Cold chains and the demographic dividend



What the arrival of 3 billion new middle class consumers means for transport refrigeration – and its emissions

Dearman.

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Dearman is a global technology company delivering clean 'cold and power'.

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We would like to thank E4tech for their analysis in support of this report.
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Editor: David Strahan

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Dearman.

“Globally, civilisation has reached a tipping point where our capacity to feed our growing numbers is of serious and increasing concern. Science has enabled us to increase food production, but much of what we produce perishes before it can reach the people we need to feed. It has therefore become imperative that mankind fully grasps and controls clean cold energy, so that our species can continue to thrive and prosper.”

Pawanexh Kohli,
Chief Advisor & CEO,
National Centre for Cold-chain Development, India

- **The cold chain industry faces a period of unprecedented demand growth due to rapid demographic change in emerging markets.**
- **The Asian middle class is forecast to expand six-fold to more than 3 billion people by 2030, two thirds of the world total; the global urban population will grow to 6 billion by 2050.**
- **Cold chains in emerging markets are rudimentary or non-existent: China has half the refrigerated vehicles of France.**
- **Cold chain investment is starting to boom in emerging markets, but relies on highly polluting diesel-powered transport refrigeration units.**
- **Air pollution causes around 600,000 premature deaths in India each year and 1.2 million in China.**



Cold chains and the demographic dividend

Cold chains in the developing world today are rudimentary to non-existent – but perhaps not for much longer. In India, for example, just 4% of fresh produce travels to market through a system of refrigerated warehouses and trucks, compared to more than 90% in the UK, causing high levels of food wastage. In China, meanwhile, there are thought to be some 66,000 refrigerated vehicles serving a population of 1.3 billion, whereas France has 140,000 for a population of just 66 million.

Cold chains are vital not only for food but also medicine: it's estimated that more than 2 million people die each year from lack of vaccines due to inadequate refrigerated distribution. In India, for example, the world's third largest pharmaceutical producer, where output almost tripled to $32 billion in the seven years to 2014, almost 20% of temperature sensitive healthcare products and 25% of vaccines arrive damaged or degraded because of a broken cold chain.

But these disparities seem unlikely to persist in the face of the tectonic demographic change that is already under way: rising incomes, urbanisation and population growth. Developing countries now face a choice: whether to build their vital new cold chains using conventional, highly polluting technologies or the clean cold technologies of the future.

The West is used to viewing Asia as the workshop of the world, but rising incomes mean the region could soon have twice the consumer spending power of Europe and North America combined. Forecasts from the OECD suggest the Asian middle class will multiply six-fold by 2030 to more than 3 billion people, two thirds of the global total. As incomes rise, people tend to eat more meat, dairy, fruit and vegetables, and to eat in restaurants more often, all of which requires cold chains.

At the same time, the global population is forecast to grow to 9 - 10 billion people by mid-century, putting ever greater pressure on the food supply. Rapid urbanisation means the numbers living in cities will rise by two thirds to more than 6 billion, making it ever more important to reduce food losses along lengthening supply chains. Around one third of all calories produced worldwide for human consumption are lost between farm and fork, but the picture in developing countries is far worse. The estimated annual cost of food wastage in India is $13 billion and China $20 billion. If developing countries had the same level of refrigerated transport and warehousing as found in the developed world, 200 million tonnes of perishable food would be saved each year – increasing the food supply by 14%.

Investment in cold chains is now beginning to boom in China and India, but based on diesel-powered technologies that produce grossly disproportionate emissions of NOx and PM. If this continues, it can only worsen the extreme levels of toxic air pollution that cause around 1.8 million premature deaths each year in those two countries alone.

Cooling is a vital foundation of modern economies, but its environmental impact is becoming punitive. The industry has made some incremental improvements in efficiency, but these are likely to be overwhelmed by demand growth in the developing world. To make cold sustainable requires a radically new approach.

Luckily there is a portfolio of new British technologies moving into demonstration and early deployment, supported by academic and industrial research and development. With the right support these technologies could coalesce into a major industry that simultaneously reduces greenhouse gas emissions, improves air quality, replaces environmentally destructive refrigerants with benign alternatives, and creates thousands of new manufacturing jobs.

This report explores the demographic drivers of cold chain demand in developing countries, and shows how growth over the next twenty years could be far stronger than anyone imagines. If these new cold chains are built using conventional technologies the pollution and health impacts will be severe. This threat is not yet widely appreciated and warrants further investigation and debate.

At the same time, "clean cold" is potentially a huge opportunity for Britain, where technology development and thinking around cold energy systems are making great strides – which are so far unmatched elsewhere. With the right support, this work could soon form the basis of a truly global market.

