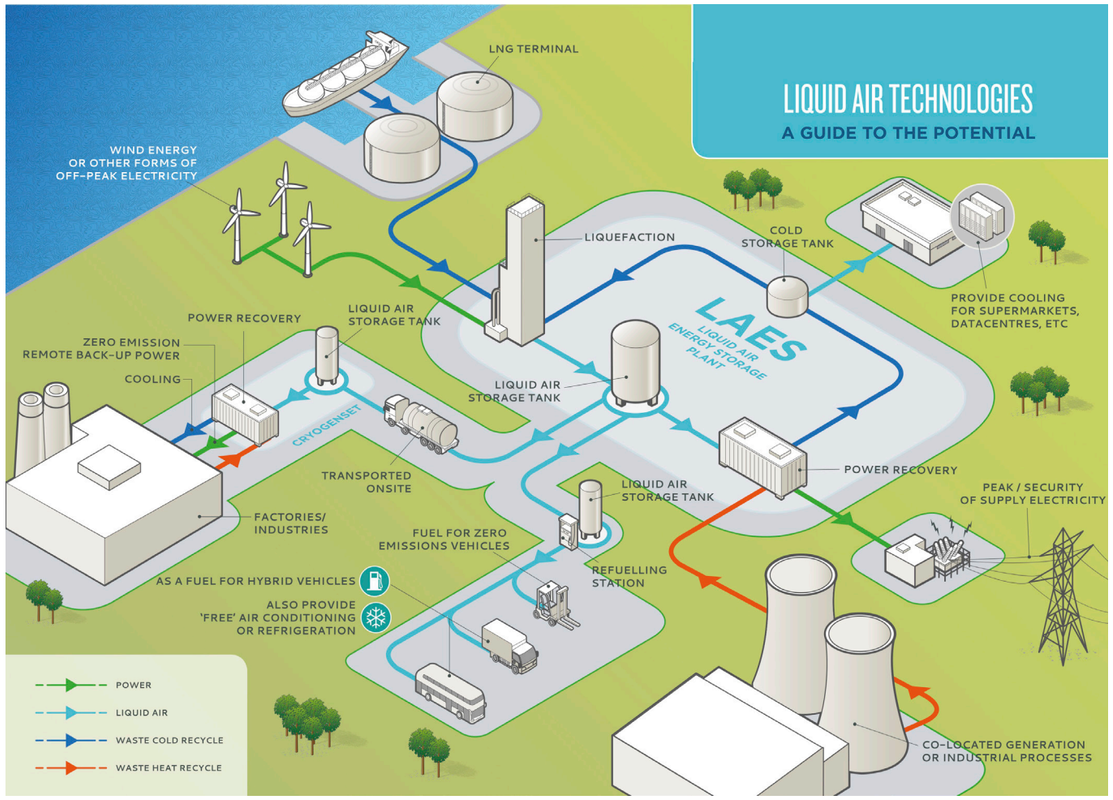


The Cold Economy

"There is a need to re-shape the way we address cold needs. Put simply, we need to 'do cold better'." Prof. Toby Peters, Founder and Senior Group Managing Director, Dearman.



The world needs cooling – air conditioning, industrial cooling, data cooling, medical cooling as well as a 'cold chain' of refrigerated food storage, processing, and transport. And as the global middle classes swell by 3 billion over the next 20 years, primarily in the developing world, demand for cooling is expected to boom.

India projects it needs to spend more than $15 billion on its cold chain over the next five years; China's refrigerated storage capacity is on track to multiply 20-fold in the decade to 2017 to 5 billion cubic feet; the USA, Europe and UK are all still seeing double-digit growth in cold transport.

In fact, global projected growth to 2030 for cooling equates to three times the total power output of Brazil or the UK. If this need is satisfied using current technologies, the impact on primary fuel consumption, cost, climate and air quality will be enormous.

Yet cold is the 'Cinderella' of the environmental debate. Almost every country has energy policies covering power, transport and heat, but cold demand is rarely broken out from the statistics for final energy demand in the various sectors. Given the environmental and economic challenges facing the energy industry, it is crucial that the primary energy demands for providing cold do not grow at the same rate as cold demand itself.

