices. Both factors would make liquid air significantly cheaper.

There is also the issue of the tax treatment of liquid air production. Liquid nitrogen is currently seen as an energy intensive industrial commodity and subject to a number of taxes intended to deter energy consumption. Liquid nitrogen or air used as a transport fuel would be quite different, since it acts as a vector to absorb zero or low carbon electricity to displace diesel in transport, so there is strong case for relieving it of at least some of those taxes, as we argue below.

In this report, we assume that spare liquid nitrogen capacity would be used to fuel the deployment of liquid air vehicles until supply constraints or rising LIN prices prompt the construction of new liquid air plants. We have modelled the price of liquid air to understand the potential implications of rising energy costs and make policy recommendations.

The CLCF report presented a model to calculate the cost of producing liquid air from a newly built plant, which concluded costs would range from 3.5p to 4.5p/kg. We have adapted this model as follows:

- Energy costs were updated, and projected to 2025;
- 'Green taxes' were stripped out and projected separately to 2025;
- Distribution costs for a 22 tonne tanker delivery were added on the basis of Spiritus Consulting's estimate of £1.50-£1.75/km, and then modelled for range of future diesel prices.

Our model suggests that on the basis of estimated average off-peak power prices in 2013 (£62/MWh, including taxes), 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 modelled in later sections of this report deliver substantial cost savings and short payback times.

The price of liquid nitrogen depends critically on the cost of the power used to make it, and to a lesser extent on the cost of the diesel used in delivery, and both seem likely to rise in coming decades. Our research suggests the industrial gas industry expects wholesale power prices to remain relatively stable in the medium term, rising at around 2.5% per year. Producers are far more worried, however, about the potential increase in network costs and environmental levies such as Renewable Obligation Certificates (ROCs), Feed-in-Tariffs (FiTs), Climate Change Levy (CCL), which some in the industry expect to rise at 6% per year in aggregate.

The Chancellor announced several measures to reduce the costs of energy intensive industries in this year's budget, but these may be of limited help to the industrial gas industry. Industrial gas producers are already excluded from the EU ETS compensation package by decision of the European Commission (EC). The government has said it will argue the case for including industrial gas producers in Carbon Price Floor (CPF) compensation, but again the decision rests with the EC. The government is also introducing another compensation scheme to cover the costs to industry of the Renewable Obligation and Feed-in-Tariffs, but eligibility has not yet been decided, and guidance is not expected until 2016/17. The Carbon Price Floor is to be frozen at £18 per tonne from 2017, but our modelling suggests the impact of this measure alone on liquid air or nitrogen prices will be modest if the carbon intensity of grid electricity falls at the rate required by the Climate Change Committee, which we assume throughout.

The impacts of power prices, delivery costs and policy measures on projected liquid air prices are illustrated in Figure 6. If there were no relief from green levies and the CPF continued to rise as originally projected, the industrial gas producers' power costs would rise to £99/MWh in 2025, at which price liquid air would cost almost 7p/kg delivered, all other factors being equal. If there were 100% relief on all green levies including the CPF, industrial gas producers' power prices in 2025 would be just £68/MWh, at which price liquid air could be supplied at little more than today's 5p/kg. If the Carbon Price Floor were frozen right through to 2025, but there were no relief from the other green levies, power prices in 2025 would be £94/MWh, and liquid air would cost 6.5p/kg delivered.

There is a strong argument for relieving liquid air or nitrogen used as an energy vector to store 'wrong time' renewable energy of at least some of the burden of the environmental levies on electricity. To impose these levies on liquid air would mean – perversely – that taxes intended to encourage decarbonisation would inhibit the development of a new energy vector capable of delivering major reductions in heavy duty and refrigerated transport emissions. If the aim of policy is to encourage the use of intermittent renewable electricity to displace diesel in transport, and coal and gas on the grid, then the means of storing that energy and delivering it on demand should not be penalised but supported.

This is hardly 'special pleading', since the same argument could be made for batteries, hydrogen and any other technology thought capable of storing and transporting energy and/or cold at reasonable cost. However, liquid air may be at greater risk of fiscal handicap than other vectors because of one if its key strengths – the ability to harness an existing industry. Industrial gas producers have traditionally been seen as heavy *end-users* of energy and been taxed accordingly, but this approach would be counterproductive if their product were being used as a temporary store of wrong time wind energy, for example, with the potential to help decarbonise transport and improve urban air quality. In these circumstances policy should aim on balance to encourage production rather than discourage energy consumption.

The cost of liquid nitrogen depends critically on the price of electricity and 'green levies' – but these should not be imposed on nitrogen used as a low carbon energy vector.

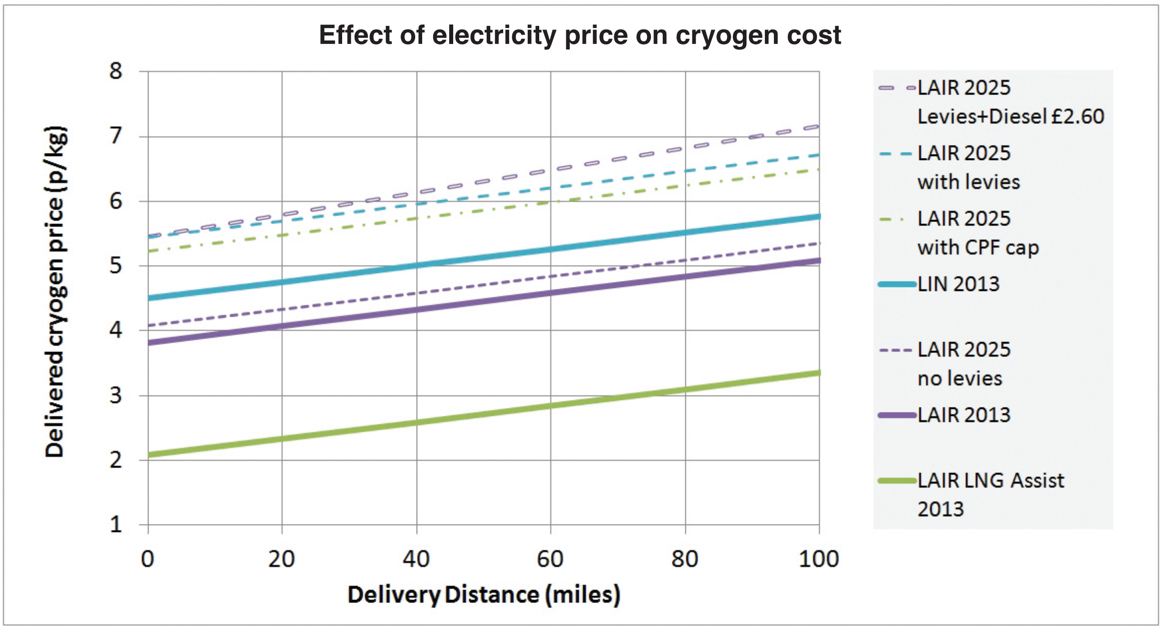



Figure 6: The effect of power prices, electricity levies and delivery distance on the cost of liquid air.

Waste cold from LNG re-gasification could reduce the energy needed to produce liquid air by two thirds.

Diesel costs are also likely to rise, however, and this would affect both the cost of delivering liquid air, and the price of the incumbent competitor. The average price of diesel has risen from just under £0.78/L in 2003 to more than £1.42/L in 2012, even as the tax element has fallen from 74% to 57%.[10] If this trend were to continue, diesel would cost £2.61/L in 2025. At this price, liquid air could be delivered at 7p/kg if all environmental levies on electricity are included, or 6p/kg if excluded.

While these prices represent a significant increase from today, the competitive position of liquid air against diesel would in fact improve in this scenario. At today's costs, the LIN price per kg equals 3.6% of the diesel price per litre; in 2025, the ratio would fall to 2.8%, even with all taxes included (see Table 3). On these assumptions, the financial savings from liquid air vehicles identified today would be significantly higher in 2025.

This is only one scenario, however, and perhaps not the most likely. If the diesel price were to rise this much, it would probably be accompanied by strongly rising oil, gas and power prices, which would raise the cost of liquefaction and erode liquid air's competitive position against fossil fuels. On the other hand, if the rate of oil and gas price inflation were to moderate – Brent crude has been fairly stable at around $110 for three years now – and environmental levies on electricity continued to rise, liquid air's competitiveness would still suffer. The impact of rising diesel prices on the price of liquid air could be eliminated, however, with the development of compact liquefiers sited at transport depots such as bus stations and logistics hubs. Air would then be liquefied right where the vehicles refuel, rather than produced remotely and delivered by road tanker.

In the longer term it may be possible to produce liquid air far more cheaply by exploiting the waste cold from LNG re-gasification, which reduces the energy required by two thirds.[11] On the basis of 2013 electricity prices, we estimate LNG-assisted liquid air could be produced for as little as 2p/kg, and supplied at 100 miles delivery distance for 3.4p/kg (Figure 6). At this price even marginal liquid air applications are transformed into highly profitable investments. However, this is a longer term prospect, and we assume no benefit from LNG in our analysis.

| | With power levies | | Without power levies | |
|---|---|---|---|---|
| | 2013 | 2025 | 2013 | 2025 |
| Off-peak electricity cost, £/MWh | 62 | 99 | 48 | 48 |
| LAIR, £/kg, (diesel = £1.4/L) | 0.051 | 0.067 | 0.045 | 0.054 |
| LAIR – diesel % ratio | 3.6 | 4.8 | 3.2 | 3.9 |
| LAIR, £/kg, (diesel = £2.6/L) | 0.055 | 0.072 | 0.049 | 0.058 |
| LAIR – diesel % ratio | 2.1 | 2.8 | 1.9 | 2.2 |

Table 3: Impact of power prices, taxes and diesel costs on the price of liquid air. Higher diesel costs increase the delivered price of liquid air, but on balance improve its competitive position against diesel

# 6 THE CARBON FOOTPRINT OF LIQUID AIR

As with all energy vectors, the carbon intensity of liquid air depends largely on the amount of electricity required to produce each tonne, and the carbon intensity of that power. Both are projected to fall, and the impacts are illustrated in Figure 7.

We assume the carbon intensity of grid electricity will fall in line with the trajectory required to meet the Committee on Climate Change (CCC) target of 50gCO2/kWh in 2030, compared to around 500g/kWh today, although the government talks of achieving this level of decarbonisation 'during the 2030s'.