Toby Peters

Senior Group Managing Director, Dearman

Visiting Professor in Power and Cold Economy, Birmingham Energy Institute, University of Birmingham

Executive summary

The emerging markets boom of the last three decades is a familiar story. Less well known is the surge in cold chain investment and consumption that has been an integral part of the rapid growth in many emerging economies. In China, for example, fridge ownership among urban households rose from 7% to 95% between 1995 and 2007[1]; and cold storage capacity soared nine-fold from just 250 million cubic feet to more than 2 billion in the three years to 2010[2], and is on track to more than double again by 2017.[3] China's cold chain business is reported to be growing at 25% per year and projected to be worth $75 billion by 2017.[4] Cold chain investment is also booming in India, and annual revenues in the sector are forecast to reach $13 billion by 2017.[5] This correlation should come as no surprise: as people's incomes rise, they naturally buy the appliances and services that improve the quality, safety and variety of the food they eat. But the question now is how far does this trend have left to run?

Growth in emerging economies has slowed sharply since the financial crisis, to less than 7.5% in China and 5% in India, reflecting the near-depression afflicting much of Europe, and in the case of China at least, a deliberate policy to slow the expansion to a more sustainable pace. Some economists distrust official Chinese GDP figures and think the economy has slowed even further to around 4%[6], while some even argue the Asian economic miracle has peaked[7], implying any future growth in cold chains would be sedate at best. We suggest, on the contrary, that there is potential for even faster expansion in cold chains in China and India – and sustainable cold chains at that – because of demographic and other factors that may not be captured by conventional forecasting approaches.

These factors include:

- the emergence by 2030 of a huge new Asian middle class of over 3 billion people, two thirds of the world total;
- headroom for growth: less than 4% of India's fresh produce is transported by cold chain compared to more than 90% in the UK;
- the critical need to reduce food waste in order to feed a population of 9 billion by 2050: it's estimated that halving food wastage could feed an extra 1 billion people[8]; fruit and vegetables worth $4.4 billion are discarded every year in India alone;
- the high environmental, health and financial costs of conventional cold chain technologies.

In the major developing economies, refrigerated transport looks likely to grow even faster than the cold chain as a whole, since investment to date has been skewed towards cold storage. To create truly integrated cold chains, developing countries will need to invest far more in transport refrigeration. End-to-end cold is also vital for transporting vaccines and medicines, and global investment in pharmaceutical cold chains is expected to grow at over 13% per year to 2019[9], although this paper focuses on food cold chains in the developing world.

Analysis by the strategic energy consultancy E4tech supports the argument that there may be far more headroom for growth in cold chain demand in countries such as China and India than suggested by conventional forecasts. Conventional 'bottom up' projections suggest the global refrigerated truck fleet could grow to five times its current size by 2025, whereas a 'top down' approach that takes account of the growth rates achieved by analogous goods and services in developing countries suggests demand could conceivably grow nine-fold. Neither figure is a forecast, and we certainly do not expect to see the very upper end of the range in so short a time-frame. But the analysis does suggest there is potential for far stronger growth than is generally expected, and that the job of dealing with its environmental and health impacts is increasingly urgent.

Demographic dividends

It's well known that the production of consumer goods has shifted overwhelmingly to the East over the past thirty years, but that consumer demand has stayed largely in the rich western economies. Most of China's break-neck growth, for example, has been fuelled by investment and exports rather than domestic consumption. While it's true that China has recently emerged as the world's largest market for both cars and cell phones, and its middle class of some 157 million people is large in absolute terms (second only to the US), it still represents just 12% of the population.[10] And the middle class is even less developed in other emerging giants such as India. But this could be about to change – according to a plethora of reports from international authorities, consultancies and investment houses[11] – creating the potential for a surge in demand for consumer goods that depend on cold chain services.

Emerging middle class

One analysis published by the OECD[11] has shown that while Asia Pacific countries account for less than 30% of the global middle class today, by as early as 2020 they could represent 50% of its population and 40% of its spending. This is because in many developing countries there is a large group of people just below the middle class – defined as those earning between $10 and $100 per day – whose incomes will be lifted over the threshold by expected economic growth. The analysis suggests that Asian Pacific middle class could grow six-fold from 525 million people today to 3.2 billion in 2030, two thirds of the global total, and its spending power could rise from $5 trillion to $33 trillion (Tables 1 and 2).

A daily income of $10-$100 may not sound particularly middle class by western standards, but calculated at purchasing power parity, which takes account of the fact that goods are much cheaper in poorer countries, it represents considerable spending power. In this income bracket, people have money to spend not only on the bare necessities but also discretionary goods and services: fridges, TVs and satellite dishes, more meat and dairy, education, eating out, and perhaps a scooter or car.