In the developed world our residential streets are clogged with supermarket refrigerated vehicles delivering to stores or direct to our homes. What we perhaps do not realise is the health cost of this service: on average the transport refrigeration unit on these vehicles emits 29 times the pm (particulate matter) and six times the NOx (nitrogen oxides) of the much larger primary diesel engine. The annual NOx emissions from China's projected truck refrigeration units alone could exceed those of the entire UK heavy commercial vehicle fleet within a decade, and this in a country already plagued by chronically polluted air. If current trends in refrigerant usage were to continue, experts project that traditional refrigerants (hydrofluorocarbons) would be responsible for nearly 20% of all global greenhouse gas emissions by 2050 (New York Times).

Food Security and health

In the developing world, by contrast, 30-50% of perishable food rots before ever reaching a market, while one in eight people goes hungry. This means the land, water, fertilizer and labour used to produce the wasted food has also been squandered. But as a recent report by the Institution of Mechanical Engineers highlighted: hunger and rural poverty could be addressed, and scarce energy and water resources better conserved, if developing countries had a sustainable 'cold chain' of refrigerated warehousing and transport to preserve the quality of food from farm to fork.

Alongside the impact on food of the lack of a cold chain in developing countries, more than two million people die each year from diseases that could otherwise be prevented through the use of vaccines. The challenge is not so much a shortage in the supply of those vaccines, but that they must be refrigerated from their point of manufacture to their point of distribution to end-users, often in remote locations that lack the reliable the power required to keep those vaccines properly chilled.

Capturing Waste Cold

There are promising opportunities for changing the way we meet and think about cold needs: 'doing cold better'. There are currently significant volumes of wasted cold such as the cold 'packaging' of imported Liquefied natural gas (LNG) and bulk cryogenic gases, and the 'coolth' generated in gas let-down stations. These cold sources are projected to grow in volume in the coming decades.

There are also significant volumes of 'wrong-time' energy – such as surplus wind power generated at night when demand is low – which is either wasted, or stored only to be converted from electricity into cold later. The amount of wrong-time energy we need to store will only expand as renewable generating capacity continues to grow.

Dearman is designing and developing sustainable clean and cheaper solutions for integrated transport and off-grid cooling and power needs. Dearman's proprietary technologies include zero-emission transport refrigeration units; high efficiency hybrid engines that harness low grade waste-heat; zero-emission power-trains for off-highway applications such as mining, where the exhaust of clean cold air is a major advantage; and larger MW-sized stationary power and cooling units (e.g. air conditioning) to work alongside renewables and displace diesel gensets.

As Pat Maughan, MD of Hubbard Products Ltd, the UK's principal designer, manufacturer, and supplier of refrigeration systems – and market leaders in refrigeration for vehicles – explains, "Hubbard, after many years of refining design, has realised that near term future requirements cannot be achieved with existing available components and technologies. Hubbard has enthusiastically engaged with Dearman to jointly develop a transport refrigeration system that will be the paradigm shift to economic clean cold on the highway. We have reviewed the Dearman technology and concluded it has enormous potential to revolutionise both the emissions and costs inherent in refrigerated road transport."

If the UK replaced 13,000 diesel transport refrigeration units with Dearman liquid air alternatives, this would reduce particulate emissions by an amount equivalent to taking 367,000 Euro VI trucks or 2.2 million Euro VI diesel cars off the road. The UK has 80,000 diesel powered TRUs, Europe more than one million. The system also does not use traditional refrigerants.

Packaged cold and power: liquid air

The core of our technology is the Dearman engine – a novel piston engine whose 'fuel' is liquid air, which is increasingly recognised as an important new energy vector. Liquid air enables wrong-time energy – such as off-peak wind generation – to be converted into both mechanical power and cold, giving 'two bangs for one buck'. It has about the same energy density as an advanced battery in terms of stored mechanical work but also stores two thirds of its energy as cold, making it an ideal form of energy storage wherever there is a need for cooling as well as power.

Liquid air offers more than just another means of storing wrong-time energy. Within the cold energy system, the Dearman engine and liquid air are the missing pieces of the jigsaw, allowing waste cold to be economically stored, moved, and deployed. Suddenly we can integrate waste cold resources and cold needs. By allowing 'packets' of cold and power to be moved in time and place, liquid air allows us to start thinking about a Cold Economy – where we provide cooling far more efficiently, in part by recycling vast amounts of waste cold.