Even if the carbon intensity of grid average electricity failed to match CCC trajectory, the cheaper *off-peak* electricity typically used to produce liquid nitrogen could still do so. The CLCF report *Liquid air in the energy and transport systems* showed how emissions from overnight electricity should fall faster because of the greater effect of wind and nuclear generation during periods of low demand.[12] The report found that if in 2030 grid average emissions were still 93g/$CO_2$/kWh, the off-peak emissions could be as little as 53g$CO_2$/kWh – more than 40% lower.

At same time, energy required to produce each unit of cryogen will also fall. Liquid air takes 20% less energy to produce than liquid nitrogen since there is no need to separate nitrogen from oxygen. Under our national projections (chapter 7 below), the current LIN surplus runs out in 2019, at which point we would need to start building new liquid air capacity. The carbon intensity per tonne of cryogen would fall 20% simply because of the lower energy requirement. In our emissions modelling we have assumed a switch from LIN to liquid air in 2019.

The energy required to produce a tonne of liquid air would fall by two thirds if the waste cold from LNG re-gasification were exploited. Another CLCF report, *Liquid air technologies – a guide to the potential*, found the waste cold from projected UK LNG imports in 2030 could support the production of 8 million tonnes of liquid air, almost 22,000 tonnes per day, or ten times current spare LIN capacity.[13] This liquid air would have a dramatically lower carbon footprint, as shown in Figure 7, as well as costing far less (see chapter 5 above). We have not assumed any LNG-assisted liquid air production in our modelling.

The distance over which the cryogen needs to be delivered also affects its carbon intensity, but as Figure 7 shows, the impact is slight compared to the carbon intensity of the electricity used in production.

The well-to-wheels greenhouse gas emissions of liquid air applications depend not only on the carbon intensity of the delivered cryogen, but also the efficiency of the vehicle. Our modelling (chapter 7 below) shows some liquid air applications such as refrigerated trailers are so efficient they produce

The carbon intensity of liquid air depends largely on the amount and carbon intensity of the electricity used to produce it. Both are expected to fall.

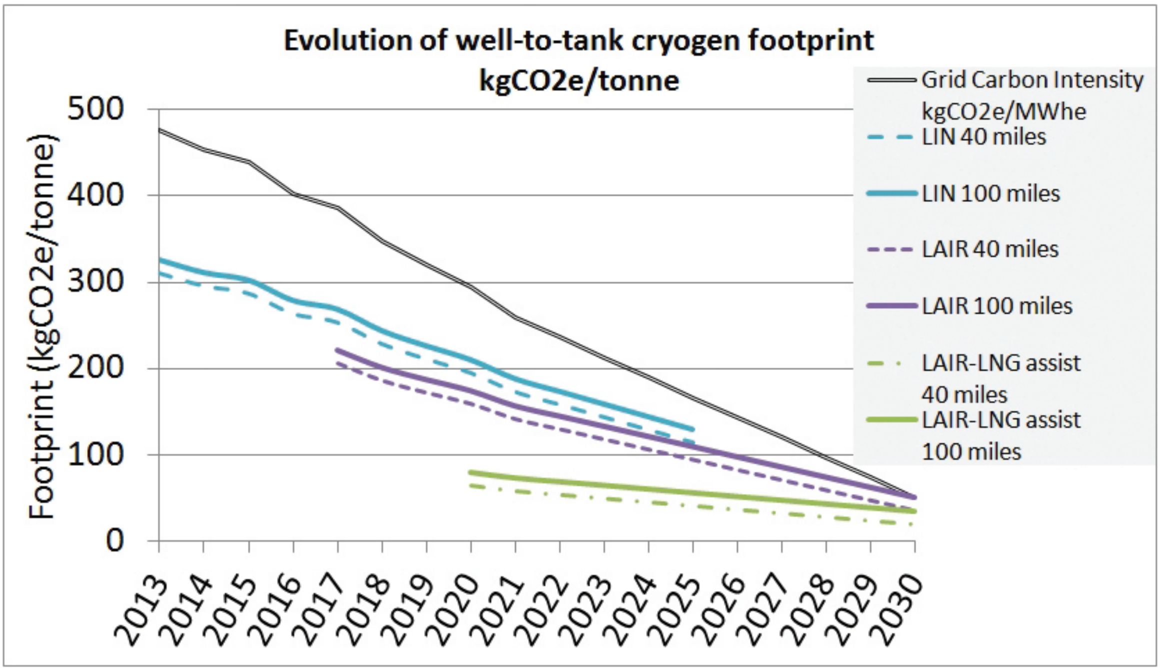



Figure 7: The impact of energy requirement, grid carbon intensity and delivery distance on the carbon intensity of liquid nitrogen and liquid air.

Some liquid air applications are so efficient they cut emissions even on the basis of today's grid electricity, others start to deliver around 2020.

substantial emissions reductions even on the basis of today's grid average electricity, while the others begin to deliver around 2020 depending on which cryogen is used as fuel. The emissions savings grow as grid carbon intensity continues to fall, and by 2025 all the applications modelled nationally produce significant annual and cumulative emissions savings.

We have not considered embedded carbon from production and disposal of liquid air engines, but since they contain no exotic materials such as lithium and platinum their embedded carbon should be lower than for other alternative powertrains. This advantage could become increasingly significant as the carbon intensity of grid electricity falls; *Liquid air in the energy and transport systems* found that on the basis of overnight electricity in 2030 a liquid air car would have lower lifecycle emissions than either an EV or a fuel cell vehicle (FCV).[14]

# 7 THE BUSINESS CASE FOR LIQUID AIR VEHICLES

The national benefit to be gained by deploying liquid air vehicles – and the amount of liquid air required to support it – clearly depends on the numbers sold and their technical performance as ZEVs, heat hybrids or transport refrigeration. This in turn will largely depend on the financial case they present – a function of performance and price. To explore the potential benefits of liquid air on the highway we have analysed five different vehicle concepts, by combining engine and market modelling with real-world data from retail and municipal fleets. These were combined to produce case studies and national projections to test the implications for cost, carbon, air quality and cryogen supply at different scales. Together they make a strong case for deploying liquid air vehicles. The combined results, along with an estimate of potential export earnings from liquid air engines, underpin our estimate of the potential benefit to UK plc. The national business case is presented below, and the regional and sectoral case studies in chapter 8.

Promising applications include refrigerated trucks and trailers, and 'heat hybrid' buses and lorries.

## Modelling approach

Our estimate of potential national demand for liquid air vehicles is based substantially on modelling conducted for the Dearman Engine Company (DEC) by two independent consultancies – E4tech and Ricardo Strategic Consulting – whose work we integrated and calibrated against real-world fleet data to produce new insights. We focused exclusively on Dearman engine applications, since Ricardo's own split cycle engine design is not yet ready for detailed modelling – although preliminary work funded by the Technology Strategy Board suggests it should achieve 60% efficiency compared to around 40% for modern diesel engines.

The characteristics of the Dearman engine (chapter 3) favour applications with a highly transient duty cycle (for instance, with many stop-starts or spikes in power demand); relatively low mileage or return to base operation; and room to accommodate the liquid nitrogen tank. On this basis, the following promising vehicle concepts were selected for study:

- 18 tonne rigid body delivery truck with 230kW 'heat hybrid' engine;
- Bus with 200kW heat hybrid engine;
- 20 foot refrigerated truck (cooling engine only);
- 40 foot refrigerated trailer (cooling engine only);
- Forklift truck with 20kW ZEV Dearman engine;
- Wheel loader with 290kW heat hybrid engine†.

In each case, DEC and E4tech developed a time-power profile for the Dearman application based either on an existing industry duty cycle or primary modelling. For heat hybrid applications the operating regime applied to the ICE-Dearman system is the 'peak lopping' approach, where the highest loads in the duty cycle (acceleration, hill climbs) are met by engaging the auxiliary engine, which allows the main engine to be downsized. This data was combined with Dearman engine cost and performance information to assess the economic and environmental case for each application. The results were compared to a baseline for the incumbent technology to produce financial and greenhouse gas emission reduction cases for all applications, as shown in Table 4 overleaf. Applications with notable cost-saving potential include the refrigerated trailer, the refrigerated delivery truck (when replacing additional power from the lorry's main engine), and the heat hybrid bus and delivery truck applications.

The liquid air refrigerated delivery truck did not compare well against an auxiliary diesel engine, because the auxiliary engine currently runs on (half price) red diesel, and its diesel consumption is in any case modest because the goods compartment is cooled only to 0C, rather than -20C as with the frozen food trailer. The fuel consumption of refrigerated delivery trucks is also sensitive to how often the compartment doors are opened – we assumed three times per hour. The wheel loader required too much liquid air to be viable. Further analysis (chapter 8) indicates the forklift might in fact present a strong financial case in circumstances where annual operating hours are low.

† A tractor-type vehicle with wheels rather than tracks, and articulated digging arms front and back

| | Incremental investment, £ | Incremental operating cost, £/year | Payback (years) | 5yr TCO, £ | 10yr TCO, £ | WTW $CO_2$ crbt grid av | WTW $CO_2$ 2030 | LIN/day kg |
|---|---|---|---|---|---|---|---|---|
| Refrigerated delivery truck | | | | | | | | |
| vs. aux eng. | +50 | +390 | n/a | +2,000 | +3,900 | +27% | -86% | 119 |
| vs main eng. | +2,000 | -680 | 3 | -1,300 | -4,700 | +27% | -86% | 119 |
| vs evap only | +1,600 | -3,100 | 1 | -13,900 | -29,400 | -64% | -65% | 119 |
| 40 ft refrigerated trailer | | | | | | | | |
| vs aux eng. | +270 | -1,200 | <1 | -5,700 | -11,700 | -23% | -92% | 275 |
| vs evap only | +2,600 | -3,100 | <1 | -12,900 | -28,400 | -43% | -46% | 275 |
| ZEV forklift | | | | | | | | |
| vs lead acid batt | -2,700 | +700 | n/a | +900 | +4,600 | +230% | +230% | 509 |
| vs fuel cell | -14,300 | +2,000 | n/a | -4,200 | +6,000 | +380% | -28% | 509 |
| WHR hybrid bus | | | | | | | | |
| vs. 200kW ICE | +6,100 | -2,100 | 3 | -4,400 | -14,900 | +0% | -23% | 185 |
| WHR delivery truck | | | | | | | | |
| vs 290kW ICE | +7,500 | -2,200 | 3 | -3,600 | -14,800 | +16% | -32% | 523 |

Table 4: Modelled performance of various Dearman engine applications. Source: E4tech. Please note these figures represent the difference between the Dearman application and the incumbent technology, and not the absolute values, except for the right hand column, which gives the absolute daily cryogen consumption of each application. Please also note that Dearman engine capital costs assume volume manufacturing of at least a thousand units per year.

