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The prospects for liquid air cold chains in India

India

Cold and Power

Birmingham Energy Institute

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The Birmingham Energy Institute (BEI) is a focal point for the University of Birmingham and its national and international partners to tackle the challenges at the heart of 'Energy Systems', 'The Business of Energy', 'Energy and Transport' and 'Breakthroughs in Energy Technology'.

Co-ordinated research, education and the development of global partnerships are at the heart of our vision, drawing on our recognised centres of excellence in Nuclear Energy, Fuel Cells and their Fuels, Railway and Automotive Systems, Policy and Economics, and Energy Storage. By informing and guiding the choices people make today we aim to help shape our world of tomorrow.

As part of this we are looking at the challenges for meeting the future demands to provide cold and power in both an environmentally and economically sustainable way, from the pure science to the logistics around scale and policy implications. In 2015, we will lead lead a 'Commission on Cold' to investigate solutions to deliver sustainable cooling and power.

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The Birmingham Centre for Cryogenic Energy Storage houses a state-of-the-art, globally leading facility to support research and development in Cryogenic Energy Storage systems. The remit of the BCCES encompasses all aspects of cold chain technology – from materials, components and devices, to systems integration and optimisation. This includes a unique laboratory, which is capable of testing a range of Liquid Air Engines, from full-scale 'production' systems to external combustion heat (Stirling) engines.

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December 2014

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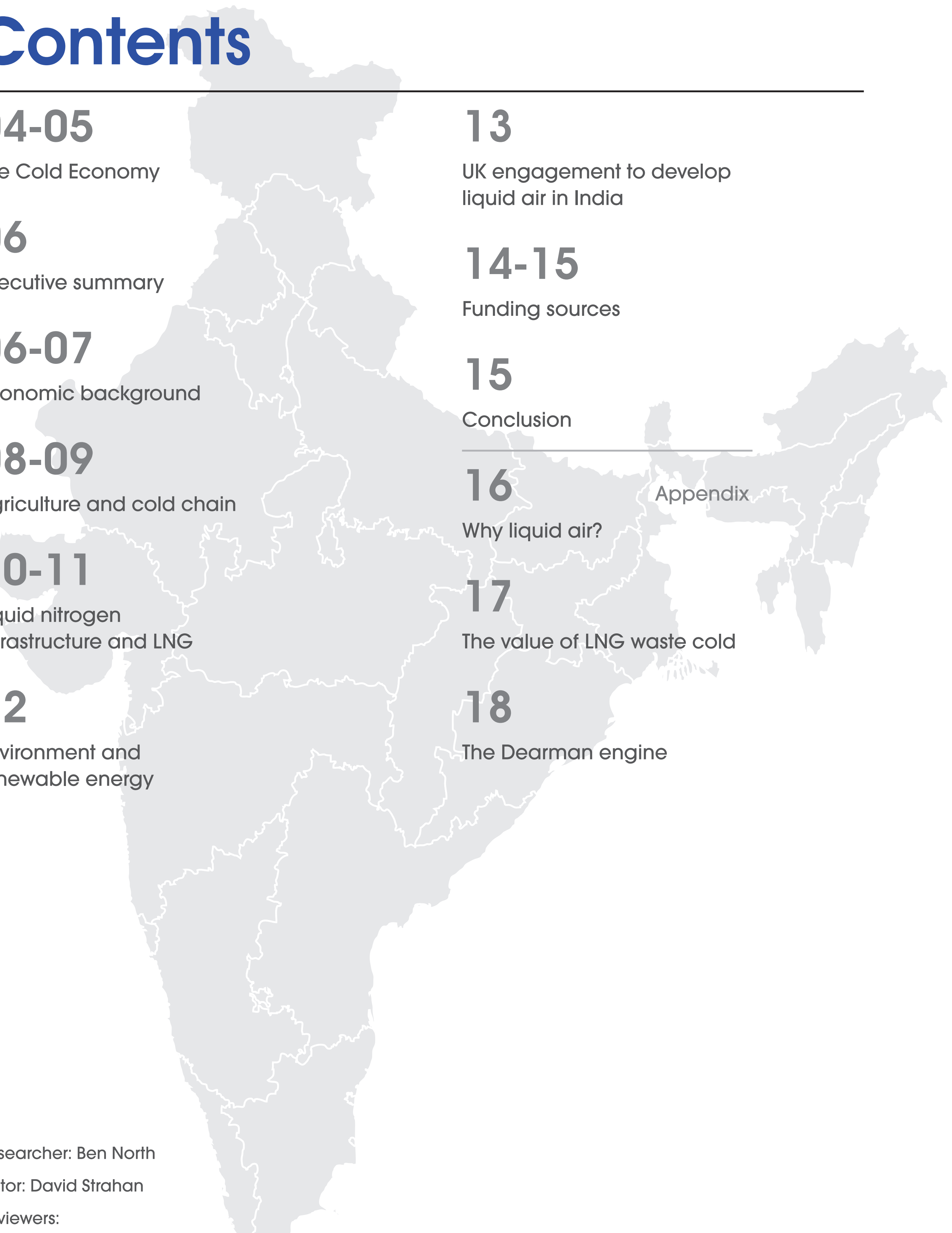
www.birmingham.ac.uk/energy

Contents



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All references in this report can be found at www.coldandpower.org.uk

Feeding 8 billion people by 2030 is the 'here now' global challenge.

We need to develop cold chains, but they must be sustainable; conventional cooling methods are energy intensive and highly polluting. Clean cold technologies are also vital to meet the soaring demands of the new aspirational middle classes of the developing world - for air conditioning, data centre cooling, convenience foods and home delivery – as well as cold chains for food and medicines.

- The International Institute of Refrigeration (IIR) estimates that more than 200 million tonnes of perishable foods could be preserved if developing countries had the same level of cold chain as found in the developed world.
- Food wastage consumes 250km^3 of water, three times the volume of Lake Geneva, and accounts for 3.3 billion tonnes of carbon emissions, and if it were a country would be the third biggest emitter after the USA and China.
- Demand for food is projected to grow by 40% by 2030. According to current trends India would be able to produce only 59% of its own food; in East Asia, only 67% of the food demand will be met from within the region, if the current rate of productivity growth and food wastage is maintained.
- The global refrigerated transport fleet is expected to double to 9.6 million vehicles by 2025, but to meet the entire demand from emerging markets, in particular Asia led by China and India, it may need to quadruple to more than 18 million vehicles.
- It is estimated that growth in global cooling to 2030 could equate to three times the current electricity generating capacity of the UK.

The Cold Economy

Cold is the Cinderella of the energy debate. Governments have developed policies governing most sectors – electricity, heat, transport – but the energy consumed for cooling gets much less attention. Yet demand for cooling in all its forms – air conditioning, data, industry, food and medicine – is soaring worldwide, and causing ever higher emissions of greenhouse gases and toxic air pollution.

Growth is nowhere stronger than in rapidly industrialising markets such as India and China, where investment in the 'cold chain' of refrigerated transport and warehousing is booming to service the lifestyles of the rapidly growing urban middle classes and reduce high levels of post-harvest food loss. India alone projects it needs to spend more than $15 billion on its cold chain over the next five years. We estimate demand for refrigerated vehicles in India could grow almost 100 fold by 2025, and the global demand could quadruple to almost 18 million.

The pollution from cooling is also little recognised but is a major contributor. One example is the diesel-powered transport refrigeration unit (TRU), the workhorse of the global cold chain, which continues to enjoy double-digit sales growth. TRUs not only consume up to 20% of the truck's fuel, but also emit 29 times as much particulate matter (PM) and six times as much nitrogen oxide (NOx) as a modern propulsion engine. What's more, leaks of TRU refrigerant gases have a grossly disproportionate impact on greenhouse gas emissions; the most commonly used 'F-gas' is almost 4,000 times more potent than CO_2. So while it is vital to expand cold chains to reduce food loss – and the consequent waste of water, energy and labour used to produce food that is never consumed – doing so with conventional technologies would only swap one set of environmental problems for another. We must find a way to 'do cold better'.

