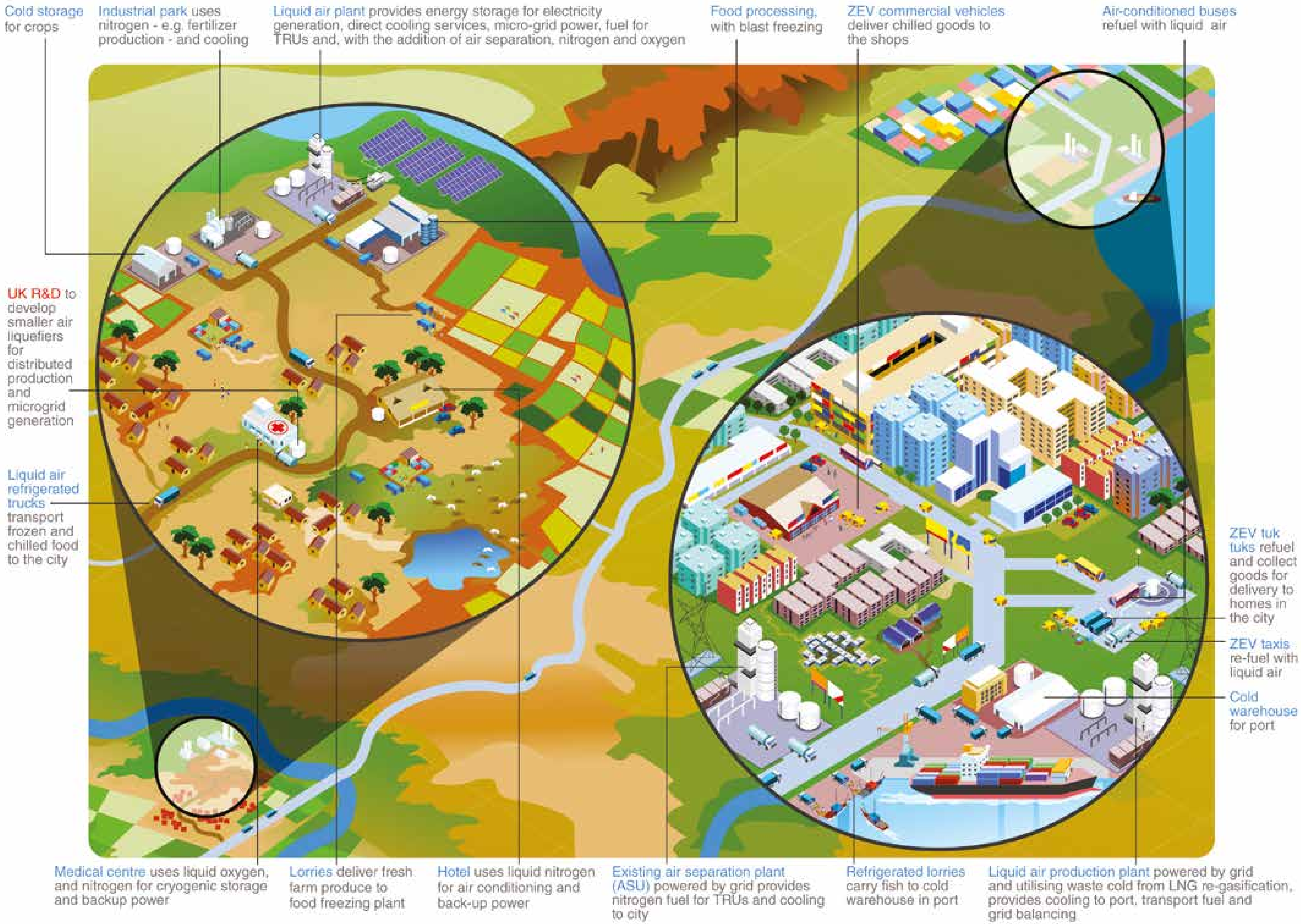
The cold economy

A liquid air solution for the developing world

Liquid Air Energy Network


Cold storage for crops
Industrial park uses nitrogen - e.g. fertilizer production - and cooling
Liquid air plant provides energy storage for electricity generation, direct cooling services, micro-grid power, fuel for TRUs and, with the addition of air separation, nitrogen and oxygen
Food processing, with blast freezing
ZEV commercial vehicles deliver chilled goods to the shops
Air-conditioned buses refuel with liquid air
UK R&D to develop smaller air liquefiers for distributed production and microgrid generation
Liquid air refrigerated trucks transport frozen and chilled food to the city
ZEV tuk tuks refuel and collect goods for delivery to homes in the city
ZEV taxis re-fuel with liquid air
Cold warehouse for port
Medical centre uses liquid oxygen, and nitrogen for cryogenic storage and backup power
Lorries deliver fresh farm produce to food freezing plant
Hotel uses liquid nitrogen for air conditioning and back-up power
Existing air separation plant (ASU) powered by grid provides nitrogen fuel for TRUs and cooling to city
Refrigerated lorries carry fish to cold warehouse in port
Liquid air production plant powered by grid and utilising waste cold from LNG re-gasification, provides cooling to port, transport fuel and grid balancing

The cold economy

A liquid air solution for the developing world

Countries in the developing world urgently need to build a 'cold chain' – the system of refrigerated warehouses and vehicles designed to preserve food from field to fork – to curb shockingly high losses of harvested crops of up to 40%. But it's also vital they avoid the highly polluting diesel systems used in the West, with their grossly disproportionate emissions of fatal pollutants NOx and PM. NOx and PM. Liquid air not only solves this problem, but could also catalyse a much broader 'cold economy' with huge economic and environmental benefits.

Liquid air technologies being developed in Britain could provide developing countries with an affordable zero emission cold chain. But they also present a wider opportunity to integrate the need for cooling with renewable generation, rural industry, zero-emission vehicles and much besides. What starts as a sustainable liquid air cold chain could build out into a fully fledged 'cold economy', reducing cost, carbon and air pollution, and boosting rural incomes, trade, food security and health.

In many developing countries as much as 40% of perishable food rots before ever reaching a plate. The scandalous loss of so much produce means the farmland, water, fertilizer, labour and diesel used to grow and harvest it has also been wasted. If developing countries had the same level of cold chain

as developed, it's estimated that reduced postharvest losses would increase the food supply by 200 million tonnes or 14%. Where cold chains are beginning to develop, in booming megacities such as Delhi and Beijing, they run on diesel and contribute to the chronic smog which in 2010 caused 600,000 premature deaths in India alone.

Alternative refrigeration technologies suitable for developing countries are beginning to emerge, such as solar powered milk-chillers, but these typically operate at a single location, and cannot provide cooling during, for example, a day-long journey from farm gate to city warehouse. Liquid air, by contrast, can not only be produced from renewable energy, but also provide the full suite of cold chain services.