For example, the cold given off by the National Grid Isle of Grain (LNG) terminal over the course of a year would be enough to fuel London's entire 7,600 strong bus fleet as liquid air 'heat hybrids' more than six times over. And the projected annual global trade of 500 million tonnes of liquefied natural gas in 2030 would give off enough waste cold to help produce 184 million tonnes of extremely cheap and low-carbon liquid air, which could in theory supply the cooling demand of the entire projected global refrigerated transport fleet!

At a more fundamental level, the recent IMechE report *A Tank of Cold: Cleantech Leapfrog to a More Food Secure World* showed how liquid air and the Dearman engine are uniquely placed to harness renewable energy for both power and cooling on demand in distributed cold chain applications in developing economies.

Together they can provide complete farm-to-market cold chains and can be practically implemented in the context of countries at different stages of economic development. In June 2014, more than 100 delegates, including government officials from India, Malaysia and Tanzania, multinationals, and academics from as far afield as Australia, met for two days of very positive discussion around the findings of the report and this was followed by several meetings in India.

Next steps for the Cold Economy

The benefits of a Cold Economy would include meeting cold needs in a more resource efficient way; spatial and temporal balancing of dynamic needs; environmental benefits including reduced greenhouse gas emissions and improved local air quality; lower overall cost; and, as with any new industry, new business opportunities. The Centre for Low Carbon Futures' recent report, *Liquid Air on the Highway*, found that liquid air engines could create or maintain 2,100 jobs – the same value as hydrogen economy.

Dearman's technology development has received £multi-million support from the UK Government. Through working with Dearman, the University of Birmingham has also secured more than £12 million of government and industry funding for a new liquid air and cryogenic energy storage research centre.

The Dearman engine is in 2014 in on-vehicle trials in the UK, the first engines will be in manufacture from 2016, and with it the opportunity to recognise the environmental and economic value of doing cold better.

"It is exciting to encounter an energy technology that is as potentially disruptive as liquid air," said strategic consultancy E4tech's Director, Adam Chase. Working with E4tech and others, Dearman is currently producing a series of reports looking at the value of a more joined-up Cold Economy and specifically the potential of harnessing stranded cold to reduce primary energy demand. The findings will be discussed in a series of workshops during the latter part of 2014 and in early 2015.

Liquid air

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

Liquefying air is the cornerstone of the industrial gas industry. Nitrogen and oxygen are liquefied in ASUs (Air Separation Units) in industrialised countries – but liquid air 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.

Liquid air as a 'fuel'

Air turns into a liquid when cooled to around -196C using standard industrial equipment. This process can be driven by renewable, wrong-time or 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 re-gasifies, expanding 710 times in volume. This expansion can drive an engine. It also exhausts lots of cold, making it highly relevant for processes which require power and cooling.

Liquid air tanks can be refilled at rates of 100 litres per minute. The liquefaction process can be driven by renewable or other 'wrong-time' energy, allowing, for example, wind power to be used in transport.

Liquid air and liquid nitrogen: what is the difference?

Liquid air is not yet produced commercially, but liquid nitrogen, which can be used in the same way, is produced throughout the industrialised world. Liquid air and liquid nitrogen can both serve as a cryogenic energy vector or transport 'fuel'. They are not identical but do share many properties, since nitrogen makes up four fifths of air. The temperatures at which air and nitrogen liquefy are similar (-196C for nitrogen, -194C for air), and both expand about 710-fold when they re-gasify.

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.

Government funding

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

- £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 Dearman liquid air vehicle engines.



As the map shows, all of Britain's major cities are within delivery distance of one of its ten Air Separation Units with spare liquid nitrogen production capacity. Spare capacity would be enough to fuel a third of the UK urban bus fleet as liquid air 'heat hybrids', or to support the projected deployment of all types of liquid air vehicles until at least 2019.

Clean and cheap

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

Power and cooling

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

Waste heat recovery

Liquid air's 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%.

Economic without subsidy

Transport solutions for lower carbon and better air quality tend to come at a high cost, taking years to pay back or needing heavy subsidies. The Dearman engine is not so costly and needs no subsidy; in many cases the operator can get a payback in a matter of months, a few years at most.

The value of LNG stranded cold



LNG Tanks at the Port of Barcelona

The cold required to liquefy natural gas and 'package' it for transport as Liquefied Natural Gas (LNG) at -160C is usually discarded on re-gasification – rather like the polystyrene packaging of a new air-conditioning unit.