Our business case analysis incorporates some of E4tech's results but not all. We relied on their outputs for capital costs, which assume manufacturing volumes of at least 1,000 units per year, and the volumes of diesel and LIN consumed. However, we replaced their financial assumptions with our own. They had assumed £1.42/litre for diesel for example, whereas we assumed a more conservative £1.40 – just below the average price in 2013. Like E4tech we assumed LIN or liquid air would cost 5p/kg ex-VAT, but we did so on the basis of our analysis in chapter 5. Our model is arguably conservative since both diesel and LIN prices are kept static at current levels, whereas there are good reasons to think the price of diesel will continue to rise and the cost of LIN could fall (chapter 5).

We also replaced E4tech's generic assumptions about vehicle operating hours and mileage with real-world fleet data from a range of bus, municipal and logistics operators. These numbers were typically higher than E4tech's initial assumptions, and had the effect of shortening the expected payback times; the more diesel a vehicle consumes, the greater the potential savings offered by a liquid air heat hybrid.

Each refined business case was tested for sensitivity to key input assumptions, and then combined with sales forecasts by Ricardo and E4tech (Table 5) to produce the case studies in chapter 8 and the national projections below. Our outputs include new transport demand for LIN or liquid air, and likely savings in diesel, cost, carbon dioxide emissions and for some applications NOx and PM. The carbon footprint analysis of diesel, LIN and liquid air supply was based on Defra's carbon accounting factors for 2013.[15]

| Annual sales '000 units | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
| Refrig. engine | 0.1 | 0.3 | 1.4 | 2.6 | 3 | 3.1 | 3.2 | 3.3 | 3.4 | 3.5 | 3.6 |
| HCV heat hybrid | 0 | 0 | 0 | 0.25 | 1.5 | 1.5 | 1.75 | 1.75 | 1.75 | 1.75 | 1.75 |
| Bus heat hybrid | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

Table 5: Projected UK sales of liquid air engines. Sources: Ricardo; E4tech

**BOX 3: Working assumptions**

Unless otherwise stated, we have assumed:

- Diesel: £1.40/litre; £1.17 ex VAT
- Red diesel: £0.70/litre; £0.67 ex VAT
- LIN/liquid air: £0.06/kg; £0.05 ex VAT
- Grid electricity decarbonises in line with Committee on Climate Change projections

Heat hybrid buses could save operators £31 million and 162,000t$CO_2$e by 2025.

## National picture

For **urban buses**, if heat hybrids captured 30% of annual sales by the early 2020s the fleet would grow to 4,100 vehicles by 2025, and produce annual fuel savings of £15 million and cumulative fuel savings of £56 million, as shown in Table 6 below.[16] After investment costs, the net benefit is £11 million in 2025, and £31 million for 2015-2025. Because the modelled fleets' operating hours and mileage were higher than initially assumed, return on investment comes in less than two years rather than the expected three. The financial case is so strong that it still delivers a modest return even if diesel were a fifth cheaper and LIN/liquid air a third more expensive than current projected prices. The impact of the Bus Service Operators Grant was not modelled, since recent reforms will break the link between BSOG subsidy and diesel consumption in more than half the bus services in the country.[17]

LIN consumption would rise to almost 390,000 tonnes per year, nearly half the available spare capacity. Liquid air buses would begin to cut well-to-wheels $CO_2$e emissions from 2019 if fuelled on LIN and 2016 if fuelled on liquid air, and the savings grow as grid electricity continues to decarbonise. Assuming a switch from LIN to liquid air in 2019, cumulative $CO_2$e savings would reach 162,000 tonnes in 2025.

In 2030, a fleet of 5,000 vehicles would produce net savings of £15 million and 90,000t$CO_2$e per year.[18] If hypothetically the entire urban bus fleet in Great Britain were to convert to heat hybrids, the savings would be £70 million and 300,000t$CO_2$e respectively.

For **heavy commercial vehicles**, we assumed heat hybrid rigid delivery trucks would achieve sales penetration of 4.7% of the entire market. However penetration would be greater among vehicles weighing less than 26 tonnes, where sales share was estimated at 7.5%, and strongest in the urban delivery segment, where lorries typically weigh 14-20 tonnes and the duty cycle involves lots of stop starts, and here the sales penetration would rise to 30%.

Because of their greater weight and average power requirement, these vehicles would consume more liquid nitrogen than a bus but also save more diesel. By 2025, a projected fleet of just under 12,800 vehicles would save 104 million litres per year of diesel compared to their conventional counterparts, and produce net benefit (fuel savings minus incremental investment) of almost £9 million per year. The business case is more sensitive to input assumptions for lorries than for buses: if diesel and LIN prices both moved 20% 'against' (diesel down, LIN up), then the heat hybrid truck would make losses not savings; but if both moved in favour, annual savings would triple to more than £5,000 per vehicle.

Such a fleet would also reduce well-to-wheel $CO_2$ emissions by over 76,000 tonnes per year if fuelled by liquid nitrogen and 118,000 tonnes if fuelled by liquid air, which requires less energy to produce. Because of the trucks' heavier cryogen consumption, the LIN surplus would be exhausted in 2021, when new liquid air production capacity would be required. By 2025, the fleet would consume 5,500 tonnes of liquid air per day, roughly two and a half times current spare LIN capacity.

In 2030, a fleet of 15,000 vehicles would produce annual savings of £14 million, 120 million litres of diesel and 277,000t$CO_2$e. If hypothetically the entire urban delivery market were to convert to heat hybrids, the savings would be £47 million, 400 million litres and 922,000t$CO_2$e respectively.

For **refrigeration**, we investigated two separate applications: a **20 foot rigid truck**, with the goods compartment cooled to 0°C

**Refrigerated trailers could save their owners £76 million and almost 900,000t$CO_2$e by 2025.**

| 2025 (Annual) | UK sales | Incremental investment, £m | Fuel savings £m | Net benefit £m | WTW $CO_2$e savings kt$CO_2$e | Diesel avoided Litres, m | LIN/LAIR cnsmptn ktpd | NOX saving tonnes | PM saving tonnes |
|---|---|---|---|---|---|---|---|---|---|
| Bus 'heat hybrid' | 674 | 4.1 | 14.9 | 10.8 | 52 | 29.4 | 1.1 | not modelled | |
| HCV 'heat hybrid' | 1,750 | 12.1 | 20.8 | 8.7 | 118 | 104 | 5.5 | not modelled | |
| 20' refrig. truck | 900 | 4.0 | 2.0 | 2.0 | 17 | 12 | 0.6 | not modelled | |
| 40' cooled reefer | 1,800 | 0.5 | 16.4 | 15.8 | 217 | 104 | 3.5 | 1,800 | 1,800 |
| TOTALS | 5,124 | 20.8 | 54.1 | 37.3 | 404 | 250 | 10.7 | - | - |
| | | | | | | | | | |

| 2015-2025 (Cumulative) | UK sales | Incremental investment, £m | Fuel savings £m | Net benefit £m | WTW $CO_2$e savings kt$CO_2$e | Diesel avoided m litres | Fleet size | Sales share | Simple payback years |
|---|---|---|---|---|---|---|---|---|---|
| Bus 'heat hybrid' | 4,127 | 25 | 56 | 31 | 162 | 111 | 4,127 | 30% | <2 |
| HCV 'heat hybrid' | 12,785 | 88.4 | 88.2 | 0.2 | 261 | 441 | 12,785 | 7.5% | ~4 |
| 20' refrig. truck | 5,850 | 14.1 | 20.6 | 6.6 | 50 | 64 | 5,850 | 15% | <3 |
| 40' cooled reefer | 13,750 | 3.9 | 79.6 | 75.7 | 881 | 505 | 12,850 | 30% | <1 |
| TOTALS | 36,512 | 131.4 | 244.4 | 113.5 | 1,355 | 1,121 | 35,612 | | |

Table 6: National costs and benefits of sample liquid air vehicles

by a compressor run off the main engine; and a **40 foot refrigerated trailer** (or 'reefer'), cooled by an auxiliary diesel engine, either to -20°C throughout, or subdivided into frozen, chilled and ambient compartments, widely used in supermarket distribution. E4tech's forecast of annual sales of 3,600 refrigeration units by 2025 was adjusted to reflect the relative strength of the business case for each application.

If **rigid liquid air-refrigerated trucks** achieved a sales penetration of 15% in the early 2020s, by 2025 a fleet of 5,850 would produce annual fuel savings of £4 million and net benefit of £2 million. The cumulative impacts include fuel savings of almost £21 million, net benefit of almost £7 million and avoided emissions of more than 50,000t$CO_2$e. Each vehicle would pay for itself in under three years, and the fleet would consume 570 tonnes of LIN per day, just over a quarter of current spare capacity. The business case is robust: even if the prices of both diesel and liquid nitrogen move 20% against, zero-emission refrigeration costs scarcely more than the highly polluting diesel alternative; if both move 20% in favour, annual savings are two and a half times higher than in the central scenario at £1,400 per vehicle.

By 2030, a fleet of 6,000 would produce net benefit of £2.4 million per year, and annual emissions savings of almost 30,000t$CO_2$e, as the grid continues to decarbonise. If hypothetically the entire fleet were to convert to liquid air refrigeration, the savings in 2030 would be £16 million and 200,000t$CO_2$e.

For **liquid air refrigerated trailers** the business case is even stronger, despite the auxiliary diesel engine running on (half price) red diesel. The incremental capital cost is trivial, since one stand-alone piston engine is being replaced with another, and each liquid air unit would pay for itself in less than three months. Assuming a sales penetration of 30% in the early 2020s, equivalent to half the total sales of refrigerated trailers to the top 30 operators, a fleet of almost 13,000 liquid air trailers would generate fuel savings of £16.4 million and net benefit of around £15.9 million per year. The cumulative fuel savings would be £80 million and the cumulative net benefit £76 million. The business case is robust and fails only if the prices of both red diesel and LIN/liquid air move 20% against. Since existing trailer refrigeration units are less strictly regulated than propulsion engines, and therefore inefficient, annual greenhouse gas savings exceed 217,000t$CO_2$e per year, and 880,000t$CO_2$e cumulative.

By 2030, a fleet of 15,000 would produce annual net benefit of £18.5 million and emissions savings of 326,000t$CO_2$e. If hypothetically the entire fleet were to convert to liquid air refrigeration, the savings would be £63 million and more than 1 million t$CO_2$e.

Diesel refrigeration units also emit high levels **of local air pollutants**; far higher, in fact, than a modern diesel lorry engine. Our projected fleet of 13,000 liquid air refrigerated trailers in 2025 would reduce emissions of nitrogen oxides (NOx) by over 1,800 tonnes, equivalent to taking almost 80,000 Euro 6 lorries off the road. It would also eliminate 180 tonnes of particulate matter (PM), equal to removing 367,000 such lorries from service (see Chapter 9).