The Chinese car market is a case in point. Even a decade ago the market was tiny, with sales of less than a million vehicles per year, but as average incomes reached $6,000 in 2008, sales took off.[15] In 2009 Chinese car and truck sales reached almost 14 million, overtaking the US with just over 10 million. Chinese vehicle sales then grew to 22 million in 2013, although they appear to have flattened in 2014 (Figure 1). In 2004 GM sold 10 cars in the US for every 1 in China; by 2009 the ratio was 1:1.

This dramatic change took place at a time when the emerging Chinese middle class was still relatively small. As Figure 2 shows, in 2009 just 12% of China's population, or 157 million people, earned more than $10 per day, but the OECD paper argues that provided the government pursues sensible policies to support income equality, this could swell to 75% by 2030, or around 1 billion people.

	2009		2020		2030	
North America	338	18%	333	10%	322	7%
Europe	664	36%	703	22%	680	14%
Central & South America	181	10%	251	8%	313	6%
Asia Pacific	525	28%	1,740	54%	3,228	66%
Sub Saharan Africa	32	2%	57	2%	107	2%
Middle East & North Africa	105	6%	165	5%	234	5%
World	1,845	100%	3,249	100%	4,884	100%

Table 1: Numbers (millions) and share (percent) of the global middle class by region. Source: OECD[13]

	2009		2020		2030	
North America	5,602	26%	5,863	17%	5,837	10%
Europe	8,138	38%	1,031	29%	11,337	20%
Central & South America	1,534	7%	2,315	7%	3,117	6%
Asia Pacific	4,952	23%	14,798	42%	32,596	59%
Sub Saharan Africa	256	1%	448	1%	827	1%
Middle East & North Africa	796	4%	1,321	4%	1,966	4%
World	21,278	100%	35,045	100%	55,680	100%

Table 2: Spending by the global middle class, 2009 to 2030 by region (billions of 2005 purchasing power parity dollars). Source: OECD[14]

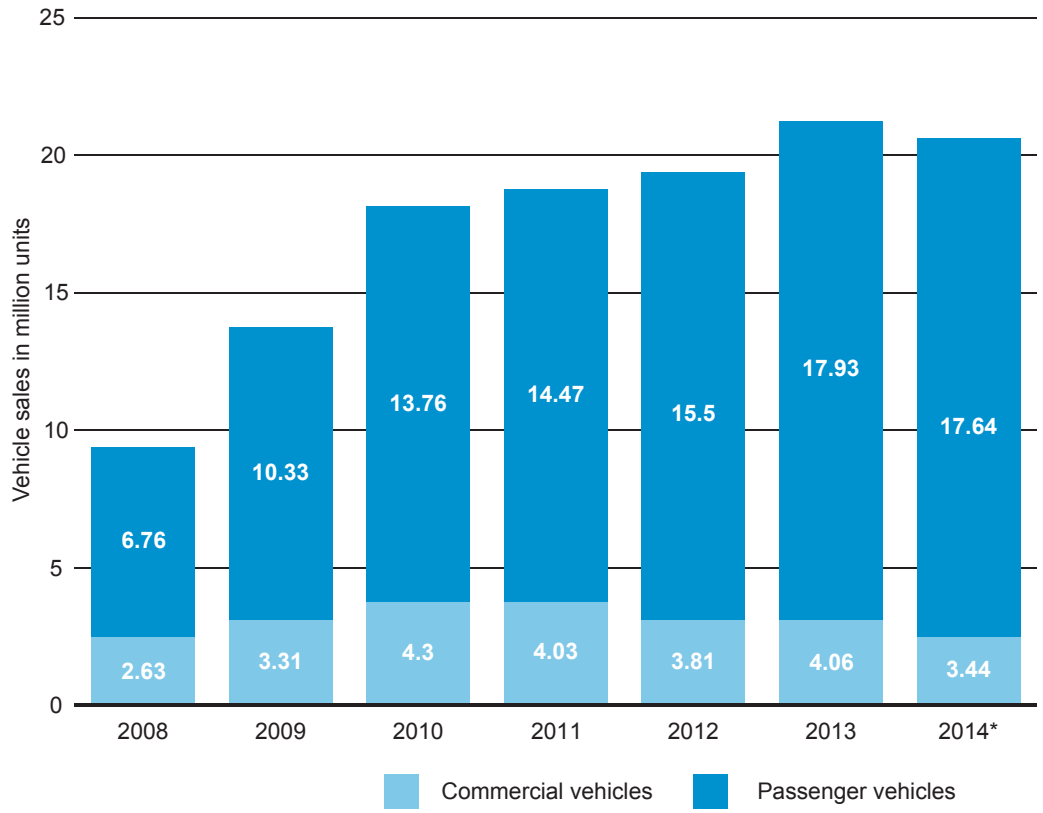


Figure 1: Vehicle sales in China 2008-2014. NB 2014 figures up to November only. Source: Statista[16]