Each tonne of LNG contains the cold energy equivalent of 240kWh, quite apart from the chemical energy contained in its methane molecules, and typically 80% of this cold energy is thrown away. The global LNG trade is expected to double to 500 million tonnes per year by 2030, representing cold energy of 120TWh, theoretically equal to the continuous output of 14 1GW nuclear power stations.

How much global transport refrigeration could be provided by the wasted cold of LNG imports in 2030?

Global LNG, 2030	500	m tonnes
Embedded coolth	120	TWh
Liquid air/year	184	m tonnes
Liquid air/day	504,359	t/day
40' Reefer consumes	275	kg/day
Reefers supported	1,834,031	
20' Rigid consumes	119	kg/day
Rigids supported	4,238,308	

This may represent just 4% of the cooling demand we have identified, but the existence of such huge absolute numbers on each side of the ledger suggests the need for a different approach to cold – allowing one to reduce the other.

Storing and moving cold and power

While larger users of cold, such as data centres or large cold/frozen food warehouses, can be located close to LNG re-gasification plants and the cold passed 'over the fence' , the key to making the most of this cold is the ability to store and transport it for use in remote applications, such as on vehicles or even in the built environment, perhaps for peak demand.

To date, as a world we have focused primarily on storing power, i.e. batteries, or heat. Liquid air stores both cold and power for use on demand by refrigerating air to -196C, when 710 litres of air become 1 litre of liquid air. This can be stored in insulated but unpressurised vessels until energy is needed, when exposure to heat – even ambient – causes rapid re-gasification, which can be used to drive piston or turbine. Liquid air has a power density close to that of advanced batteries, but on top of this, it stores two thirds of its energy as 'coolth', meaning it can provide power and cooling loads simultaneously.

Using cold and power

The devices required to make use of the power and cold in liquid air – turbines and piston engines – are mature, cheap, scalable, and require no exotic materials. In the same way, liquid air is made using standard industrial gas liquefaction plants. These can be integrated with LNG re-gasification plants to capture and harness waste cold and thereby convert it into a mobile energy storage medium – liquid air. The waste cold of LNG regasification can be used to reduce the energy required to produce liquid air by two thirds. Liquid air can in turn be used in both transport and grid applications providing clean power and cooling.

Recycling cold

Liquid air could help close the loop of the Cold Economy by recycling the vast amounts of waste cold given off by LNG re-gasification. A global trade of 500 million tonnes of LNG in 2030 would give off enough waste cold to help produce 184 million tonnes of extremely cheap and low carbon liquid air. This, theoretically, in turn could supply the cooling for 1.8 million refrigerated articulated trailers, or 4.2 million refrigerated delivery trucks. More than the entire global fleet!

Given the projected growth of the global LNG trade, recycling its waste cold would be a significant step, yet the challenge of meeting future global cold demand remains huge. If we are going to feed the world, manage our natural resources, conquer local air pollution, cut carbon and maintain political stability, we need to find new joined-up solutions to providing zero-emission cold more sustainably and economically throughout the global economy.

LNG stranded cold in India

Recycling stranded cold from LNG re-gasification represents the biggest single prize in the Cold Economy.

In rapidly developing economies, where LNG import capacity is growing fast, cold chain capacity – though booming – is still tiny compared to unmet demand. Historically, no country has significantly reduced the poverty of its population without increasing agricultural productivity and connecting farmers to market options – a sustainable, integrated cold chain is a key component.

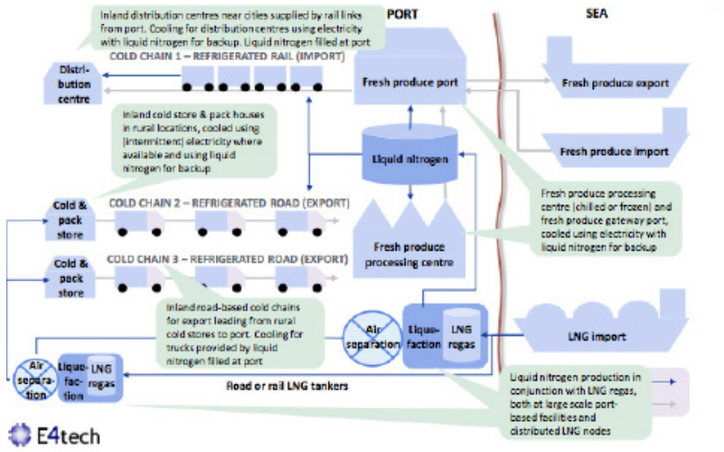
In countries such as China and India, LNG-assisted liquid air presents the opportunity to leapfrog highly polluting and increasingly expensive diesel technologies and develop clean, efficient, and economic cold chains.