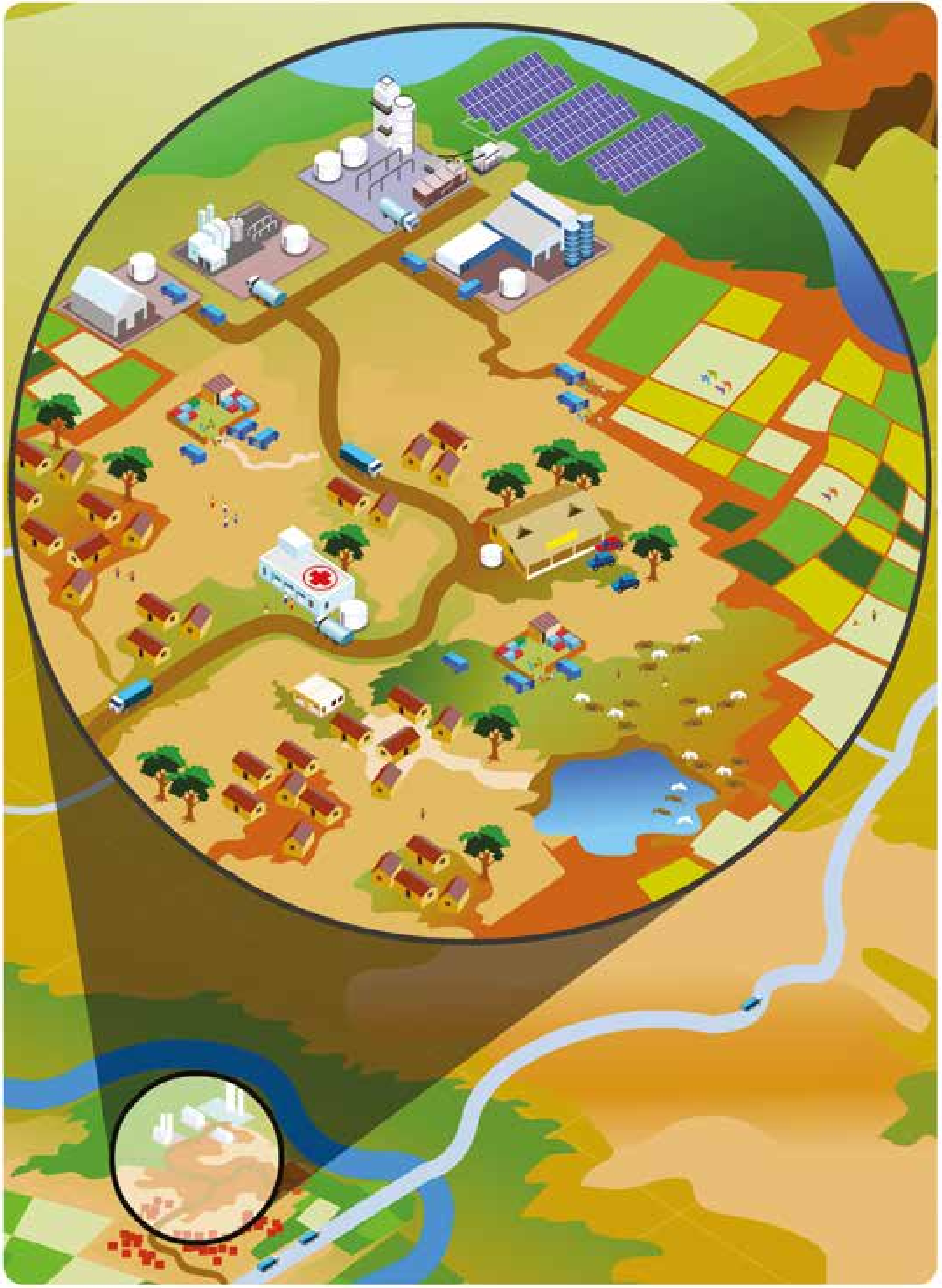
There is nothing new about liquid air. Cryogenic liquids such as liquid nitrogen – which can be used in the same way – have been produced in bulk for industrial purposes and blast freezing for many decades. What is new, however, is using liquid air or nitrogen as an energy 'vector' or store of power and cooling.

Air liquefies when cooled to -196C using mature industrial equipment and can be stored until needed in an unpressurised but insulated tank. When exposed to ambient temperatures liquid air boils, causing a 700-fold expansion that can be used to drive a piston engine, and simultaneously gives off large amounts of cold. In a rural setting, an air liquefier powered by renewable energy could be used to supply a centrally located tank, which would then service a wide range of functions.

Unlike other alternative refrigeration technologies, liquid air could provide the full range of cold chain services, from pre-cooling of produce from the field, to warehouse cold storage and long distance vehicle refrigeration – from field to urban consumer or export terminal. It could also supply the cold for blast freezing and other forms of food processing, developing rural industry and creating jobs to help stem the exodus from village to city slum. As a flexible store of zero-emission power and cooling, liquid air could also find many uses beyond agriculture: oxygen and cold for hospitals; back-up power and air-conditioning for hotels.

In cities, liquid nitrogen – which can be used in the same way as liquid air – will often already be available from industrial gas producers. India has spare liquid nitrogen capacity of 3,500 tonnes per day, for example. Here too a tank of cryogenic fluid would act as a store of both cold and energy, and could supply not just the cold chain but also other valuable services: transport fuel for zero-emission 3-wheeler taxis ('tuk tuks'), or for 'heat hybrid' buses that reduce diesel consumption by almost 50%; air conditioning for buildings or vehicles; emergency back-up power in areas with weak electricity grids; and cold for medical purposes.

So by building a liquid air cold chain across both grid and transport, developing countries could progressively create a broader 'cold economy' with major economic, environmental and social benefits – which we explore in more detail in the following pages.



Liquid air in the countryside

Grid electricity in developing countries is often highly erratic, and in the countryside may be non-existent. In Tanzania only 2% of the rural population has access to electricity. This means any refrigeration in the countryside is powered by polluting and expensive imported diesel. A more sustainable cold chain would need to run on renewable energy, but the intermittency of wind and solar means this would also require some form of energy storage - for which liquid air is the ideal solution.