Even as cooling demand is soaring, vast amounts of cold are lost to the environment, especially during the re-gasification of Liquefied Natural Gas (LNG) at import terminals. LNG is simply natural gas 'packaged' in cold, which is then thrown away when the gas is regasified and 'unpacked'. This cold can in fact be re-cycled to produce cheap, low-carbon liquid air and provide zero-emission cooling and power in a wide range of static and mobile applications. Liquid air can also be produced from 'wrong time' renewable energy – such as surplus wind or solar produced when demand is low – to deliver near zero-carbon cold and power on demand, while helping to solve the problems caused by the intermittency of renewables.

If wrong time renewable energy and stranded LNG cold were used in this way, we could begin to talk of a joined-up 'Cold Economy'. This approach would cut energy consumption, greenhouse gas emissions, toxic air pollution and cost. In developing countries it could also help reduce high levels of food waste, which in turn would conserve water, land and energy, improve farmers' incomes, reduce food prices and stimulate trade and growth.

The full potential of a joined up Cold Economy is only just beginning to emerge but is evidently huge. 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. These would reduce emissions by as much as electric hybrids for a fraction of the cost. 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 for more than 4 million refrigerated trucks – almost equal to the entire current global fleet. If we only recycled a fraction of the waste cold, the environmental and economic savings would still be significant.

Sustainable cooling is a little recognised but urgent global challenge. 'Clean cold' is a new, multi-billion pound market and the UK is well-placed to become a world leader. This short report explores the potential in India. Here the rapid growth in both LNG imports and booming investment in new food distribution cold chains creates a clear opportunity to leapfrog the old wasteful ways of the developed world towards a new and more sustainable approach to cold.

Professor Toby Peters

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DISCLOSURE STATEMENT

Toby Peters is the Founder and Senior Group Managing Director of Dearman Engine Company, a privately-owned developer of liquid air engines for transport and the built environment. He also founded and is a shareholder in Highview Power Storage which is developing Liquid Air Energy Storage for grid-based applications.

Executive summary

The prospects for developing liquid air cold chains in India appear promising: the need is vast; investment in the sector is booming; much of the necessary infrastructure already exists; government policy is supportive; investment funds are available; and liquid air technologies would be economically competitive against diesel, and are zero-emission and environmentally sustainable.

In spite of the recent slowdown in developing world economies, India continues to grow at a decent clip. Rising incomes are swelling the ranks of the Indian middle class – expected by 2030 to be larger than the combined populations of the US, Japan and the UK – whose diets and lifestyles will depend increasingly on cold chains.[1] The revenues of India's fast food sector, for example, are forecast to triple to $8 billion by 2020.[2]

Yet cold chain capacity in India today is tiny compared to potential demand. Less than 4% of the country's fresh produce is transported by cold chain compared to over 90% in the UK.[3] In India's highly agrarian economy, this means that fruit and vegetables worth over £4.4 billion[4] are discarded each year – the figure rises to $13 billion if meat, fish and dairy are included – and that all the water, energy and labour used to produce them has also been squandered. This scandalous waste means farmers stay poor, children go hungry, food prices are inflated, and a country that produces 11% of the world's vegetables makes up just 1.7% of its vegetable trade.[5]

Investment in India's cold chains is now beginning to boom: India is expected to invest $15 billion in the sector in the next five years[6], where annual revenues are forecast to reach $13 billion by 2017.[7] But conventional forecasts may massively underestimate potential cold chain demand growth in the developing world; new analysis for this report suggests the Indian refrigerated vehicle fleet may need to grow almost 100 fold by 2025.

The new cold chains are overwhelmingly dominated by highly polluting diesel Transport Refrigeration Units (TRUs), whose disproportionate emissions of NOX and PM can only worsen the appalling smog that caused 600,000 premature Indian deaths in 2010 alone.[8] So reducing food loss using conventional cold chain technoloiges would ease one set of environmental problems only by worsening another.

TRUs fuelled by liquid air for power and cooling, such as the UK-developed Dearman engine, would be cheaper to buy and operate than a diesel unit; would eliminate all tailpipe emissions; and would be zero-carbon if the cryogen were generated from renewable energy – whereas diesel transport refrigeration emits up to 50tCO_2e per truck per year.[9] Liquid nitrogen, which can be used in the same way as liquid air, is already widely available in India, and the industry has 3,500 tonnes per day of spare production capacity – enough in principle to cool some 17,000 refrigerated vehicles, twice the size of India's current refrigerated truck fleet, and equal to estimated immediate unmet demand.[10]

A report from the Institution of Mechanical Engineers (IMechE) has shown the economics of a liquid air cold chain are compelling in India.[11] The business case becomes supercharged if waste cold from LNG re-gasification is used to help produce liquid air or nitrogen, reducing the electricity required by about two thirds. India's LNG imports are growing strongly, and import terminals could in future form the hubs of extensive import-export cold chains. The cold from projected Indian LNG imports in 2022 could in principle help produce enough liquid air to fuel half a million liquid air refrigeration units (TRUs) or 1 million auto-rickshaws (tuk-tuks).

The Dearman Engine Company is working with India's National Center for Cold-chain Development, and in discussion with leading Indian companies in engine manufacturing and industrial gas production to introduce a technology which could reduce emissions, food waste, food prices, poverty and hunger, and increase farmers' incomes, international trade and growth.

Economic background

India is the world's second most populous country and fourth biggest economy. After the start of economic liberalisation in the early 1990s, the country enjoyed almost two decades of 7% growth and became a global leader in IT and business outsourcing.[12] Growth has fallen below 5% for the last two years, but is predicted to recover this year and next.[13] Reforms are expected to continue following the election of Prime Minister Narendra Modi in May 2014, who campaigned as a moderniser, promising an east Asian investment-heavy model of development.[14]

[1] *All source references can be found at dearmanengine.com*

Agriculture remains huge in India but performs far below its potential. The sector employs over half the workforce, yet generates less than 14% of national income.[15] India is second only to China in fruit and vegetable production, but exports of horticultural produce account for less than $1 billion[16] compared to total agricultural exports – dominated by grains and pulses – of $39 billion.[17] One reason is the almost complete lack of cold chain, which results in up to 40% of produce being lost before ever reaching the consumer, which in turn raises retail prices and suppresses rural incomes.[18]

Almost 400 million Indians subsist on less than $1.25 a day. That's about a third of its population, and also a third of the global total living in extreme poverty.[19] Two thirds of India's poor live in the countryside, and rural destitution is one major cause of migration to city slums.[20] By raising the level of economic development, and creating more and better jobs for those Indians living in poverty, whether in the cities or the countryside, cold chains could contribute significantly towards achieving and maintaining the Millennium Development Goals. If those cold chains were developed using liquid air, they could also be zero-emission and cheaper than diesel.

Demographics

India stands to benefit from a situation known as the 'demographic dividend': half the population is under 24, and therefore about to enter their most economically productive years.[21] The population continues to grow fast, and by 2026, just 13% are expected to be over 60.[22] In the decade from 2020 to 2030, 275 million Indians are expected to join the new middle class – which at 475 million will be larger than the combined populations of the US, Japan and the UK – prompting the rise of a huge consumer economy.[23] The demographic dividend is expected to keep paying off until the 2040s in India; by contrast China's aging population means that it will lose its dividend by 2015.[24]

Educating and training this huge population could be an enormous opportunity for liquid air technologies such as Dearman, the Cold Economy and ancillary industries. 17 ministries are engaged in various initiatives, with a combined target of training 350 million Indians by 2022[25], and the government has also approved the creation of the National Skill Development Agency[26]. The development of liquid air cold chains would involve training significant numbers of engineers to operate, maintain and eventually manufacture the necessary equipment, and would therefore align with the government's aims for job and skills growth.