The potential of stranded cold from LNG is starkly illustrated in India, where the National Centre for Cold Chain Development (NCCD) estimates the country needs to double its cold store capacity of 30 million tonnes and add another 17,000 refrigerated trucks to satisfy minimum demand – and the market is then expected to quadruple by 2020. At the same time, India's imports of LNG are projected to rise five-fold to about 60 million tonnes per year in 2022. According to a recent report from the Institution of Mechanical Engineers (IMechE), the waste cold from re-gasification could in principle help produce almost 22 million tonnes of liquid air, enough to fuel over half a million truck refrigeration units, or 230,000 heat hybrid buses or 1 million urban auto-rickshaws ('tuk-tuks').

The concept of an Indian 'Cold Economy' based on recycled LNG cold is now being developed in detail by Dearman, supported by E4tech, the strategic energy consultancy. The idea initially is to use an LNG import terminal as the hub of a new zero-emission cold chain to service both imports and exports.

Cold Economy: the workings

Waste cold from re-gasification would be used to produce liquid air to support cold store sites clustered around the terminal, facilities at the other end of the cold chain further inland, and the refrigerated trains and trucks that connect them. Initial modelling suggests a single LNG import terminal could provide enough liquid air to fuel more than 2,000 refrigerated vehicles and service the peak demand of more than a million square



metres of cold storage capacity. The elements of the scheme are described in the diagram above.

The heart of the system is the LNG re-gasification terminal co-located with a fresh produce port. The terminal gives off vast amounts of waste cold, which is recycled in an air liquefaction plant to produce liquid nitrogen, so reducing the electricity required, the cost and the carbon intensity by about two thirds.

This low-cost, lower carbon liquid nitrogen is used to provide efficient refrigeration on trucks and trains equipped with a Dearman transport refrigeration unit (TRU). These vehicles carry fresh produce from inland pack-houses to the port for export, and imports from the port to distribution centres inland. They refuel with liquid nitrogen while at the port. Refrigeration in the warehouses at either end of the cold chain is powered mainly by electricity, but liquid air is supplied to both by road or rail tanker to fuel a static Dearman 'power and cooling' engine for peak shaving and as backup against frequent power-cuts (in place of diesel generators). Liquid nitrogen could also provide cooling for blast freezing or other food processing operations.

Scale of the potential

E4tech's modelling suggests that a terminal re-gasifying just 7,100 tonnes of LNG per day could produce 2,600 tonnes of liquid nitrogen. This would be enough to provide refrigeration at the port for 1.15 million square metres of chilled or frozen warehousing, 15 times more than the world's largest such facility.

At the same time it would also provide enough liquid nitrogen to refrigerate 2,200 chilled trailers ('reefers') and 220 frozen reefers. Alternatively, some of the liquid nitrogen could be diverted to fuel highly efficient diesel-Dearman 'heat hybrid' propulsion engines for trucks and buses, or Dearman ZEV refrigerated and powered zero-emission tuk-tuks to deliver produce from distribution centres to city centre shops or homes.

$7 million savings

Liquid nitrogen supplies from an LNG-assisted plant would be not only copious but also cheap. E4tech estimates the vehicles described above would save their owners 256 million Rupees or $4.25 million per year compared to diesel, while the buildings would save 200 million Rupees or $3.3 million per year. But this would be the least of the financial benefits; E4tech's analysis takes no account of the potential reduction in India's post-harvest food losses, which can be as high as 50% and currently cost the country some $4.5 billion per year; nor does it account for the likely additional export earnings, nor the economic value from reduced emissions and environmental impact.

Future plans

E4tech's analysis so far is robust but high level, and a number of uncertainties remain. These will ideally be the subject of a future study, which will conduct an in-depth analysis with the help of a range of interested stakeholders. Partners are likely to include LNG, port, and logistics operators; food processors; technology developers; and government agencies. The scale of the opportunity is not in doubt, however, and the ultimate aim is to identify a specific LNG terminal/cold gateway location for a full-scale feasibility study.