## Combined UK impact

If the numbers of all the vehicles modelled were to grow by the projected rate (Table 6 above), by 2025 a combined fleet of around 36,500 would generate annual fuel savings of £54 million and net benefit of £37 million, while the cumulative figures would reach £244 million and £113 million respectively (Table 6). $CO_2$e emissions savings would rise to 404,000 tonnes per year, and the cumulative saving almost 1.4 million tonnes. The liquid air fleet would also save a cumulative 1.1 billion litres of diesel, and sharply reduce emissions of local air pollutants (see Chapter 9), although we have modelled this only for refrigerated trailers. Once vehicles are equipped with a tank of cryogenic fuel, the cooling potential could be used to further increase vehicle efficiency in various ways (chapter 10).

By 2030, the projected fleet would produce annual net benefit of almost £50 million, and emissions savings of 723,000t$CO_2$e. If hypothetically all these applications captured 100% of their respective markets, the savings would be £196 million and 2.4 million t$CO_2$e per year.

The liquid air fleet would exhaust current spare LIN capacity in 2019, and by 2025 would consume more than 10,000 tonnes of liquid air per day, almost five times current spare capacity. This would represent a major opportunity for the industrial gas producers. To satisfy this level of demand would require 14 new liquefiers costing £242 million to build, and potentially generating revenue of £143 million per year (Table 7 below). Total revenue from new transport demand for LIN and liquid air, including that satisfied by existing spare capacity, could be £195 million per year.

The liquid air fleet could save Britain £113 million and 400,000t$CO_2$e by 2025.

| New cryogen production capacity required | t/day | mt/year |
|---|---|---|
| New LIN/LAIR demand | 29,227 | 10.67 |
| Spare LIN capacity | 2,205 | 0.80 |
| New LAIR capacity required | 27,022 | 9.86 |
| | | |
| **600tpd liquefier** | | |
| Annual production, tonnes | | 216,000 |
| Capital cost, £million | | £17 |
| Liquefiers needed to supply new demand | | 46 |
| Investment cost, £million | | £773 |
| Revenue from new liquefiers/year, £million | | £493 |
| Revenue from spare capacity, £million | | £40 |
| Total revenue from transport LAIR demand, £million | | £533 |

Table 7: Additional liquid air capacity required to support projected fleet

Manufacturing liquid air engines could bring export revenues of over £700 million and create more than 2,100 jobs.

## UK production, exports and jobs

The Dearman, Ricardo and EpiQair engines may be British inventions, but if liquid air vehicles develop as planned, they would also be sold abroad. Indeed, sales projections developed by Ricardo Strategic Consulting and E4tech for the Dearman Engine Company suggest UK sales of liquid air engines in 2025 of just under 6,000, while worldwide sales top 550,000, swelled by booming demand in Asia for refrigerated and air conditioned vehicles, and 3-wheeler taxis, known as 'tuk tuks'. Many countries would no doubt produce the vehicles domestically under licence, but since Britain is already a major engine producer, exporting 1.6 million units, more than half its output, in 2012[19], it is fair to assume a portion of global liquid air engine sales would be exports from the UK.

To assess the potential impact of liquid air on vehicle manufacturing, exports and jobs in the UK, we first assumed that all sales forecast for China, India, the rest of Asia, and South America would be produced in those countries or regions. For the remainder we devised two scenarios:

- Cautious: Britain manufactures all liquid air vehicle systems sold in the UK and the EU only;
- Ambitious: Britain manufactures all liquid air vehicle systems sold in the UK, the EU and the 'rest of the world', meaning the main markets bar those excluded above – principally North America, Russia and Australia.

For the UK, the analysis relies on the vehicle deployment modelled in this report, and for all other countries it depends on sales projections developed by Ricardo Strategic Consulting and E4tech. E4tech then used these figures to calculate the impact each scenario would have on the economy and jobs in Britain, using a slightly modified version of DECC's Technology Innovation Needs Assesment (TINA) methodology.

First, the analysts estimated the value from the projected sales volumes of various implied revenue streams: engine manufacture; onboard nitrogen storage tank; additional components; vehicle integration; manufacturer mark-up; dealer mark-up; and liquid nitrogen sales. Then they estimated how much of each revenue stream would accrue to Britain, and the value of any current economic activity that would be displaced. This then allowed them to calculate the additional revenue to British companies, and the Gross Value Added – a measure of economic value, equivalent to GDP after taxes and subsidies have been discounted. Finally, they combined GVA with standard multipliers from the BIS (Department for Business, Innovation and Skills) annual business survey to estimate the number jobs that would be created.

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, generating net revenues of £276 million and net GVA of £47 million, and create or maintain almost 1,100 jobs.

| | Engines made in UK, 2025 1000s | UK Gross Revenues, 2025, £m | UK Net GVA, 2025, £m | New jobs by 2025 | Engines made in UK 2015-2025 1000s | UK Revenues 2015-2025, £m |
|---|---|---|---|---|---|---|
| UK sales to UK | 5 | £175 | £18 | 675 | 38 | £921 |
| UK sales to EU | 46 | £180 | £29 | 410 | 296 | £1,130 |
| UK sales to RoW | 122 | £474 | £81 | 1,034 | 598 | £2,240 |
| | | | | | | |
| Cautious: UK + EU | 51 | £355 | £47 | 1,085 | 333 | 2,052 |
| Ambitious: UK + EU + RoW | 173 | £829 | £129 | 2,119 | 931 | 4,292 |

Table 8: UK revenue and jobs impact of liquid air engine manufacturing and exports.

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

If Britain were to capture all sales in the UK, EU and the 'Rest of the World' (principally North America, Russia, Australia), it would manufacture 173,000 engines in 2025, generating 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[20], while 2,100 new jobs broadly matches the 2,200 the fuel cell and hydrogen industry has predicted it will create in Britain by 2020.[21]

The production of liquid air vehicles in Britain would also play to the country's traditional strength in cryogenics, much of it concentrated in and around Oxfordshire. The industry is represented by the British Cryogenics Cluster, an organisation whose 70 members have a combined turnover of some £2 billion and employ 20,000 people.

The Cluster includes multinationals including Siemens, Agilent Technologies, Linde and Air Products, but predominantly comprises Small and Medium Enterprises (SMEs), which could particularly contribute to and benefit from the development of liquid air vehicles in Britain. Many of these companies employ 20-100 people, turn over £10-£20 million, and could respond nimbly to the needs of low volume vehicle production. They include companies such as the tank manufacturer Wessington Cryogenics, based in Tyne & Wear; Quantum, which makes electronic monitoring equipment; and piping specialist Thames Cryogenics.

British cryogenic companies already export around the world against competition from low cost manufacturers in developing countries, and some have worked with the motor industry. Others, such as Bestobell Cryogenic Valves, are growing strongly by supplying the LNG industry, and the emergence of a new liquid air vehicle sector could have a similar impact. Growing SMEs are very likely to take on both graduates and apprentices.

**Liquid air would play to Britain's traditional strength in cryogenics.**

# 8 CASE STUDIES

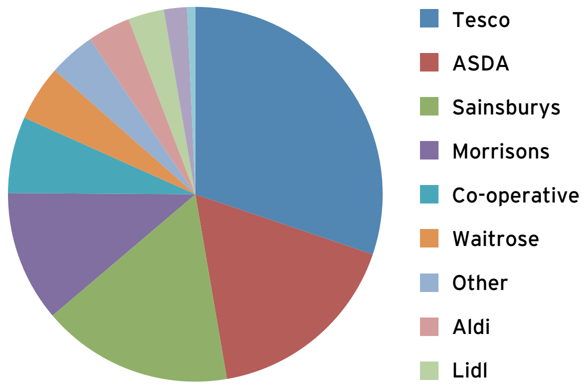
Liquid air vehicles could save the supermarket sector £19 million and over 250,000t$CO_2$e by 2025.

The case studies in this chapter are based on data supplied by a range of supermarkets, transport operators and local authorities, and are intended to illustrate the potential impacts of liquid air vehicles on business sectors and regions. We used the data to calibrate our initial modelling and to test the implications for cost, carbon, air quality and cryogen supply. The case studies also informed the modelling in our national business case analysis in chapter 7.

## Supermarket sector

The UK grocery market could benefit substantially from liquid air. Supermarkets run large fleets of refrigerated vehicles, where liquid air looks particularly attractive, which are likely to expand as online shopping and home delivery continue to grow. The resurgence of smaller supermarkets and convenience stores in town centres, many of which are covered by Air Quality Management Areas, can only increase the need for distribution vehicles with lower NOx and PM emissions and which are quieter.

Supermarkets' transport $CO_2$ emissions are not directly regulated but are reported annually. Adopting liquid air vehicles would allow operators immediately to reduce their Scope 1 emissions – those made directly by the company (see Box 1, page 7). Many supermarket chains have also set themselves stiff well-to-wheels (WTW) emissions reduction targets, which liquid air vehicles could help them achieve as the carbon intensity of grid electricity falls. The opportunity is substantial, since the sector is forecast to grow from £170 billion in 2013 to £206 billion by 2018.[22] Supermarkets including Nisa-Today's and Marks & Spencer are trialling refrigeration based on the simple evaporation of liquid nitrogen, but the liquid air 'cooling and power' approach would be more efficient (see Chapter 9) delivering financial and emissions savings.




| Supermarket | Market share |
|---|---|
| Tesco | 29.8% |
| Asda | 17.2% |
| Sainsbury's | 16.8% |
| Morrisons | 11.5% |
| Waitrose | 4.8% |
| Iceland | 2.0% |
| Aldi | 3.9% |
| Lidl | 3.0% |

Table 9: UK supermarkets by market share, November 2013. Source: Kantar Worldpanel[23]

This case study is based on confidential fleet data supplied by three supermarket chains – Sainsbury's, John Lewis Partnership and Iceland Foods Ltd – which together form a significant percentage of the supermarket sector. Fuel economy, mileage and duty cycle data were analysed and blended, and grossed up to represent the entire sector. The market penetration of various liquid air vehicles was derived from Ricardo Strategic Consulting and E4tech, and projected over a 10 year roll-out period. The results of this case study – and the others – informed the national projections presented in chapter 7. Our model is arguably conservative since both diesel and LIN prices are kept static at current levels, whereas there are good reasons to think the price of diesel will continue to rise and the cost of LIN could fall (chapter 5).