Energy, infrastructure and logistics

India's economy faces major challenges around energy, infrastructure and logistics:

- The annual energy import bill could spike from today's $120 billion to as high as $230 billion in 2023[27];
- India's electricity grid suffers daily power cuts; transmission and distribution losses of around 30% compared to 6% in the UK; and an energy shortfall at peak times of up to 20% in some regions;
- Up to $1 trillion investment is required in transport and power infrastructure[28];
- $132 billion in infrastructure projects are currently stalled by bureaucratic delays[29];
- By one estimate, the poor condition of transport infrastructure means that logistics add 20% to the cost of Indian goods, compared to 6-8% in China[30];
- While India has the world's second most extensive rail network, the cost per tonne/km is three times greater than in China[31];
- By 2030, the country is expected to have 68 cities with a population of 1 million or more[32]; but up to 70% of the cities and infrastructure required in 2030 are yet to be built.[33]

Investment is both planned and underway, however, and all signs point to a huge expansion of the Indian logistics industry and infrastructure to support it. By 2020:

- Agricultural output is expected to rise from 207 to 295 million tonnes[34];
- Transportation and logistics are expected to grow at 8% annually between 2013 and 2018[35];
- The market share of organized retail is expected to grow from 5% to 20%[36];
- Cargo handled at Indian ports is expected to rise from 890 to 2,800 million tonnes as part of the Maritime Agenda 2010-2020[37];
- The government plans to spend 2,870 billion rupees (£28.7 billion) in the decade to 2020 to build a total port capacity of 3,200 million tonnes.[38]

The need is clearly acute. India has just 3.3km of roads per 1,000 people, compared with more than 22km in the US, and over 15km in France[39], and it shows: the Financial Times has described an India, even at relatively low levels of growth, where "railways, roads, ports and airports are clogged by high traffic volumes and poor management".[40] With just 500km of National Highways road building projects awarded in 2013[41], the Modi administration has significant work to do to improve Indian transport infrastructure.

Agriculture and cold chain

India is home to more than 25% of the world's hungry poor, with 43% of children under 5 considered undernourished.[42] Yet the country is also the world's largest producer of milk, and second largest producer of fruit and vegetables – £4.4 billion of which go to waste in the supply chain every year.[43] The government has over the past five years become increasingly aware of the poor state of the Indian cold chain and the importance of post-harvest food waste typically between 30 and 40%.[44] This contributes to:

- Low levels of food processing and therefore no value added;
- High levels of food price inflation that have contributed to domestic political instability, street demonstrations etc;
- Depressed farm incomes[45], and lost export opportunities;
- Malnutrition, illness and rural poverty.

Agriculture employs more than half of India's workforce, but productivity is extremely low: just half the level in found in construction, for example, itself one of the poorest performing areas in the economy.[46] So any plan to tackle rural poverty, urban migration or growth more generally must address agricultural productivity. The government spends large sums ($11 billion in 2009-10) on subsidies for inputs such as fertiliser, but much less ($2 billion) on investments in storage and irrigation systems that would raise productivity for the long term.[47] From this it is clear India could rebalance its sizeable existing expenditure to favour assets that would lock in improved agricultural growth for years to come, and that these productivity gains could be cost neutral. One effective way of raising agricultural productivity would be to reduce post-harvest food losses by developing cold chains.

Cold chain

The cold chain market is expected to grow at a compound annual growth rate (CAGR) of 13.2% worldwide between now and 2017; and in India a CAGR of more than 25% is projected.[48] There is clearly a huge market need in India: the country has just 7 - 8,000 refrigerated trucks[49] (excluding milk distribution), whereas the UK, with a grocery market half the size and far lower ambient temperatures, has roughly 10 times more.[50] Related industries built on cold chains such as chilled pharmaceuticals and fast food are growing at 15%[51] and 34% a year respectively.[52]

Even these growth forecasts may not reflect the full potential for cold chain markets in India and the developing world more generally. Conventional 'bottom up' forecasts are typically produced by extrapolating current population and income growth trends, but tend not to capture structural factors such as urbanisation, changing diets, and new business models like home food delivery. Yet these factors are transforming India: by 2020, fast food revenues are expected to triple to $8 billion per year; by 2030 the country's middle class of 475 million will outnumber the combined populations of the US, Japan and the UK; by 2050, the UN predicts its urban population will double to more than 800 million. An estimated 16 million Indians migrate from the countryside to cities each year – equal to another New Delhi every twelve months – and the government plans to build 100 new 'Smart Cities' to relieve the pressure.

A 'top down' analysis for the Dearman Engine Company by E4tech assumes these factors mean developing world consumers will eventually demand a level of cold chain service closer to that found in the UK. This 'aspirational' demand may not be wholly satisfied over the next decade or so, but may be a more realistic measure of the long term potential. In India, which has some 27,000 refrigerated vehicles (including milk tankers) today, a bottom up analysis suggests the fleet will grow to around 250,000 by 2025, whereas the top down analysis projects a need for almost 2.5 million (Figure 1). At 250,000, India would have just 22 refrigerated vehicles per million of population, compared to 1,700 per million in the UK, suggesting the bottom up projection could be extremely conservative. The E4tech analysis does not mean that the higher 'aspirational' figure is likely to be achieved, but it does show there is enormous headroom for further growth beyond the bottom up forecast. For the world as a whole, the more conservative approach suggests refrigerated vehicle numbers will double from 4.7 million today to 9.7 million in 2025, whereas the top down analysis suggests they could quadruple to 17.9 million.

Growth and investment

Of the 104 million tonnes of fresh produce transported in India every year, just 4 million or 3.8% is transported within any form of cold chain, compared to over 90% in the UK.[53] The value lost to wastage in the Indian supply chain is $13 billion per year.[54] Even higher value items such as fish and milk that might be suitable for export suffer: 20-30% of fish spoils through lack of cold, and although 127 million tonnes of milk were produced in 2010-11, total milk cold storage capacity is just 80,000 tonnes.[55] Organised retail, though growing fast, has a market share below 5%[56]; and the agricultural sector as a whole is characterised by small farm sizes, yields well below international norms, and farmers unable to escape a cycle of poverty because high crop losses prevent them from reinvesting into their businesses.

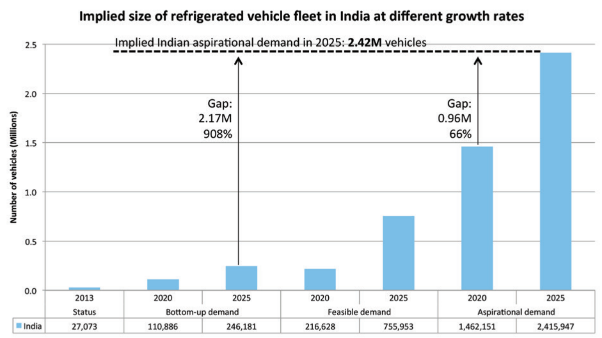


Figure 1: Potential refrigerated vehicle demand in India. Source: E4tech

Recognising the weakness of India's cold chain, in 2011 the government set up the National Center for Cold Chain Development (NCCD) to advise it on future development of the sector. The Center estimates that cold storage capacity falls 46 million tonnes short of what is required, and that 80% of existing capacity is suitable only for the storage of potatoes.[57] The geographical distribution of cold stores is also very uneven. In 2012, more than 60% of Indian cold storage facilities were located in just 4 of India's 28 states; largely in North and Central India, whereas large sections of South and East India have very little – Tamil Nadu for example has just 3% of the required cold storage facilities.[58] Where cold stores exist, anecdotes abound of unusual business practices such as using rice husk for insulation, rather than a fit-for-purpose product. As a result, energy efficiency is significantly behind comparable facilities in industrialised countries.