As the illustration shows, an air liquefier located near a rural town is driven by a large solar array. During the day the plant cools air to around -196C, at which point it turns into a liquid and can be stored in an insulated tank until needed. In effect, the renewable energy is stored as one third power, two thirds cold. The liquid air could either be used at its production site – perhaps to generate electricity at peak times or at night for the local micro-grid – or delivered by road tanker to customers nearby.

The first and most energy intensive stage of the cold chain is to 'pre-cool' produce from ambient to the temperature that will best preserve it – e.g. 18C for tomatoes, 0C for apples and -18C for frozen foods including high value products such as fish. For some crops such as tomatoes it would be possible to pre-cool the crop on-board a liquid air refrigerated truck, meaning the load could be transported to nearby cold storage or direct to market with minimal deterioration due to heat. Other crops would be pre-cooled and stored at the local cold warehouse using liquid air, and then delivered by liquid air refrigerated truck to the city or port. (Standard diesel TRUs are not powerful enough to pre-cool produce on-board, which would have to be done in a pre-cooling room powered by grid electricity - if available – or more likely by static diesel generator).

Liquid air transport refrigeration is particularly efficient because it extracts both cooling and power from the same unit of fuel. First the liquid air is passed through a heat exchanger in the cargo compartment, which cools the produce and warms the liquid air into a high pressure gas. This then drives a small piston engine to power a conventional refrigeration compressor – so the liquid air delivers two bangs for one buck. Modelling shows that in Tanzania, for example, transporting a variety of crops over long distances would be 40-50% cheaper using liquid air pre-cooling and refrigeration than diesel pre-cooling and refrigeration. A report on the potential of liquid air vehicles in Britain, Liquid Air on the Highway, found that liquid air refrigerated trailers would repay their investment in three months.

With a liquid air production plant in place, farmers or rural businesses could set up new ventures to process their food – for instance through blast freezing – and capture more of the value. The price of mangoes in Tanzania, for example, falls to $100 per tonne at harvest time, but rises to more than $3000 out of season, and a liquid air quick freezing system could freeze one tonne for just $137, creating a huge margin to cover the necessary investment.

Other local businesses such as hotels could use liquid air for air conditioning and back-up power generation, while the local hospital could use the cold for medical purposes. If the liquid air plant invested in the equipment to separate air into liquid nitrogen and oxygen, there could be additional benefits such as nitrogen fertilizer production and oxygen for medical use.

Liquid air in the city

Many major cities in the developing world will already have a ready supply of liquid nitrogen – which can be used in the same way as liquid air – from existing industrial gas production sites nearby. India for example has some 3,500 tonnes per day of spare liquid nitrogen production capacity, enough to cool 29,000 refrigerated trucks, or four times the current Indian fleet.

Coastal cities such as Mumbai with an LNG import terminal could also produce extremely cheap liquid air by co-locating a production plant to harness the waste cold of LNG re-gasification, reducing the energy consumed by air liquefaction by two thirds. We estimate the waste cold from India's projected LNG imports in the early 2020s could in theory produce enough liquid air to fuel a fleet of 1 million 3-wheeler taxis ('tuk tuks'). And by 2030, the projected global trade of LNG (500 million tonnes) would give off enough waste cold to provide cooling for the entire projected global refrigerated lorry fleet.

Either spare nitrogen or LNG-assisted liquid air could complete the liquid air cold chain and provide cities with zero-emission transport fuel, reducing fatal transport emissions of NOx and PM in smog-stricken cities like Delhi and Beijing. The impact of a zero-emission cold chain could be significant: in Europe, a Transport Refrigeration Unit emits six times as much NOx and almost 30 times the PM of a modern diesel propulsion engine.

As shown in the illustration, industrial gas production plants within delivery distance of the city produce liquid nitrogen from grid electricity. On the coast, liquid air production could be sited at an LNG import terminal. In either case, a liquid air refrigerated warehouse could be built nearby to store chilled or frozen produce delivered from the hinterland. On the coast, the warehouse could also refrigerate locally caught fish for the domestic market or freeze it for export.