For **rigid delivery trucks** weighing less than 26 tonnes, we assumed liquid air heat hybrids would capture just 7.5% of annual sales, but 30% of sales in the urban delivery market (14 – 20 tonnes), where the competitive advantage is greatest. For the supermarket sector this results in a fleet of 586 in 2025 (Table 10 below). Each vehicle pays for itself in just over 4 years, and from 2025 onwards the net financial benefit is £400,000 per year. Fleet operators would be able to report immediate reductions in Scope 1 emissions, and by 2025 the cumulative WTW carbon savings reach almost 12,000t$CO_2$e. Annual net reductions of 5,400t$CO_2$e in 2025 would continue to grow thereafter as the carbon intensity of grid electricity falls. By 2025 the

| | Incremental investment, £m | Fuel savings, £m | Net benefit, £m | WTW $CO_2$ savings $ktCO_2e$ | Diesel avoided m litres/yr | LIN/LAIR consumption, tpd | NOX saving tonnes | PM saving tonnes | Simple payback, years | Sales share | Fleet size |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2025, annual | | | | | | | | | | | |
| **HCV heat hybrid** | 0.6 | 1.0 | 0.4 | 5 | 4.8 | 252 | not modelled | | ~4 | 7.5% | 586 |
| **Refrigerated HCV** | 0.1 | 0.2 | 0.1 | 1 | 0.6 | 29 | not modelled | | <3 | 15% | 300 |
| **Refrigerated trailer** | 0.12 | 4.0 | 3.9 | 54 | 26 | 725 | 450 | 45 | <1 | 30% | 3,165 |
| **TOTAL** | 0.8 | 5.2 | 4.4 | 65 | 31.4 | 1,006 | - | - | | | 4,051 |
| 2025, cumulative | | | | | | | | | | | |
| **HCV heat hybrid** | 4.0 | 4.1 | 0.03 | 12 | 20.3 | - | - | - | - | - | - |
| **Refrigerated HCV** | 0.7 | 1 | 0.3 | 3 | 3.16 | - | - | - | - | - | - |
| **Refrigerated trailer** | 0.9 | 19.6 | 18.7 | 217 | 125 | - | - | - | - | - | - |
| **TOTAL** | 5.6 | 24.7 | 19.0 | 254 | 148.0 | - | - | - | - | - | - |

Table 10: Supermarket sector, liquid air costs and benefits

**Liquid air refrigerated trailers could reduce supermarkets' NOx emissions by 450 tonnes, equal to taking 19,000 Euro 6 lorries off the road.**

fleet would have saved 20 million litres of diesel and would be consuming just over 250 tonnes of liquid air or nitrogen per day, 11% of the current surplus.

For **refrigeration**, E4tech modelled two separate applications: a **20 foot rigid truck**, with the goods compartment cooled to 0°C by a compressor run off the main engine; and a **40 foot refrigerated trailer** (or 'reefer'), cooled by an auxiliary diesel engine to -20°C throughout, or subdivided into frozen, chilled and ambient compartments.

For **rigid refrigerated trucks**, a sales penetration of 15% would produce a supermarket fleet of around 300 vehicles in 2025. Cumulative incremental investment of £700,000 would produce operating savings of £1 million, giving a net financial benefit of £300,000. From 2025, annual replacement costs of £100,000 would produce twice that in operating savings, giving a net financial benefit of £100,000 per year. Cumulative carbon savings would reach 2,600$tCO_2e$ in 2025, and annual savings of almost 900$tCO_2e$ would continue to rise thereafter. The fleet would have saved over 3 million litres of diesel, and would consume just 29 tonnes of liquid air or nitrogen per day, or 1.3% of the current surplus.

For **liquid air refrigerated trailers** the business case is even stronger, despite the auxiliary diesel engine running on (half price) red diesel. The incremental capital cost is trivial, since one stand-alone piston engine is being replaced with another. Analysis of partner data revealed supermarkets run their refrigerated trailers far more intensively than first assumed – typically 13 hours per day rather than nine – meaning the returns were even higher, and each liquid air unit would pay for itself in less than three months.

On this basis we assumed a higher sales penetration of 30%, producing a fleet in the supermarket sector of almost 3,200 liquid air refrigerated trailers in 2025. A cumulative incremental investment of less than £1 million would produce operating savings almost 20 times larger, and a net financial benefit of almost £19 million. The net benefit from 2025 would run at almost £4 million per year. These trailers would produce modest net $CO_2$ savings immediately, and by 2025 annual reductions would reach 54,000$tCO_2e$, while cumulative savings would top 217,000$tCO_2e$. By now the fleet would have saved 125 million litres of diesel, and would consume 715 tonnes of cryogen per day, a third of the current surplus.

**Supermarkets could also achieve substantial reductions in local air pollutants** by adopting liquid air trailers. Comparing regulatory standards suggests that a diesel trailer refrigerator engine emits six times as much NOx and 29 times as much PM than a Euro 6 lorry engine (see Chapter 9). On this basis, a supermarket fleet of roughly 3,200 liquid air trailers would reduce NOx emissions by 450

Liquid air vehicles could save Leeds £14.5 million and 50,000t$CO_2$e by 2025.

| 2025 | Vehicles bought | Incremental investment, £m | Operating savings, £m | Net benefit, £m | Diesel saved m litres | $CO_2$e saved (LIN) kt$CO_2$e | $CO_2$e saved (LAIR) kt$CO_2$e | LIN/LAIR demand tpd | Share of local LIN 'surplus' % |
|---|---|---|---|---|---|---|---|---|---|
| Arriva Yorkshire | | | | | | | | | |
| annual | 35 | 0.2 | 1.1 | 0.9 | 2.1 | 3.5 | 4.0 | 77 | 8 |
| cumulative | 279 | 1.7 | 4.9 | 3.2 | 9.7 | 11.0 | 14.6 | | |
| First Bus | | | | | | | | | |
| annual | 123 | 0.7 | 3.7 | 3.0 | 7.4 | 12.1 | 14.1 | 270 | 28 |
| cumulative | 977 | 6.0 | 17.2 | 11.2 | 34.0 | 38.5 | 51.3 | | |
| Leeds City Council | | | | | | | | | |
| annual | 0 | 0 | 0.07 | 0.07 | 0.35 | 0.3 | 0.5 | 19 | 2 |
| cumulative | 49 | 0.34 | 0.43 | 0.09 | 2.1 | 0.3 | 1.5 | | |
| Totals | | | | | | | | | |
| annual | 158 | 0.9 | 4.9 | 3.9 | 9.8 | 15.9 | 18.6 | 366 | 38 |
| cumulative | 1,305 | 8.0 | 22.5 | 14.5 | 45.8 | 49.9 | 67.4 | | |

Table 11: Leeds City Region, liquid air costs and benefits. Note Leeds City Council's refuse collection fleet conversion would be completed by 2021

tonnes, equal to taking 19,000 Euro 6 lorries off the road. It would also eliminate almost 45 tonnes of PM each year, equal to removing 93,000 such lorries from service. The same results could be achieved using simple liquid nitrogen evaporative cooling, which has been trialled by several supermarkets, but the liquid air 'cooling and power' approach would be more efficient and require less cryogen per unit of cooling.

To summarise, if the supermarket sector were to convert to liquid air as projected, by 2025 a fleet of more than 4,000 vehicles would have delivered cumulative fuel savings of almost £27 million and net benefit of £19 million (Table 10 above). The annual net benefit would be £4.4 million from 2025 onwards. Cumulative net carbon emissions would be reduced by more than a quarter of a million tonnes, while the fleet would consume 996 tonnes per day, or 45% of the current LIN surplus.

## Leeds City Region

Leeds City Region, which includes Bradford, York and Wakefield, has an economy worth £54 billion and generates 4% of the UK's economic output. Leeds has a particular problem with local air pollution, and West Yorkshire is one of the regions likely to breach the 2015 EU limits (see Chapter 9).

Of Britain's five largest cities, Leeds is among the better supplied with liquid nitrogen, and can draw on 225 tonnes per day of spare LIN capacity within about 40 miles and over 1,000tpd within 100 miles.

**Arriva Yorkshire is the region's second largest bus operator**, with a fleet of 340 buses that travel 1.3 million miles per month from five depots to the southeast of Leeds. Data supplied by the company showed its buses operate for significantly more hours per day than assumed in the initial E4tech modelling, meaning the potential operating savings (diesel saved minus LIN bought) were larger, and a return on investment would come in less than two and a half years per vehicle rather than the predicted three. As shown in Table 11, if the company were to convert its entire fleet (279 buses, excluding the smaller 'Midi' buses) over the course of ten years, the incremental investment cost would be £1.7 million, but the cumulative fuel savings after a decade would be £4.9 million, giving a net benefit of £3.2 million. Annual net benefit from 2025 onward would be £860,000.

These buses would be carbon neutral on the basis of the carbon intensity of grid average electricity from 2018, but could immediately report a 20 tonne reduction per bus in Scope 1 emissions – those made directly by the company (see Box 1, page 7). The fleet would make progressively larger WTW carbon savings as more vehicles were converted and grid emissions continue to fall. By 2025, cumulative carbon savings would range from 11,000t$CO_2$e for liquid nitrogen to 14,600t$CO_2$e for liquid air. The bus fleet would consume just 8% of the spare LIN capacity within 100 miles.

Arriva Yorkshire has a market share of around 20%, and the regional market leader, First Bus, has around 70%. If both were to convert their fleets, the combined net financial savings after conversion would amount to almost £4 million per year and more than £14 million in total. The combined fleets would consume 36% of the spare LIN capacity within 100 miles. In 2025, cumulative emissions savings would be at least 50,000t$CO_2$e, and then continue to grow by 16,000t$CO_2$e per year.

**Rubbish collection is another area of transport that ought to present a strong case for converting to a liquid air heat hybrid engine.** Leeds City Council runs a fleet of 74 standard 26 tonne bin lorries with an average fuel economy of less than 4mpg; rubbish collection accounts for just 7% of the council's fleet, but 25% of its fuel bill. Bin lorries also typically emit high levels of local air pollutants, because of the additional strain on the engine of powering the hydraulic compacter and bin lifting equipment.

However, while bin lorries are thirsty vehicles, their annual mileage is typically low, meaning the potential fuel savings from conversion are also small. In Leeds, our analysis of the data provided by the city council showed the *average* mileage of the fleet too low to justify the additional investment. On further investigation, however, it transpired the average was depressed by a minority of vehicles with very low mileage, and once excluded, the business case improved. If the 49 vehicles with the highest mileage, representing two thirds of the fleet, were converted to heat hybrids over the course of a decade, an incremental investment of £340,000 would produce fuel savings of £430,000, and a net benefit of £90,000, and each vehicle would pay for itself in 4.8 years. In 2025, the fleet would consume just 2% of the current local LIN surplus, and by then would have saved 1,500t$CO_2$e.[24] Although the financial and carbon case is not as strong for bin lorries as for buses, Scope 1 emissions for each of these higher mileage vehicles would immediately fall by 23 tonnes per year.