The shortage of refrigerated vehicles is even more acute. The NCCD estimates that to meet current demand, India requires a further 17,000 refrigerated vehicles. Chief Executive Pawanexh Kohli has also calculated that to make proper use of just 10% of India's existing cold storage capacity, the country needs to build 30,000 new pack-houses with pre-cooling facilities, and 60,000 refrigerated trucks.[59]

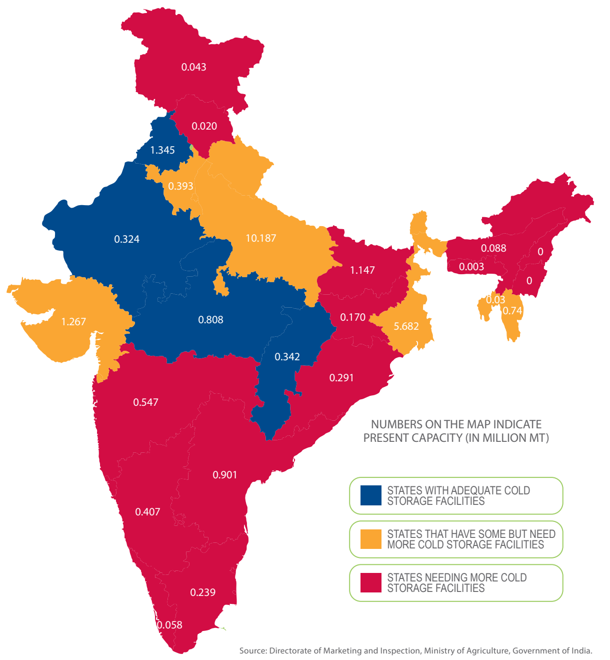


Figure 2. Cold storage capacity by state. Source: Ministry of Agriculture

Taking a broader international perspective, if India had the same ratio of refrigerated vehicles to the value of its grocery market ($375 billion in 2012) as Britain ($243 billion), it would have 129,000 refrigerated vehicles, 18 times more than at present.[60] And if it had the same ratio of refrigerated trucks to population as Britain, its fleet would number more than 1.5 million.[61] If anything like these sorts of numbers were satisfied using conventional cold chain technologies the local air pollution and greenhouse gas emissions impacts would be severe.

As part of the solution, the Indian government has designated the cold chain a 'sunrise sector', which presents major business advantages:

- grants of up to 55% of a refrigerated transport project's capital cost;
- truck refrigeration units exempt from basic customs duties;
- duty free import of refrigeration units used in refrigerated trucks; and
- 100% direct foreign investment in the cold chain permitted.[62]

Investments in food processing zones can also be self-sustaining, yielding internal rates of return to the Indian government of more than 25% per year, which generates funds for future investment.[63] Over the next 10 years, the Confederation of Indian Industry (CII) estimates the industry has the potential to attract $33 billion of investment[64], which would bring the processing of fruit and vegetables from 2% of the total to 24% by 2025. There is similar potential in meat and poultry, where currently only 1-2% of the meat is converted into a value-added product.[65] Given a favourable policy climate – food processing profits are fully tax deductible for the first five years of operation, and 25% deductible for the next five – there is good reason to expect this investment to materialise.[66]

There can be little doubt that demand for cold chain services will continue to grow strongly. The Indian fast food (or 'quick service') market – estimated at $2.5 billion in 2013 – is expected to grow to $8 billion by 2020[67], and its grocery market to be worth $566 billion by 2015.[68] Many of India's biggest conglomerates are starting to invest in cold chain including Reliance, Ranger Farms, Bharti, ITC, Food World and Spencer, as are some of the world's biggest fast food brands. McDonalds has tripled its Indian outlets to 300 over the last six years, for which it has built a bespoke cold chain to 35 suppliers across the country.[69] Yum Brands (which owns Pizza Hut, KFC and Taco Bell) also intends to triple its outlets in India to 1,000 by 2015[70], which will need the same kind of support , and Burger King will open its first restaurant in 2014. India's young population – two thirds are under 35 – is developing a taste for eating out, and incomes are rising, so there is clearly significant headroom for further growth.[71] It also means there is an urgent need to make cold services more sustainable.

Liquid nitrogen infrastructure and LNG

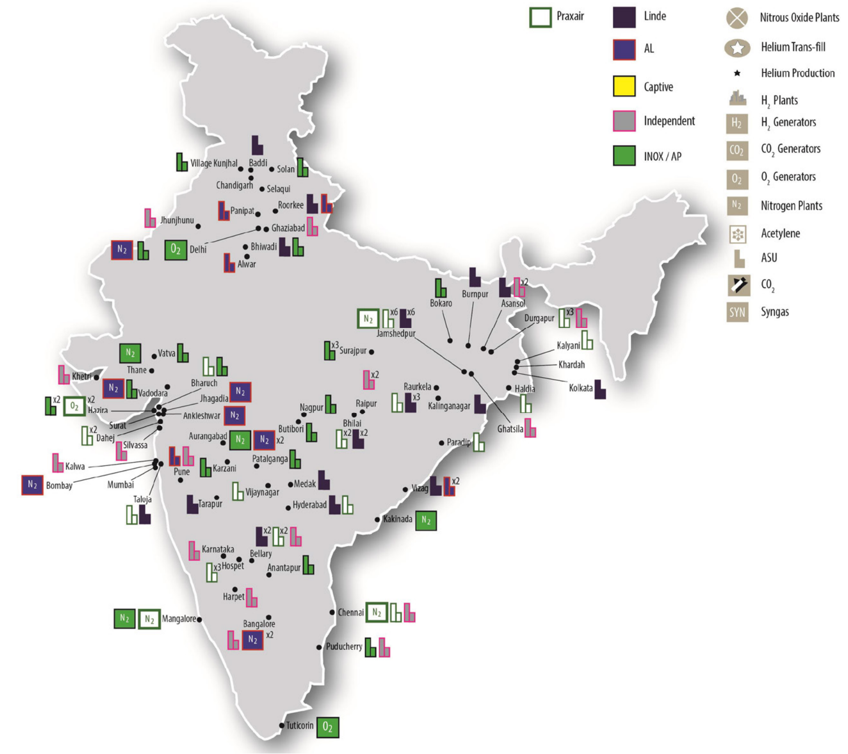


Figure 3. ASU facilities in India, main industrial gas companies. Source: gasworld 2014

A major advantage of liquid air technologies is that there is no 'chicken or egg' dilemma around the supply of fuel for field trials and early deployment in industrialised countries, because liquid nitrogen, which can be used in the same way as liquid air, is already produced in bulk. In fact, India has 3,500 tonnes per day of spare liquid nitrogen production capacity, enough to provide cooling for 17,500 refrigerated trucks, more than twice the entire current Indian fleet, and equal to the NCCD's estimate of immediate unmet demand.[72] What's more, INOX-AP, a joint venture including a current UK Dearman partner, Air Products, has confirmed it has the infrastructure to support field trials, and that capacity could be easily expanded to meet future demand.