Liquid air can be used in different mobile cold chain applications

Dearman engine technology harnesses the characteristics of liquid air to deliver zero-emission power and cooling across a range of transport and grid applications.

The Dearman engine is an innovative expansion engine. Liquid air or liquid nitrogen is pumped through a heat exchanger, where it is exposed to ambient heat. This heat causes the liquid cryogen to re-gasify and rapidly expand.

The expansion creates pressure, which can be used to drive the engine's piston; it also gives off cold, which can be used to deliver refrigeration or air conditioning. This means the Dearman engine gives 'two bangs for one buck'.

The novel step

The novelty of the Dearman engine lies in the use of a heat exchange fluid (HEF – water or water and glycol mix) that promotes extremely rapid and near-constant rates of heat transfer inside the engine.

This allows a small, single-stage Dearman engine to achieve levels of thermal efficiency that would otherwise require more costly, multi-stage expansion with re-heating.

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

Applications and advantages

Dearman's modular technology has relevance across the transport industry, from cold chain operators to urban buses and mining vehicles, and in on-/off-grid applications.

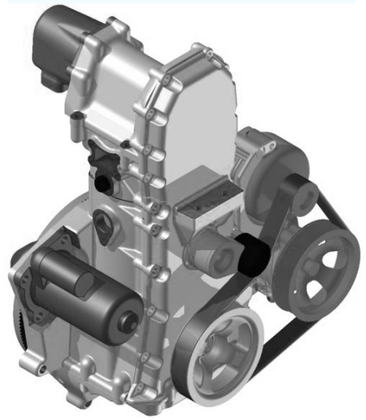
Dearman has developed a unique expertise in cold and power through a team of more than 30 in-house engineers and analysts, and a deep network of academic and industry partners.

The Dearman engine is constructed almost entirely like a conventional piston engine, made predominantly from aluminium, steel, and plastic.

The majority of the engine's parts and materials can be sourced from the existing automotive supply chain.

Dearman is developing a modular hardware family – minimising engineering cost and risk.

Dearman's rigorous research and development programme is building a family of technologies with the potential to create a joined-up 'Cold Economy' and spread the benefits of liquid air worldwide.



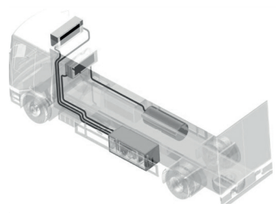
The Dearman engine delivers zero-emission power and cooling for a range of applications

Here-now technology

The Dearman engine's first application, transport refrigeration, goes into on-vehicle demonstration at MIRA this year.

The second application – a waste heat hybrid, which can be integrated into buses or heavy duty vehicles, so reducing diesel consumption by up to 25% – is currently in development.

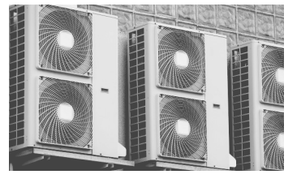
Dearman liquid engine air in cold chain and static applications



Dearman TRU
(Transport refrigeration unit)

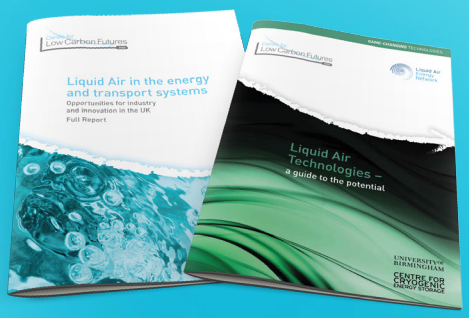


Dearman ZEV
(Zero-emission Vehicle)



Dearman static
power and cooling

- Nitrogen expanded in piston engine to provide mechanical energy for refrigeration unit, plus direct cooling effect of liquid nitrogen on cargo
- >30% more efficient than incumbent liquid nitrogen evaporation systems
- Dearman engine technology can also be used to provide primary power and cooling
- Best suited to shorter range low power cargo vehicles such as auto-rickshaws
- Large scale Dearman engines can be used to provide distributed cooling and power on demand.
- The system can be used for back-up power to replace diesel gensets.





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

Dr Lisa Kitinoja, Postharvest Education Institute

To find out more about the Cold Economy, and for recent reports on liquid air and its potential, please contact Prof. Toby Peters or Jess Lingwood at jessica.lingwood@dearmanengine.com.

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