It may be possible to raise the fuel efficiency of bin lorries, and reduce their NOx and PM emissions, sooner and more cheaply by installing a stand-alone liquid air auxiliary power unit to power the vehicle's compactor and bin lift, rather than installing a fully integrated heat hybrid powertrain. As with refrigerated trailers, this would eliminate all emissions from the functions supplied by the auxiliary engine, and would not require power from the two engines to be blended through a single transmission.

In summary, if Leeds were to convert the bulk of its bus and bin lorry fleets to liquid air heat hybrids, by 2025 cumulative net benefit would be £14.5 million, and the continuing annual net benefit £4 million. Greenhouse gas emissions would be reduced by a cumulative 50,000t$CO_2$e, and annual emissions savings of at least 16,000t$CO_2$e in 2025 would grow in subsequent years as the carbon intensity of grid electricity continues to fall.

## London buses

We selected London for a second bus case study because it is by far the largest market, but its liquid nitrogen supply is weak, particularly to the east of the city. Again, E4tech's application modelling was calibrated using local fleet data to test the financial, environmental and cryogen supply impacts of the adoption of heat hybrid buses in the capital. London could draw on 700 tonnes of spare LIN capacity today from plants at Thame, Didcot and Fawley.

Go-Ahead Group is a major public transport operator with a fleet of 1,855 buses in London, almost a quarter of the total. The company provided fuel economy, mileage and duty cycle data for three of its depots in south London, which we used to model several scenarios.

If Go-Ahead were to convert all the buses excluding electric hybrids at the three depots over ten years to 2025, a cumulative investment of £3.2 million would produce operational savings of more than £11 million and net benefit of £8 million, as shown in Table 12 below. The company would also have saved over 22 million litres of diesel and reduced emissions by almost 31,000t$CO_2$e. The fleet would consume 164 tonnes of liquid air per day, or 23% of local spare liquid nitrogen capacity.

If Go-Ahead were to convert all its London buses excluding electric hybrids over the same period, an investment of £9 million would deliver operational savings of £33

London could convert a third of its bus fleet to heat hybrids before exhausting local spare nitrogen capacity.

The biggest opportunity for liquid air forklifts may be at major distribution centres where forklift utilisation is relatively low.

| 2025 | Number of buses | Incremental investment, £m | Operating savings, £m | Net benfit, £m | Diesel saved m litres | $CO_2e$ saved $ktCO_2e$ | LIN demand tpd | Share of local LIN 'surplus' |
|---|---|---|---|---|---|---|---|---|
| **Go-Ahead 3 depots** | | | | | | | | |
| annual | 522 | 0.3 | 2.3 | 2.0 | 4.5 | 8 | 164 | 23% |
| cumulative | 522 | 3.2 | 11.2 | 8.0 | 22.1 | 31 | | |
| **Go-Ahead all buses** | | | | | | | | |
| annual | 1,532 | 0.9 | 6.7 | 5.8 | 21.6 | 25 | 483 | 68% |
| cumulative | 1,532 | 9.3 | 32.8 | 23.5 | 64.9 | 90 | | |
| **London buses, 30% share** | | | | | | | | |
| annual | 1,902 | 1.2 | 8.4 | 7.2 | 17 | 30 | 599 | 84% |
| cumulative | 1,902 | 11.6 | 40.8 | 29.2 | 81 | 112 | | |

Table 12: London buses, liquid air costs and benefits

million and net benefit of £23 million. The company would also have saved 65 million litres of diesel and reduced emissions by more than 90,000t$CO_2$e. The fleet would consume 483 tonnes of liquid air per day, or 68% of the current local liquid nitrogen 'surplus'.

If instead liquid air heat hybrid buses achieved a 30% market share of the entire London bus market over the same period, a collective investment of less than £12 million would produce a net benefit of more than £29 million and reduce emissions by 112,000t$CO_2$e. The fleet would consume 600 tonnes of liquid air per day, or 84% of the current local nitrogen surplus. This demonstrates that even in the city with the worst per capita LIN supply in the country, up to a third of the bus fleet could be converted to heat hybrids before exhausting current spare capacity.

## Forklift trucks

Initial modelling of the liquid air forklift truck did not look particularly promising. On a forklift, the liquid air engine would act not as a heat hybrid but as a zero-emission main drive engine, competing with battery electric and hydrogen. E4tech's modelling (Table 4) showed the liquid air truck would have lower capital costs than the battery electric machine, and much lower than the fuel cell option, but would be more expensive to operate because of the relatively low cost of electricity. Over ten years, the Total Cost of Ownership (TCO) of the liquid air forklift would be £4,600 higher than the battery electric and £6,000 higher than the hydrogen alternative.

However, the amount of liquid air required depends entirely on how intensively the forklift is operated. In a distribution hub, for example, the machines may only be needed intermittently to load lorries and otherwise remain idle for much of the time. Data supplied by a major supermarket chain showed that more than a third of its relevant electric forklifts ('reach' and 'counterbalance' types) operate for fewer than 2,000 hours per year, with a median of 1,500 hours. On this basis the liquid air machine becomes far more attractive since less cryogen is required.

We estimate the liquid air forklift's TCO would be £8,500 lower than that of a hydrogen machine over five years, and £2,600 lower over ten years. The benefit shrinks over time, as liquid air's higher operating costs progressively eat into its capital cost advantage, but remains substantial even after a decade. Against the standard BEV forklift, where the liquid air machine's capital cost advantage is not as great, its five year TCO would be £600 lower, but its ten year TCO would be £1,500 higher.

The business case against the BEV is quite sensitive to the fuel price, however, and if we replace our usual 5p/kg cryogen cost assumption with 4p/kg – entirely plausible at high volumes, or with on-site or LNG-assisted production – the case becomes incontrovertible. The liquid air machine costs £5,400 less to own over five years, and over ten it is £8,100 cheaper. This suggests the biggest opportunity for liquid air forklifts may be at major distribution centres that are already supplied with large volumes of liquid air for other applications such as trailer refrigeration, and where forklift utilisation is relatively low. On the other hand, higher cryogen prices would make the economics less attractive.

In any event, if the liquid air forklift captured just 15% of sales in the low-utilisation-battery-electric market by the early 2020s, the fleet would grow to almost 1,400 units in 2025 and deliver a cumulative net benefit of £12 million at 5p/kg, or £16 million at 4p/kg, and would consume more than 20% of the current nitrogen surplus. The well-to-wheel carbon emissions would be higher than those of a battery electric, but these are in any case extremely small in the overall context of total national carbon emissions.

The government could procure eleven times more low carbon buses as liquid air heat hybrids than as electric hybrids for the same money.

### BOX 4: Heat hybrid versus electric hybrid

Many bus companies are converting to electric hybrid powertrains, which reduce diesel consumption by around a quarter, but also raise the capital cost of a bus by about 50% – from around £200,000 to £300,000. The taxpayer has subsidised 70% of the additional cost through the Green Bus Fund. A liquid air heat hybrid would be far cheaper to buy, at around £206,000 assuming volume production, and would save almost as much diesel, but its need for liquid air would increase operating costs by around £9,000 per year compared to the electric hybrid. Which is better?

As things stand, the bus operator would be foolish to choose anything other than the electric hybrid, but this is entirely due to the impact of the large capital subsidy – as shown in Table 13. After five years, the bus company's Total Cost of Ownership (TCO) would be almost £27,000 lower owning a subsidised electric hybrid compared to a standard diesel model, and only £17,000 lower if it chose the liquid air heat hybrid. Remove the subsidy from the equation, however, and the electric hybrid's TCO would be £43,000 higher than the diesel, and £60,000 higher than the heat hybrid.

If the heat hybrid were to receive the same level of subsidy as the electric hybrid, the TCO saving to the bus operator would be more than three times larger – £87,000 rather than £27,000. Alternatively, if the subsidy did not exist, and the bus company opted for the heat hybrid, it would still be £17,000 better off compared to owning a diesel, the Treasury would save £70,000 and emissions would fall by about the same amount. Put another way, the government spent around £87 million on the first four funding rounds of the Green Bus Fund, which subsidised the purchase of 1,187 electric hybrid buses. Had heat hybrids been available, and had the government funded 100% of the incremental capital expenditure, it could have procured over 14,500 buses – eleven times more.

The heat hybrid would pay for itself in half the time taken by the electric hybrid – 1.3 years rather than 2.6. After five to seven years the electric hybrid would need to replace its battery, which we estimate conservatively would cost £25,000. So after a decade, the annual return on investment would be three times higher for heat hybrid (66%) than the electric (20%). Yet still the cash impact of the initial subsidy would encourage the operator to choose the electric hybrid, at great expense to the public purse.

Given that new technologies have emerged since the government devised the Green Bus Fund, we suggest its eligibility criteria should be reviewed. By focusing solely on capital cost, policy is in effect 'picking winners' rather than remaining technology neutral. If the idea is to socialise the cost of reducing carbon and other emissions, it makes no sense to discriminate between solutions on the basis of capital or operating costs, particularly when this would direct public funding towards technologies with a higher total cost and away from those that may offer better value. If subsidy were allocated on some other basis – such as miles driven, for example, or a flat lump sum for any technology that achieves the required emissions reduction – it should be possible to eliminate this distortion and make better use of taxpayers' money.