Capturing stranded cold

Liquid air could also be an excellent fit with Liquefied Natural Gas (LNG) in India, where imports are projected to rise five-fold to about 60 million tonnes per year in 2022.[73] When LNG at -162C is re-gasified to enter the gas network it gives off vast amounts of cold that are usually lost to the environment. This could instead be recycled in a co-located air liquefaction plant to produce liquid air or nitrogen, so reducing the electricity required and the carbon intensity by about two thirds. This process has already been adopted by LNG plants in Osaka and elsewhere. According to the IMechE report, the waste cold from re-gasification of 60 million tonnes of LNG could in principle help produce enough liquid air to fuel over half a million Dearman engine TRUs.[74]

A more detailed analysis – part of a report for the NCCD by the strategic energy consultancy E4tech – indicates that a typical LNG terminal re-gasifying 7,100 tonnes of LNG per day could produce 2,600 tonnes of liquid nitrogen, enough to fuel 415 chilled reefers and 665 frozen reefers operating around the clock; and peak cooling (3 hours a day) for 7,500,000m³ of chilled and frozen buildings, both at the port and at inland warehouses at the other end of the cold chain. By 2020 India plans to have doubled its number of LNG re-gasification terminals – from four to eight. For reference, the largest such facility in the world measures around 600,000m³, and the UK has total capacity of 25,000,000m³.[75]

Liquid nitrogen supplies from an LNG-assisted plant would not only be plentiful but also cheap. E4tech estimates the vehicles described above would save their owners 900 million rupees or $15 million per year, a near 75% saving (net of capital costs) against the diesel system, which would have cost them $20.4 million. The buildings would save 560 million rupees or almost $9 million per year, a reduction of almost a third compared to back-up refrigeration with diesel, which would cost $27 million. These savings are likely to rise in future now the Indian government has stopped subsidising the price of diesel and started to raise excise duties on transport fuel. 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 of $13 billion per year; nor increased export earnings; nor the economic value of reduced emissions and improved health.

Because there is essentially no incumbent industry to displace, there are many possible applications, buildings and industries that could be supplied by liquid nitrogen from an LNG/ container port. These include inland cold stores and pack houses; refrigerated trucks to bring produce from the interior to the port; inland distribution centres supplied by refrigerated rail containers from the port; and fresh produce processing centres. Given India's demographic, growth and investment trends (see previous section), there can be little doubt that demand for cold chain services will continue to grow. It is vital, therefore, that these services are provided using zero-emission and low carbon technologies.

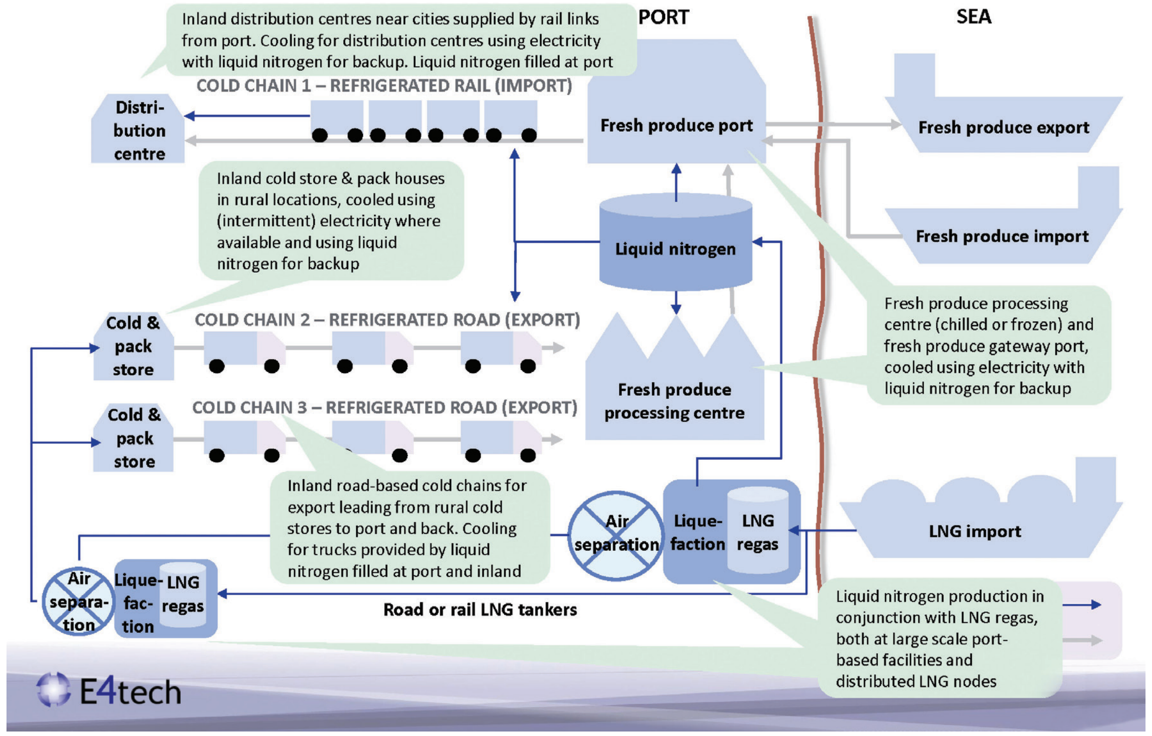


Figure 4. How waste cold from LNG re-gasification could power the 'Cold Economy' in India. Source: E4tech

Economics of liquid air refrigeration

Even without the help of waste LNG cold, the economics of liquid air refrigerated transport in India look compelling. A report by Dr Lisa Kitinoja of the Postharvest Education Foundation found a particularly strong case for urban delivery using liquid air equipped reefer vans, which Dearman believes will be a major growth opportunity. As one example, Dr Kitinoja found that for a 1 tonne reefer van liquid air refrigeration could be 20%-35% cheaper per kg of cargo than diesel, and for a 0.5 vehicle 23%-33% cheaper (see Figure 5 below).

	1 tonne capacity (small reefer van) Load market value $1000		0.5 tonne capacity (very small reefer van) Load market value $500	
Reefer target temperature	Diesel/ICE 5kW engine	Liquid Air/cryogenic engine	Diesel/ICE 5kW engine	Liquid Air/cryogenic engine
2°C	$25 to maintain temperature (21 L) $0.025/kg	$20 to maintain temperature (112 kg) $0.02/kg	$13 to maintain temperature (11 L) $0.013/kg	$10 to maintain temperature (56 kg) $0.01/kg
12°C	$23 to maintain temperature (20 L) $0.023/kg	$15 to maintain temperature (84 kg) $0.015/kg	$12 to maintain temperature (10 L) $0.012/kg	$8 to maintain temperature (42 kg) $0.008/kg

Figure 5. Estimated comparative costs for refrigerated transport in India. Source: Exploring the Potential for Cold Chain Development in Emerging and Rapidly Industrialising Economies through Liquid Air Refrigeration Technologies, Dr Lisa Kitinoja

Environment and renewable energy

Wind power park in Kanyakumari, South India

Environmental issues

Indian cities without doubt suffer some of the worst air pollution in the world. A report by India's Central Pollution Control found Delhi's annual mean nitrogen dioxide level was almost twice the World Health Organization (WHO) limit, and its PM10 level was thirteen times the limit.[76] PM10 levels were even worse in five other cities, and in total 24 made it onto the critical list. A report produced by the WHO itself found that the four cities with the world's worst air pollution were all in India, although this may be skewed by Chinese under-reporting.[77] In any event, air pollution caused 600,000 premature deaths in India in 2010.[78]

Booming investment in conventional cold chains can only worsen air pollution in Indian cities, since it is based on diesel TRUs which are heavy emitters of nitrogen oxides (NOx) and particulate matter (PM)[79] that brew the chronic smog afflicting many of India's major cities. Compared to a modern (Euro VI) diesel propulsion engine, a diesel TRU emits six times as much NOx and 29 times as much PM.[80] Transport refrigeration also consumes around 20% of the vehicle's fuel and causes carbon emissions as high as 50 tonnes of CO_2e per truck per year.[81] In stark contrast, a TRU fuelled with liquid air or nitrogen would be zero-emission, and zero carbon if the cryogen were produced from nuclear power or renewables.