These warehouses could also be the hub of a new model of food distribution for congested cities, where it is difficult for lorries to deliver to shops in the centre. Instead, refrigerated food and liquid air would be transferred to a hub on the outskirts, to be collected by 3-wheeler 'tuk tuk' delivery vans, which would be both refrigerated and powered by liquid air. Having taken on goods and fuel, the tuk tuks would negotiate city traffic to deliver to city centre shops and even individual homes.

Again, liquid air would not be limited to the cold chain, but could also provide zero-emission fuel for tuk tuk taxis – with the benefit of free air conditioning – and diesel-liquid air 'heat hybrid' buses, which compared to a diesel lorry with air conditioning would reduce diesel consumption by almost 50%. It is the combination of cold chain, power generation and transport demand that would justify the investment in new liquid air production capacity.

Nor would the liquid air be limited to transport: as in rural areas, it could also provide fuel for distributed back-up power generation, and even grid-balancing if liquid air electricity generators were installed alongside the air liquefaction plant ('Liquid Air Energy Storage'). Datacentres and other processes that require cooling could also be integrated with liquid air production or LNG terminals.

The road ahead

The liquid air cold chain and cold economy are unlikely to emerge in the developing countries of their own accord. The default option – now being pursued in megacities like Delhi and Beijing – is dirty diesel. The point is to catch the process early enough before business-as-usual thinking and investment becomes entrenched. One major advantage of the liquid air approach is that liquid nitrogen is already widely available, and can be re-purposed for use in transport and energy storage.

Plenty of organisations are beginning to develop the technologies and systems thinking needed to make the liquid air cold chain and cold economy happen. In Britain the Institution of Mechanical Engineers has published a ground-breaking report, A Tank Of Cold: Cleantech Leapfrog To A More Food Secure World, launched at the Clean and Cool Summit hosted by IMechE in London on 1st July 2014. The report is supported by a detailed paper by Lisa Kitinoja, a cold chain expert and founder of the Postharvest Education Foundation. Both reports conclude that liquid air technologies would be practical and economic both in emerging but highly agricultural economies such as Tanzania and rapidly industrialising ones like India.

Also in Britain, the Dearman Engine Company (DEC) - along with Loughborough University and Air Products - is testing a novel zero-emission power and cooling engine for refrigerated vehicles which runs on liquid air or nitrogen. The University of Birmingham recently launched a new cryogenic energy storage centre with government backing to explore new materials for storing and moving cold. DEC, Birmingham, and other academics are working on processes to miniaturise and mass-produce air liquefaction plants, which could be integrated with renewables to produce zero-carbon liquid air at the community scale in developing countries.

In the US, the Lenfest Center at Columbia University is developing a small-scale modular system for local production of nitrogen fertiliser. Such a plant could be integrated with a modified liquid air plant - or conventional air separation unit - to provide the necessary nitrogen, and this idea is being investigated as part of the project. Recent work at Columbia has also shown that cost reductions achievable through mass producing large numbers of small units can outpace those seen from scaling-up individual unit sizes.

Although small-scale liquefiers are likely to be an important part of the cold economy in rural areas, in major cities liquid nitrogen, which can be used in the same way, is already widely available. India for example is expected to invest over $15 billion in cold chain over the next five years, yet it is already well supplied with liquid nitrogen production plants (see map), which are estimated to have spare liquid nitrogen capacity of 3,500 tonnes per day, enough to cool 29,000 refrigerated trucks, or four times the current Indian fleet.

It is perhaps in the megacities of the developing world – where air pollution is such a critical problem - that the liquid air cold chain and cold economy will first emerge. In India, the economics are already favourable. DEC modelling suggests a zero-emission liquid air Transport Refrigeration Unit would cost just £300 more than a diesel unit, repay its investment in under four months, and make its owners £10,000 better off after 10 years. A liquid air 'heat hybrid' bus with air conditioning would cut the vehicle's diesel consumption by almost half, repay its investment in under a year, and after a decade its owners would be £70,000 to the good.

Cold is still the Cinderella of the energy debate – largely overlooked in favour of power, heat and transport. But this cannot last: we estimate the additional cooling demand by 2030 equates to 340 x 1GW new nuclear power stations, or three times the power output of Brazil. If this demand were satisfied using conventional fossil technologies the results would be ruinous. We urgently need a sustainable alternative.