**Without subsidy, the ten-year cost of a heat hybrid bus would be £17,000 less than a diesel and £60,000 lower than an electric hybrid.**

| Top-level investment comparison between electric hybrid and heat hybrid double decker buses | | | | |
|---|---|---|---|---|
| Double deck bus in London | Subsidised Electric Hybrid | Electric Hybrid: no subsidy | LIN/LAIR Heat Hybrid | Subsidised LIN/LAIR Heat Hybrid |
| Base price £000s | £200 | £200 | £200 | £200 |
| Additional cost £000s | £100 | £100 | £6 | £6 |
| Subsidy (Green Bus Fund) | 70% | 0% | 0% | |
| Subsidy £000s | £70 | £0 | £0 | £70 |
| Net additional cost £000s | **£30** | £100 | **£6** | -£64 |
| Total price £000s | £230 | £300 | £206 | £136 |
| | | | | |
| Approx. fuel saving | 28% | 28% | 25% | 25% |
| Average fuel saving (litres/year) | 9,729 | 9,729 | 9,137 | 9,137 |
| LIN/LAIR use (tonnes/year) | | | 121 | 121 |
| | | | | |
| Diesel savings (£/year) | £11,351 | £11,351 | £10,660 | £10,660 |
| LIN/LAIR cost (£/year) | | | £6,037 | £6,037 |
| Opex savings (£/year) | £11,351 | £11,351 | £4,623 | £4,623 |
| | | | | |
| *Additional investment case* | | | | |
| Simple payback (years) | 2.6 | 8.8 | 1.3 | - |
| 5 year TCO | -£26,753 | £43,247 | -£17,014 | -£87,014 |
| Battery replacement cost | £25,000 | £25,000 | | |
| 10 year TCO | -£58,506 | **£11,494** | -£40,128 | -£110,128 |
| Annual ROI over 10 years | 20% | | 66% | |
| | | | | |
| *BSOG and Green Bus payments* | | | | |
| BSOG Foregone p.a. | £3,363 | £3,363 | £3,159 | |
| Estimated green bus payments | £1,452 | £1,452 | | |
| Net subsidy | -£1,911 | -£1,911 | -£3,159 | |
| | | | | |
| *Assumptions:* | | | | |
| Assumed all VAT costs are reclaimed – fuel and LIN | | | | |
| LIN/LAIR | 5p/kg ex VAT | | | |
| Diesel | £1.40/litre inc VAT =£1.17 Ex VAT @ 20% | | | |
| BSOG | 34.57p/litre on average | | | |
| Additional subsidy for E-hybrid | 6p/km | | | |
| | 3.75p/mile | | | |
| | | | | |
| Double deck average fleet fuel consumption figures from three *Go Ahead* group depots in London | | | | |
| Average fuel use d/deck | 34,589 litres p.a. | | | |
| Average distance d/deck | 38,718 miles p.a. | | | |
| Ave distance e-hybrid d/deck | 33,311 miles p.a. | | | |
| Estimated fuel savings^ | 9,729 litres p.a. for electric hybrid | | | |
| ^Note that actual electric hybrid mileage is smaller than for conventional d/deck fleet | | | | |
| Hence, fuel savings may over-estimated | | | | |
| | | | | |
| Battery pack cost | £25,000 | | | |
| Replaced after | 7 years | | | |
| Annualised replacement cost | £3,571 p.a. | | | |

Table 13: Financial case for heat hybrids and electric hybrids compared

# 9 LOCAL AIR POLLUTION

In this report we have focused mainly on the financial and carbon savings of liquid air, but another major benefit could be improved local air quality. Heavy vehicle and refrigeration engines emit large quantities of pollutants such as nitrogen oxides (NOx) and particulate matter (PM), which contribute to respiratory illnesses and 29,000 premature deaths in Britain each year.[25] The government estimates the annual cost is up to £20 billion.[26]

In 2025, liquid air trailers could reduce NOx emissions by 1,800 tonnes per year, equal to removing 80,000 Euro 6 lorries or 1.2 million Euro 6 diesel cars from the road.

Emissions have fallen since the 1990s, but many British cities continue to break pollution limits set by the EU Air Quality Directive. A Supreme Court decision in May 2013 leaves Britain open to substantial fines and other unspecified enforcement action – yet to be determined by European and British courts.[27] This could include the imposition of much stricter air quality management zones in the 16 areas likely to miss the EU nitrogen dioxide ($NO_2$) targets, which include London, Birmingham, Manchester, Leeds, Liverpool, Hull, Glasgow and Southampton. If so, it seems likely the same restrictions would be imposed throughout the country.

The new Euro 6 engine standard is expected to reduce NOx and PM emissions substantially, but many in the industry think this may represent the limit of significant improvements from a conventional diesel engine; Euro 7 is likely to focus on reducing $CO_2$ and – as traffic continues to grow – further cuts in NOx and PM emissions will need to come from the introduction of alternative engines.

Liquid air heat hybrids could reduce diesel consumption by up to 25%, meaning they might also cut NOx and PM emissions – although a precise estimate would require detailed engine modelling.[28] It is easier to calculate the air quality benefit of replacing the separate diesel-powered Transport Refrigeration Unit (TRU) of an articulated trailer with a zero-emissions liquid air system, since the diesel emissions from refrigeration would be wholly eliminated. These so-called 'donkey' engines are particularly inefficient, and emit far more NOx and PM than either a modern lorry propulsion engine or a diesel passenger car over the course of a year.

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 lorry 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 (see Table 14).

| | NOx | PM |
|---|---|---|
| TRU v Euro 6 diesel car | 92.6 | 164.6 |
| TRU v Euro 6 lorry engine | 6.2 | 28.6 |

Table 14: Annual emissions multiples – total yearly emissions from a 40ft auxiliary TRU versus other applications.[29]

This analysis is based on a comparison of regulatory standards which assumes that each vehicle or engine class will emit as much of each pollutant as permitted. Since 'non road' diesel engines below 19kW – which includes TRUs – are currently unregulated in the EU, it is assumed that European manufacturers adhere to US standards in order to sell the same engines in both jurisdictions. In the modelling, European manufacturers are assumed to apply a blend of US Tier 3 and the latest Tier 4 standards – although this may be optimistic. Even so, their TRUs will emit many times more NOx and PM than Euro 6 lorries or diesel cars (Table 14).

The European Commission (EC) is expected to approve proposals to restrict NOx and PM emissions from diesel engines below 19kW with the adoption of Non Road Mobile Machinery (NRMM) Stage 5 later this year, although these regulations are not expected to come into force until around the end of the decade.[30] The proposed standards match those of US Tier 4 exactly, and so will make essentially no difference; in 2020 the new European rules will still allow TRUs to emit many times more NOx and PM than Euro 6 lorries or diesel cars.

Government sponsored studies[31] have shown that diesel cars' NOx and PM emissions can be up to five times higher than their rated level in real-world driving conditions, which may mean TRUs are not quite so much worse than cars as we suggest. The E4tech analysis remains robust, however, for two reasons: first, the TRU emissions are clearly massively higher than even than the real-world emissions of diesel cars; and second, the EU rolling-road test cycle for cars reflects urban and suburban driving conditions, those most relevant to the congested cities where air pollution is such a critical health issue.

**Liquid air trailers would also cut PM emissions by 180 tonnes, equal to retiring over 2 million Euro 6 diesel cars, or three times the UK articulated lorry fleet.**

Based on the E4tech air pollution analysis, our 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 lorries or 1.2 million Euro 6 diesel cars from the road. It would be the PM equivalent of retiring 367,000 Euro 6 lorries or 2.2 million Euro 6 diesel cars. Regulating emissions from vehicle refrigeration would therefore be a timely and effective way of reducing emissions in polluted city areas, and we suggest the development of liquid air 'cooling and power' refrigeration means the emissions limit in such areas could soon be reduced to zero.

Since all the cities on our 'top 30' list already operate air quality management zones, and many could eventually be exposed to fines for breaking nitrogen dioxide limits[32], any technology capable of reducing local emissions cost effectively should interest local authorities and transport operators – particularly if tighter standards are imposed.

Vehicle manufacturers and industrial gas producers have begun to offer vehicle refrigeration based on liquid nitrogen evaporation under various trade names. The cold logistics operator Gist operates FROSTCRUISE trailers for Marks & Spencer and Starbucks, while Nisa-Today's is trialling natureFridge. Such systems are zero-emission at the point of use and quieter than diesel, so useful for making deliveries at night. The liquid air 'cooling and power' approach would have the same advantages, but would be more efficient than evaporative cooling since it extracts both cold and power from the same unit of cryogen. It would therefore consume less liquid air or nitrogen to produce the same amount of cooling.

# 10 THE ROAD AHEAD

This report has focused tightly on liquid air technologies for commercial vehicles likely to be quickest to market, and the cryogen supply needed to support their roll-out in Britain over the next decade. There is however a wider and longer term context that should be explored. During the course of our research, it has become clear that there are many potentially fruitful areas for further research and development in both cryogen production and on-board technologies. It has also become clear that there are many potential synergies to be explored between liquid air and nitrogen and 1) internal combustion engines, 2) other cryogenic fuels such as LNG or liquid hydrogen, and 3) electric technologies that may benefit from cold. After discussion with industry experts, we sketch the most promising areas below.

There are many synergies to be explored between liquid air, conventional engines, other cryogens and fuel cells.

## Cryogen production

The projections in chapter 7 imply new transport demand for liquid air or nitrogen of 10,000 tonnes per day by 2025, more than doubling the existing nitrogen market. To supply this in the traditional way would require the equivalent of 14 new 300tpd liquefiers, which is of course perfectly feasible. However, given the potential scale of the new demand, and its distributed nature, cryogen production plants may need to become both larger and smaller, and more efficient at both ends of the spectrum.

Liquid air production could be both large scale and highly efficient by making use of the waste cold given off by LNG re-gasification. Where this approach has been adopted at LNG terminals in Japan and Korea the nitrogen liquefier requires two thirds less electricity than a conventional unit. According to a recent report from CLCF[33], capital costs would be higher, but developers believe these can be reduced significantly through engineering and process design. The combination of lower capital costs and a much reduced electricity bill would cut the cost of liquid air dramatically. The same report calculated that if all the cold from Britain's projected LNG imports in 2030 were used in this way, it would help produce over 8 million tonnes of liquid air – enough in principle to fuel Britain's entire bus fleet as heat hybrids more than twice over.

At the same time, there is an evident need to improve the efficiency of smaller scale liquefiers, which are typically much less efficient than industrial scale plants today. The development of plants capable of efficiently producing just a few tonnes of liquid air per day – to be installed at bus depots, logistics hubs for example – would eliminate the cost of distribution and potentially increase the number and types of transport operators for whom liquid air would be economically attractive. In the longer term, research and development may lead to new ways of producing cold.

Cryogenic vectors such as liquid air or nitrogen might ultimately be produced onboard a vehicle using a shaft driven micro-liquefaction plant. This would allow 'cryo-hybridisation', where cryogen is produced from re-generative braking, meaning the cryogen tank would never have to be re-filled from an external source. The challenge would be to make the technology sufficiently small, efficient and cheap. Since the most efficient liquefiers today are large scale industrial plants, this might require substantial R&D, but the advantages would also be significant.

## Other cryogens

The discussion about how to exploit cold energy vectors in transport has so far centred on liquid air or liquid nitrogen. But other cryogens are already used in vehicles. LNG, for example, is beginning to be adopted in lorries as a cleaner alternative to diesel, but this fuel can also be seen as a cryogenic energy vector: a litre of LNG contains around 13% more cold than one of liquid nitrogen. This cold energy is in addition to the chemical energy contained in the fuel's molecules, but is currently usually wasted – in one niche application, we understand that it is used to improve the engine's intercooling, but this is the exception today. This presents two further opportunities to increase fuel efficiency: first, it should be possible to apply the same kinds of heat-recovery approaches currently being developed for liquid air to LNG and other cryogenic fuels such as liquid hydrogen; and second, there should be synergies to be gained by combining the use of liquid air or nitrogen and other cryogens on a single vehicle.