Renewable energy

Renewable generation now constitutes 29% of India's installed capacity, largely due to extensive hydropower (16%) in areas such as the Himalayas, with other renewables making up a further 13%.[82] With energy demand set to double in India over the next 20 years[83], and in the context of severe electricity shortages that frequently leave areas without power for hours or days at a time, the Modi administration appears to have recognised the need for a large-scale expansion of renewable capacity. In November 2014, the Minister of Power and Energy, Piyush Goyal, announced a plan to add 10GW of wind power to the grid annually, and raised India's solar capacity target fivefold to 100GW by 2022.[84]

The problem with renewable generation is of course intermittency, particularly on a grid as weak as India's where lengthy power cuts happen every day. But liquid air provides its own means of storing 'wrong time' electricity as cold and power for use on demand. Those uses extend well beyond cold chain refrigeration to include diesel-liquid air 'heat hybrid' propulsion engines for lorries and buses, and cryogenic electricity generation to provide back-up power or grid balancing. If renewable generation in India grows as fast as Mr Modi's government promises, liquid air could provide vital energy storage and balancing. This could work in both an industrial setting and in more remote areas, where liquid air or nitrogen could be produced directly from renewables to provide cooling and reliable power for local micro-grids. This could revolutionise the prospects for cold chain and other energy services in rural areas.

UK engagement to develop liquid air in India

Clean and Cool Summit

The arguments for developing a liquid air cold chain in India have been explored in two reports launched at a global summit hosted by the Institution of Mechanical Engineers (IMechE) in Westminster in July 2014. The reports, *A Tank of Cold: Cleantech Leapfrog to a More Food Secure World*[85], and *Exploring the potential for cold chain development in emerging and rapidly industrializing economies through liquid air refrigeration technologies*[86], investigated the business case for various applications of liquid air in developing countries including India and Tanzania, and found that liquid air cold chain technologies would reduce post-harvest losses, raise farmers' incomes and improve air quality.

The summit drew delegates from as far afield as the Netherlands, Tanzania, Australia and the US, and speakers included two senior Indian officials: Pawanexh Kohli, Chief Adviser to the National Center for Cold-chain Development (NCCD), and Dr Ravinder Sharma, former Director of the National Horticulture Board. The event proved to be a springboard for commercial engagement, with a particular focus on the benefits of integrating liquid air cold chains with LNG regasification and the Cold Economy. The Dearman Engine Company and E4tech, a strategic energy consultancy, are now working with NCCD to develop LNG-liquid air integration, and Dearman is in discussion with leading Indian companies in engine manufacturing and the industrial gas industry.

Following the summit, a ten-day roadshow across India by IMechE to promote their report sparked considerable media interest, with articles published in Bloomberg, Press Trust of India, The Economic Times, Business Standard, News today, the Hindu Business Line and many local and industry publications.

Other engagement

Professor Toby Peters, Senior Group Managing Director of Dearman, spoke at the Automotive Worlds Megatrends conference in Chennai in February 2014, where the technology attracted significant interest. A roundtable hosted to test market receptiveness to liquid air technologies ended with a significant Indian industrial gas supplier (Inox-Air Products) advising that they foresaw no problem with the supply of liquid nitrogen to support field trials.

As part of a broader programme of events, in December 2014 Dearman will be taking up an invitation from the Deputy British High Commission to present on refrigeration technologies at a workshop in Pune. Dearman is also looking towards international trials in India and Tanzania, having signed an agreement with Hubbard Products Ltd, a Zanotti Group Company, to deliver 5-15 Dearman powered transport refrigeration units.

Back row L-R: Professor Richard Williams, FREng, University of Birmingham; Pawanexh Kohli, National Center for Cold-Chain Development; Eric Trachtenberg, McLarty Associates; Adam Chase, E4tech **Front row L-R:** Dr Tim Fox, Institution of Mechanical Engineers; Dr R. K. Sharma, formerly Ministry of Agriculture, Government of India; Dr Lisa Kitinoja, Postharvest Education Foundation; Jacqueline Mkindi, Tanzania Horticultural Association

Funding sources

Investment in India's cold chain is booming, driven by demand and supportive government policies. There are also significant pools of potential funding available from a range of international donors that could support innovative cold chain technologies such as liquid air.

USAID

The India Mission of USAID, the American Government's main international aid organisation, is transforming itself into a testbed to demonstrate innovations which can then be rolled out through the rest of USAID's global network. The India Mission supports innovations that improve the lives of the very poorest (those at the 'Base of the Pyramid'); reduce greenhouse gas emissions; and can be replicated in other developing countries, which at present seems to be happening mainly through Kenya, Liberia and Malawi. Specific work areas include reducing the costs of renewables; improving energy efficiency in buildings, industry, and transport; and extending energy access to remote rural areas through renewable microgrids.

Funding is largely delivered through the USAID India Partnerships Program (IPP) on a partnership model that now seeks to take advantage of India's new Companies Act, which requires qualified companies to spend 2% of their average net profits on CSR activities. Liquid air technologies could qualify for support under USAID's clean energy and forestry programmes, intended to improve off-grid energy access and reduce air pollution, and its food security and nutrition programmes, where a liquid air cold chain should be eligible under "Innovations that transform primary products to value-added goods and service for focus value chains and markets".[87]

The IPP supports projects of at least $1 million, although at least 50% must come from non-USAID sources, and a high level of local involvement is expected. But USAID will also support foreign technologies with the potential to significantly improve the lives of the poorest, particularly if a strong Indian-foreign partnership model is devised to deliver the project. A major benefit of IPP funding is its speed: a project can be up and running within 5-9 months of the initial application. USAID will also help co-design the application, the delivery partnership and strategy, meaning partnerships can exploit not only USAID funding but also its network of contacts.[88]

Aside from its India Mission and the IPP, USAID runs several other programmes that may be relevant to liquid air cold chains. Development Innovation Ventures is a Global Development Labs-administered project with a yearly call to fund demonstration projects up to $1.5 million, and proven projects up to $15 million. And the Clean Energy Access Network (CLEAN) is an alliance of businesses, not-for-profits, and government intended to strengthen India's market-driven approaches to energy access. Power Africa is a programme that works to bring electricity to the 600 million sub-Saharan Africans who have none, and Powering Agriculture increases food security and economic growth by bringing clean energy to farmers.

Key Country Programmes

The US-India Partnership to Advance Clean Energy (PACE) brings together the US Departments of Commerce, State and Energy along with the Export-Import Bank, the Overseas Private Investment Corporation (OPIC), the US Trade and Development Agency (USTDA) and USAID to support energy access, renewable energy, smart grids, building and industrial energy efficiency, clean energy finance and dialogue with India. The programme started as an initiative of the US-India Energy Dialogue in 2009, and has grown in breadth every year.

Notable programme achievements include:

- $2.4 billion mobilised for clean energy finance;
- OPIC disbursed $250 million to the Indian infrastructure lender Infrastructure Development Finance Co for onward lending to green energy projects;
- Ex-Im Bank is currently one of the largest financiers of renewable energy projects in India, whose Indian solar portfolio of 289MW is worth over $353 million;
- Ex-Im Bank and the Indian Renewable Energy Development Authority have concluded a Memorandum of Understanding to make $1 billion available for low carbon projects.

Promoting Energy Access through Clean Energy (PEACE) is another programme, launched as part of PACE, which aims to harness business to bring electricity to un- and under-served Indian villages, through renewable microgrids. This will partly be through the PACEsetter Fund, which will provide seed funding to support the development of early-stage, innovative off-grid clean energy solutions.