Liquid air is by no means a silver bullet, but combined with renewables or waste cold it could provide a low carbon, zero-emission solution for many applications for which no other good options currently exist. What's more, in many cases liquid air would be immediately cheaper than the fossil fuel incumbent – the very definition of 'free green'. The widespread existing liquid nitrogen infrastructure means early progress could be fast, but at the same time, the sheer scale of projected investment in cold and cooling over the coming decades means that – for the moment – large areas of the canvas are still blank. The key now is to develop the joined-up thinking that allows us to maximise the environmental and economic gains of the cold economy.

Liquid nitrogen production sites in India

Liquid air TRU	Vs Diesel
CapEx	+£270
Yearly OpEx	-£1,000
Payback Time	~ 4 months
10yr TCO saving	-££10,000

Liquid air transport refrigeration unit vs diesel in India

Heat hybrid bus	Vs Diesel
CapEx	+£6,300
Yearly OpEx	-£7,000
Payback Time	< 1 year
10yr TCO saving	-£64,000

Liquid air-diesel 'heat hybrid' bus vs diesel, both with air conditioning, in India

What is liquid air?

Liquid air is about storing cold and power produced by renewables to use in a vehicle or the built environment. This cuts diesel consumption, emissions and cost.

A means of storing energy is vital if renewables like wind and solar are to replace fossil fuels in grid and transport applications. Unlike hydrogen or batteries, liquid air stores energy as both power and cooling, giving it a unique advantage when there is a need for cooling or heat recovery.

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

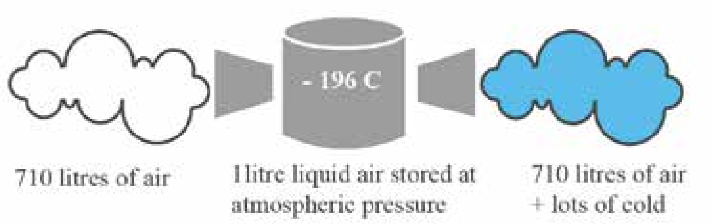
Air turns into a liquid when cooled to around -196C using standard industrial equipment. This process can be driven by renewable or wrong-time/off-peak energy. 710 litres of ambient air becomes about 1 litre of liquid air, which can be stored in an unpressurised, insulated vessel.

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

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

These grants include:

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



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

The Dearman engine

The Dearman engine is a novel piston engine - now in demonstration - powered by the phase-change expansion of liquid air or liquid nitrogen. The only exhaust is cold air.

The Dearman engine was invented by Peter Dearman, a classic British 'garden shed' inventor. Peter has already demonstrated his engine on a modified car, and it is now being commercialised by the Dearman Engine Company together with partners including Hubbard Products, Air Products, MIRA and the Manufacturing Technology Centre.

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

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

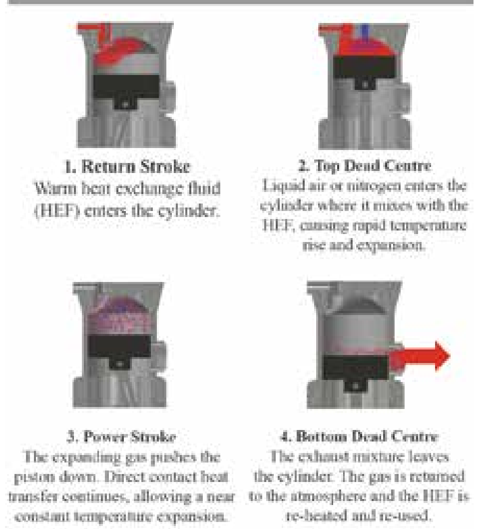
Running on a cryogenic fluid gives the Dearman engine two major advantages.

Peter Dearman, the inventor of the Dearman liquid air engine

- First, the evaporation of liquid air or nitrogen gives off large amounts of valuable cold, which can provide 'free' refrigeration or air conditioning.
- Second, the low boiling point (-196C) means that low grade waste heat of around 100C, harvested from diesel engines or in future, hydrogen fuel cells, can be used to boost the cryogen's expansion to produce additional power at practical conversion efficiencies approaching 50%. These features are the basis of the first two applications of the Dearman engine.

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

DEARMAN ENGINE STROKE DIAGRAM



"The ultimate potential of the uses of liquid air technologies can be limited only by our collective imagination".

Dr. Lisa Kitinoja, Postharvest Education Institute

Liquid Air Energy Network

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