**Heat recovery.** In the Dearman engine heat hybrid (chapter 3), liquid air is used to absorb heat from the internal combustion engine, causing it to expand and push a piston. LNG used as lorry fuel needs to re-gasify before it enters the engine to be combusted, and there is no reason why this expansion should not

Liquid air could usher in a new generation of novel internal combustion engine designs.

also be used to drive a small Dearman engine, or some similar kind of expander, which would then supply parasitic loads such as lighting or air conditioning. The exhaust – consisting of natural gas – would then be used as fuel in the main engine. In this way the LNG would serve first as a working fluid, and then as a fuel, so increasing the work extracted from a single store of energy. Another possibility could be to expand the heated cryogen through a turbine the other side of which drives a rotary compressor, either to compress air as a supercharger, or generate electricity and replace the alternator, both of which would reduce fuel consumption.

**Onboard synergies between cryogens.** There are potential synergies between cryogenic technologies on the vehicles themselves, as well as in cryogen production. If an LNG lorry were converted into an LNG-liquid air heat hybrid, for example, the LNG tank at -162°C could be enclosed within the liquid air or nitrogen tank at -196°C, so reducing evaporation losses from the more expensive and environmentally harmful hydrocarbon fuel. The LNG could also re-gasify through a small expander (see above) to generate additional power to run auxiliary loads such as headlights. These efficiency gains would come on top of the major improvement in fuel economy provided by operation of the heat hybrid itself (chapter 3).

Hydrogen fuel cell vehicles could also be converted into heat hybrids to recover their low grade waste heat, and if hydrogen were stored onboard as liquid rather than compressed gas, could also benefit from the same cryogenic synergies as LNG.

## New engine designs

Cryogens could also be incorporated into new ICE engine designs to raise thermodynamic efficiency. The difference here is that the heat recovery approach becomes integral to the main engine, rather than a separate or hybrid system. One example is the Ricardo split cycle liquid nitrogen engine (chapter 3), which injects liquid nitrogen into the compression cylinder to enable exhaust heat recuperation.

Another example could involve expanding cryogen through an exhaust turbine where the heat is provided by the exhaust stream. First the turbine drives a rotary compressor to compress air. The cool exhaust is then mixed with the compressed air and, if the cryogen is also a fuel such as LNG, fuel, to produce a cool, compressed charge to enter an engine. This engine may sit after the first stage of compression using exhaust energy and an intercooler, so increasing the density and pressure of the air inlet gas without increasing exhaust back pressure.

## Enabling technology – a tank of cold

Combining a diesel engine with a liquid air engine increases the efficiency of both through the transfer of waste heat from one to the other. However, this is not the end of the efficiency improvements that could be gained from liquid air. Once a vehicle has been fitted with a tank of cryogenic liquid at -196°C, as with heat hybrids or liquid air refrigerated vehicles, the cooling potential could be used to further raise the efficiency of several important processes, all of which could improve fuel economy.

**Charge cooling.** Turbochargers are used to increase the flow of air into the engine to enable an increase in power and efficiency, allowing the engine to be downsized. Almost every turbocharger uses a 'charge cooler', to cool and further increase the density of air entering the engine. Typically this is done with an ambient heat exchanger, but if liquid air were used to reduce the air temperature even more, greater efficiency and downsizing could be achieved. With a lighter engine, other components such as the vehicle sub-frame and brakes could also be downsized, helping raise the fuel economy yet again. As mentioned above, we know of one application where LNG is used in this way to good effect.

**Knock limit improvement.** In spark ignition engines 'knocking' or 'pinking' is a problem caused by the auto-ignition of fuel-air mixture within the cylinder when the mixture temperature is too high, and is one of the limits faced by engine designers. Liquid air charge cooling would lower the intake air temperature and therefore improve the knock limit, allowing the engine to produce more torque and be downsized further. Knock limit affects only spark-ignition engines and not diesels, so this benefit would only apply to heavy duty vehicles such as buses or lorries once they have converted to spark ignited fuels such as natural gas. Natural gas lorries that run on cryogenic Liquefied Natural Gas (LNG), stored at -160°C, might find further synergies if combined as a heat hybrid with liquid air at -196°C (see main text).

**Thermal loading.** Certain parts of an engine such as the exhaust valves, ports and manifold get particularly hot, and since the strength of metals declines sharply at high temperatures (e.g. cast iron above approximately 450°C), this 'thermal loading' is another limit in engine design. If components such as the exhaust port region or manifold could be cooled with on-board liquid air, the engine could be designed to produce more torque and power and therefore downsized.

**Exhaust gas recycling.** Many engines recycle some exhaust gas into the cylinder to lower the flame temperature, which reduces the formation of nitrogen oxides (NOx, see Chapter 9). The exhaust gases need to be cooled, however, requiring potentially sizeable heat exchangers. Cooling the exhaust gases with liquid air rather than water from the radiator loop would allow the heat exchanger to be more compact and effective.

**Electrical component cooling.** As circuits heat up, electrical resistance usually increases, so raising energy consumption. This issue will become more important as the spread of hybrid technologies increases the proportion of the drive train that relies on electricity. This approach might also allow 'high temperature' super-conductors (HTC) to be used as efficient electrical storage devices on vehicles for the first time.

**Fuel Cells.** The fuel cell is a device which converts the chemical energy in a fuel directly into electricity – in simple terms, a refuelable battery. Fuel cells running on hydrogen are a long term alternative to battery-electric propulsion or a range-extender for it, especially in heavier vehicles. They are highly efficient, but reject all their waste heat at low temperatures. This alone makes them ideal for waste heat harvesting using liquid air and an expander such as the Dearman engine; further synergies include cryogenic cooling of electrical systems as described above, and the thermal synergy between liquid air and liquid hydrogen, both on and off the vehicle.

**HTS technologies.** Cryogens could also make it possible to introduce high temperature superconducting technologies (HTS) to electric vehicles, where high voltages are a concern, and heat losses from the motor, power electronics and cabling a problem. If so, for electric or hybrid vehicles the motors would be smaller, the power electronics more efficient and the voltages and omhic losses reduced. Boil-off from the cryogen could also help reduce air conditioning loads on the battery. A final benefit would be the reduction in bearing losses through using HTS bearings where possible.

Liquid air could raise the efficiency of internal combustion engines in many different ways.

# GLOSSARY

## Acronyms

ASU – air separation unit

BIS – Department for Business, Innovation & Skills

BEV – Battery Electric Vehicle

BSOG – Bus Service Operators Grant

CCC – Committee on Climate Change

CCL – Climate Change Levy

CLCF – Centre for Low Carbon Futures

$CO_2e$ – Carbon Dioxide equivalent: ($CO_2e$ allows other greenhouse gas emissions to be expressed in terms of $CO_2$ based on their relative global warming potential (GWP).)

CNG – compressed natural gas: methane stored at high pressure (3000-3600psi)

CPF – Carbon Price Floor

DE – Dearman engine

DEC – Dearman Engine Company

DECC – Department for Energy and Climate Change

Defra – Department for Environment, Food and Rural Affairs

DfT – Department for Transport

EC – European Commission

EPSRC – Engineering and Physical Sciences Research Council

ERTRAC – European Road Transport Advisory Council

EU ETS – European Union Emissions Trading Scheme

EV – electric vehicle: an automobile that is powered entirely or partially by electricity

FCV – fuel-cell vehicles: a type of vehicle which uses a hydrogen fuel cell to provide motive power

FiT – Feed-in Tariffs

GAN – gaseous nitrogen

HEF – heat exchange fluid: a fluid barrier that enables the transfer of heat from a fluid on one side of the barrier to one on the other side, without bringing the fluids into contact and allowing them to combine

ICE – internal combustion engine

LAEN – Liquid Air Energy Network

LIN/LN2 – Liquid nitrogen

LNG – Liquefied natural gas

$MtCO_2$ – million tonnes of $CO_2$

MW – megawatt

MWh – megawatt hour

MIRA – an engineering, research and testing consultancy.

MRI – Magnetic Resonance Imaging

NOX – nitrogen oxides

PM – particulate matte

R&D – research and development

ROC – renewable obligation commitment

RPM – revolutions per minute

SME – Small and Medium Enterprises

TCO – Total Cost of Ownership

TPD – tonnes per day

TRU – transport refrigeration unit

WTW – well-to-wheels (see technical terms below)

ZEV – Zero-emission vehicle

## Technical terms

Adiabatic: taking place without loss or gain of heat

Air separation: process in which air is cooled until it liquefies, then the components are selectively distilled at their various boiling temperatures

Cold chain: a temperature-controlled supply chain of goods (often produce)

Embedded greenhouse gas emissions(GHGs): the emissions produced in the manufacture and disposal of equipment such as vehicles or engine

Energy vector: a medium of moving, storing, and releasing energy

Environmental levies: collective term for a range of taxes relating to the consumption of fossil fuels and emission of carbon dioxide

Euro 6 (VI) lorry: a vehicle complying with the most recent European Union exhaust emission regulations (NOx emissions of 0.46 g/kWh, PM of 0.01g/kWh)

# GLOSSARY

Heat hybrid: a vehicle in which a diesel engine and a liquid air engine are integrated so that waste heat and cold are exchanged between the engines to increase the efficiency of both and reduce diesel consumption.

Isothermal: maintaining a constant temperature

Liquefaction: the process of cooling a gas to the point of becoming liquid (-194C for air)

Liquid air: a cryogenic fluid comprising an atmospheric mixture of nitrogen, oxygen, and the trace gases

Low-grade waste heat: waste heat below 150C that is difficult to harvest using conventional technologies

Re-gasification: the process in which a liquid becomes a gas

Reefer: refrigerated trailer or shipping unit

Scope 1: category of emissions defined as coming from sources that are owned or controlled by the reporting entity (eg. fuel used by a company's vehicle fleet). See Box 1 on page 7

Well-to-wheel emissions: the combined emissions from the production, processing, distribution and end-use of a unit of fossil fuel from its point of origin (oil well) to its consumption by an engine

Zero-emission vehicle: a vehicle which produces no emissions such as PM or NOx at the point of use

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## ABOUT THE CENTRE FOR LOW CARBON FUTURES

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

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## ABOUT THE LIQUID AIR ENERGY NETWORK

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

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