Other Funding Opportunities

Significant sums are also available from investors, NGOs and governments, who increasingly recognise the value of moving away from large scale food aid programmes towards smaller, targeted programmes, which have the potential to leverage smaller pots of money to greater effect by engaging business and industry.

Among these is the £500 million Indian Inclusive Innovation Fund, run by India's National Innovation Council, which was launched in January 2014 with a mandate to use a venture capital model to "provide financial support to innovative projects with a social cause". The fund will begin making investments in November 2014, with a maximum investment in the region of £500,000.

The Millennium Alliance is a network of donors, investors, companies and social innovators that arranges financial contributions from the private and public sectors. It offers a tiered grant scheme and funds demonstration projects up to a value of $750,000, and beyond this funds larger-scale roll out of their most successful projects.

Conclusion

This brief review suggests the prospects for developing liquid air cold chains in India are promising. The need is vast; investment in the sector is booming; much of the necessary infrastructure already exists; government policy is supportive; investment funds are available; and liquid air technologies would be economically competitive against diesel and zero-emission. Dearman continues to work with partners in India and internationally to bring about field trials to demonstrate the technology and then commercial roll-out.

Cold chains are only one aspect of the Cold Economy, however, and the potential for exploiting waste LNG cold through the medium of liquid air or nitrogen extends to many applications not considered in this report: diesel-liquid air 'heat hybrid' propulsion engines for trucks and buses; zero-emission engines for auto-rickshaws; cryogenic power generation and grid balancing; and many other forms of cooling. These are explored in depth in reports already published by the Institution of Mechanical Engineers and the Liquid Air Energy Network, and will also be the subject of future reports in this Cold Economy series.

Hyderabad financial district – part of the new 'cold hungry' India

Pharmaceutical cold chains

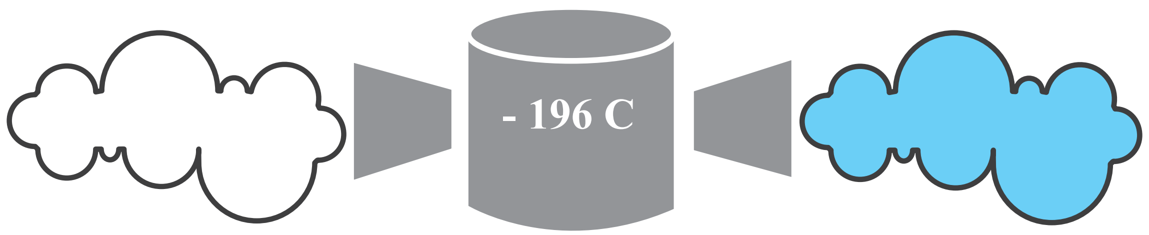
This report focused mainly on food, but cold chains are just as vital for preserving medicines. India is the world's third largest pharmaceutical producer – output almost tripled to $32 billion in the seven years to 2014 – and its domestic market is expected to be worth $55 billion by 2020. But like agriculture the industry is plagued by inadequate cold logistics: it's estimated almost 20% of temperature sensitive healthcare products arrive damaged or degraded because of a broken cold chain, including 25% of vaccines. Investment in pharmaceutical cold chains is growing faster in Asia than any other region – up 50% to $1.5 billion in the five years to 2012 – but relies overwhelmingly on conventional technologies. The industry is acutely aware of the need to develop sustainable cooling, but so far the focus has been on incremental improvements in the fuel efficiency of highly polluting diesel TRUs. By contrast liquid air technologies and the Cold Economy would offer a step change towards sustainability. Pharmaceutical cold chains will be the subject of a future study.

Appendix

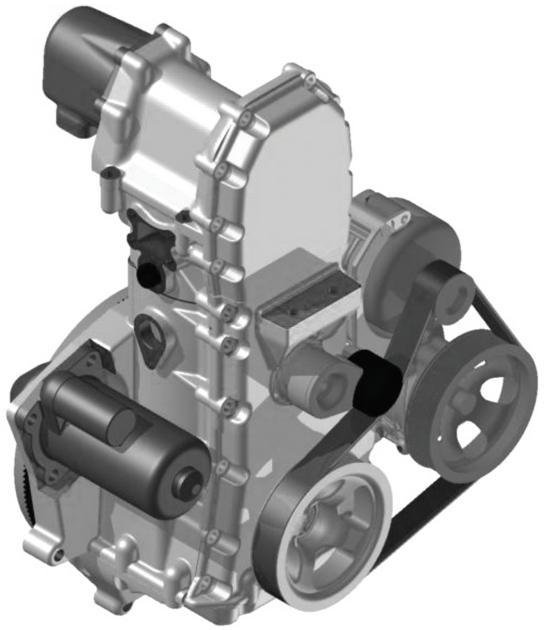
Why liquid air?

The key to replacing fossil fuels in transport with renewable energy is finding a convenient way to store power from intermittent sources such as wind and solar so it can be used in vehicles on demand. Existing technologies like batteries and hydrogen all have drawbacks. One recent innovation, liquid air, although not a silver bullet, is increasingly recognised as part of the solution, particularly where there is a need for power and cooling, as in the rapidly expanding global cold chain.

Liquid air is not yet produced commercially, but liquid nitrogen, which can be used in the same way, has long been produced for industrial purposes in all the major economies. The innovation is to think of liquid air or nitrogen not as an industrial chemical, but as a store of cold and power, which can be produced from surplus or 'wrong time' renewable energy or waste cold and stored until needed.



There is already substantial spare liquid nitrogen production capacity in most industrial countries. Britain, for example, has 2,200 tonnes per day of spare nitrogen production capacity which could fuel a projected fleet of 36,000 liquid air vehicles until the end of the decade.



The UK-developed Dearman engine

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 710-fold expansion in volume, which can be used to drive a turbine or piston engine. The only exhaust is clean cold air. The main potential applications are in electricity storage, refrigeration and as a transport 'fuel'. The addition of waste heat – for instance, from an internal combustion engine – increases the work that can be extracted from the expansion of liquid air. That expansion also gives off large amounts of valuable cold, which can provide 'free' refrigeration or air conditioning, or be used to increase the efficiency of diesel engines or hydrogen fuel cells.

Liquid air as a new energy storage vector – delivering cold and power – is making rapid progress and has now received some £20 million in government grants. These 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 Dearman liquid air vehicle engines. Liquid air has been recognised in the technology roadmaps of both the Automotive Council and the European Road Transport Advisory Council.

The value of LNG waste cold

Natural gas is refrigerated to -162C to become Liquefied Natural Gas (LNG) for transport by supertanker from producing to consuming nations. At the import terminal the LNG is warmed to re-gasify before entering the pipeline network, and most of the cold that kept it in compact liquid form during the sea voyage is usually discarded. This spectacular waste of energy is increasingly significant since the IEA forecasts European LNG imports will double to 120bcm/year by 2040.

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 annual output of 14 1GW nuclear power stations. To save energy, emissions and cost it is vital to find productive uses for LNG waste cold.

Large users of cold such as data centres could be built close to LNG plants to access its waste cold 'over the fence'. But to make use of as much of the waste cold as possible, it needs to be transformed into a storable and transportable form, allowing it to be used in vehicles and at remote locations. One way to achieve this is through liquid air.

When LNG is re-gasified from its liquid state at -162C to enter the gas grid, the cold it gives off can be recycled through a co-located air liquefaction plant to help produce liquid air or nitrogen (see previous section) at around -196C. This reduces the electricity required to produce the cryogen – and its carbon intensity – by about two thirds, and the cost by almost as much. This approach has been demonstrated for some years at an LNG terminal at Osaka in Japan. If it were adopted more widely the impact could be huge. Our modelling suggests:

- the cold given off by the Isle of Grain LNG terminal each year could fuel London's entire bus fleet as liquid air 'heat hybrids' more than six times over, reducing diesel consumption by 25%;
- the waste cold from India's projected LNG imports in 2022 could provide liquid air cooling for over half a million refrigerated lorries, or fuel 230,000 heat hybrid buses or 1 million autorickshaws;
- the projected global LNG trade in 2030 could provide liquid air cooling for 4.2 million refrigerated delivery lorries – more than the current global fleet.

Once converted into liquid air, LNG waste cold could be used in applications as diverse as static and vehicle refrigeration, heat hybrid lorry and bus propulsion engines, zero-emission emergency electricity generation, and bulk energy storage and grid balancing. These applications would reduce diesel consumption, greenhouse gas emissions and local air pollution, and would reduce costs even more than those operating on conventionally produced liquid nitrogen. In this way LNG waste cold could provide the 'fuel' for the Cold Economy.

LNG tanks at the Port of Barcelona

The Dearman engine

Peter Dearman, inventor of the Deaman engine

The Dearman engine is a novel piston engine powered by the phase-change expansion of liquid air or liquid nitrogen. In principle it works just like a steam engine, only 300°C colder. It was invented by Peter Dearman (pictured), a classic British 'garden shed' inventor, and is being developed by the Dearman Engine Company to perform a variety of roles.

Because it produces both power and cooling from the same unit of 'fuel', the Dearman engine can serve as an efficient and zero emission transport refrigeration engine to replace the highly polluting secondary diesel units used on trucks today. The Dearman refrigeration engine will be in on-vehicle trials with MIRA in 2014 and fleet trials in 2015. Modelling shows the engine would repay its investment within three months.

Because liquid air boils at -194°C (and liquid nitrogen at -196°C), its work output can be raised by the addition of waste heat from another source. This means the Dearman engine can be combined with a diesel engine or hydrogen fuel cell to form a 'heat hybrid', where waste heat and cold are exchanged between the engines to increase the efficiency of both and reduce fuel consumption.

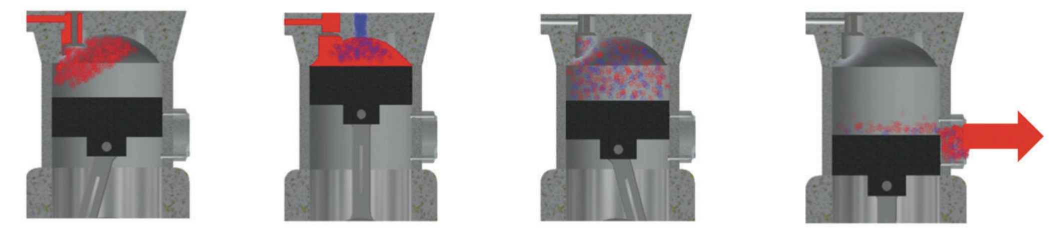
Modelling suggests this arrangement would turn waste heat into extra power at practical conversion efficiencies approaching 50%, and reduce bus and lorry diesel consumption by 25%. A consortium including Dearman, Air Products, MIRA, Cenex, TRL, The Manufacturing Technology Centre and The Proving Factory has been awarded nearly £2 million by Innovate UK to build a heat hybrid prototype by 2016.

In future, the Dearman engine could also be used as a stand-alone propulsion engine for smaller, shorter distance vehicles such as auto-rickshaws ('tuk tuks') in developing countries, where the exhaust of clean cold air would provide 'free' air conditioning. It could also be used as a static back-up electricity generator to replace highly polluting diesel gen-sets.

Cryogenic expansion engines have existed for over a century, but the Dearman engine is novel because it uses a heat exchange fluid (made of water and glycol – just like conventional radiator fluid) to promote rapid and efficient re-gasification inside the engine cylinder.

To find out more about the Dearman engine please visit: *www.dearmanengine.com*

An example power cycle is shown on the diagram below



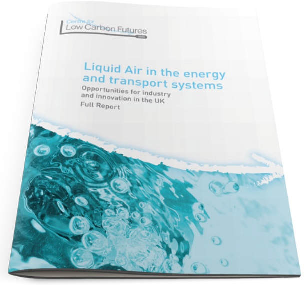
Return Stroke
Warm heat exchange fluid (HEF) enters the cylinder.

Top Dead Centre
Cryogenic liquid is injected directly into the cylinder. Heat transfer with the HEF causes rapid vaporisation and pressure rise.

Power Stroke
The vaporised cryogenic liquid expands pushing the piston down. Direct contact heat transfer continues allowing near isothermal expansion.

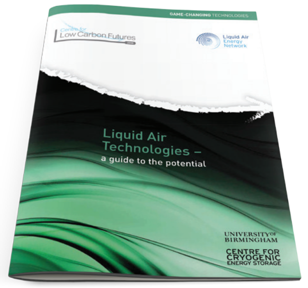
Bottom Dead Centre
The exhaust mixture leaves the cylinder. The gas is returned to the atmosphere and the HEF is re-heated and re-used.

Liquid air reports



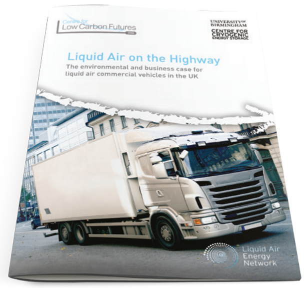
Liquid Air in the energy and transport systems: Opportunities for industry and innovation in the UK

Centre for Low Carbon Futures, 2013



Liquid Air Technologies – A guide to the potential

Liquid Air Energy Network, Centre for Low Carbon Futures, University of Birmingham, 2013

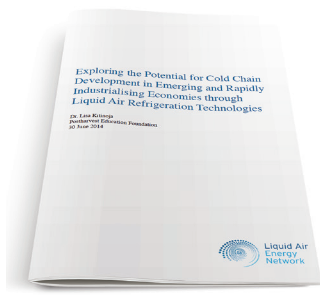


Liquid Air on the Highway: The environmental and business case for liquid air commercial vehicles in the UK

Liquid Air Energy Network, Centre for Low Carbon Futures, University of Birmingham, 2014

A Tank of Cold: Cleantech Leapfrog to a More Food Secure World

Institution of Mechanical Engineers, 2014

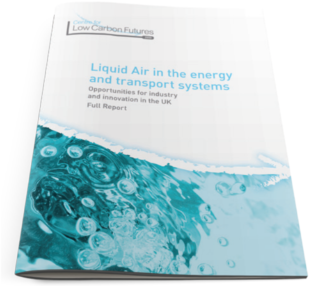


Exploring the Potential for Cold Chain Development in Emerging and Rapidly Industrialising Economies through Liquid Air Refrigeration Technologies

Dr Lisa Kitinoja, Liquid Air Energy Network, 2014

All references in this report, and copies of the above, can be found at www.coldandpower.org.uk

Liquid air reports



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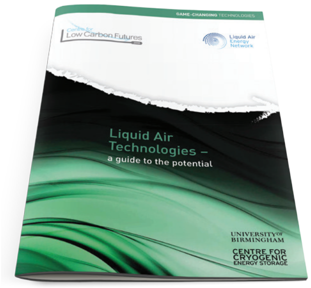

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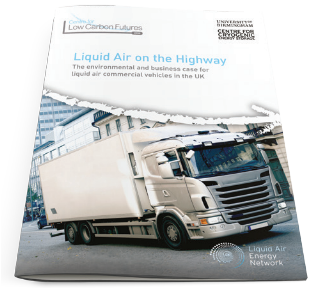

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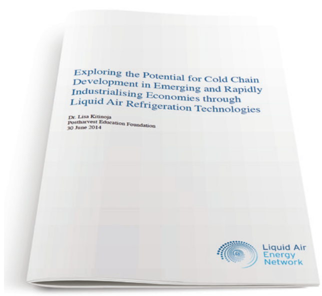

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