The emergence of a middle class in developing countries is important because it can create a 'sweet spot' or virtuous growth cycle: rising incomes lead to increased discretionary spending, which in turn stimulates economic growth and raises incomes even further. The Indian economist and asset manager Surjit Bhalla estimates that for every 10% expansion in a country's middle class, its growth rate rises 0.5%.[18]

Many other large developing countries are on the brink of this transition, notably Indonesia and India (Table 3). A recent analysis by the Centre for Economic and Business Research forecast that India's economy would overtake Britain's in 2018 to become the largest in the Commonwealth, and concluded the country's rise "looks unstoppable".[19]

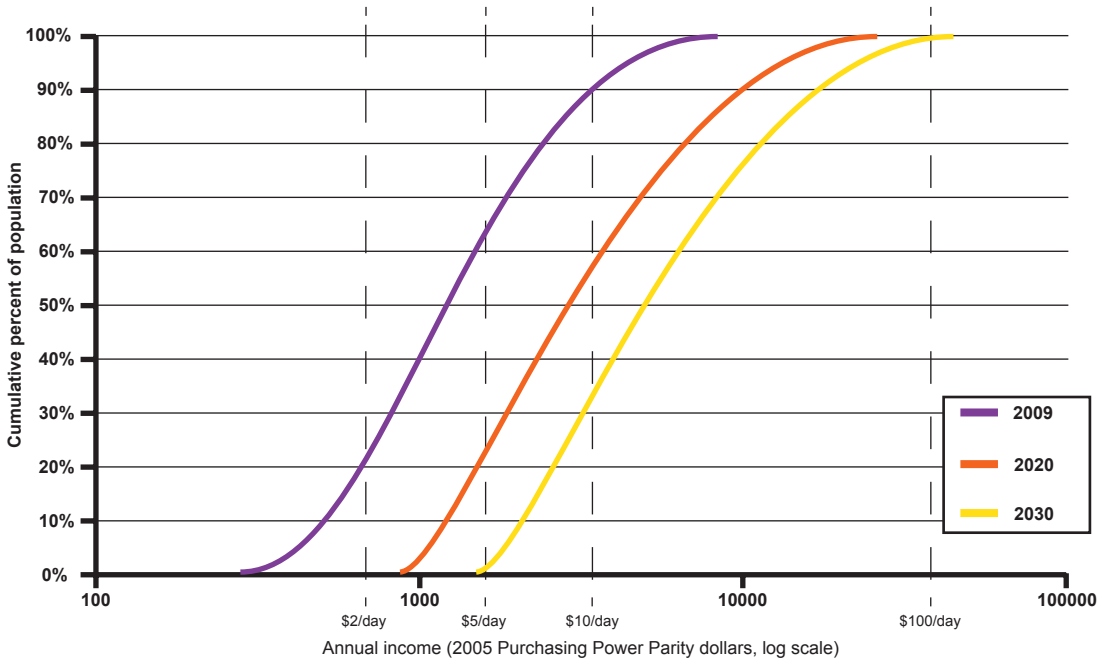


Figure 2: China's middle class is small, but quickly rises. Source: OECD [17]

Some Asian societies will not only be richer but younger, which brings its own demographic dividend. In India, for example, half the population is under 24, and therefore about to enter their most economically productive years.[21] Over the next three decades, the Indian labour force is expected to grow 0.5% faster each year than the population as a whole, reducing the dependency ratio and raising household incomes.[22]

Country	Year
Egypt	2011
Indonesia	2015
India	2017
Philippines	2019
Vietnam	2019
Pakistan	2024
Nigeria	2025
Bangladesh	2029

Table 3: When will emerging economies hit their projected 'sweet spots'? Source: EY [20]

Urbanisation is another powerful trend supporting growth. An estimated 16 million Indians migrate from the countryside to cities each year – equal to another New Delhi every twelve months – and this tends to raise labour force participation and productivity. India's labour force participation rate of around 60% lags China's by about 20%, suggesting substantial headroom for further growth. Goldman Sachs expects India's cities to swell by 500 million people over the next 25 years, and the UN forecasts the global urban population will rise from 3.9 billion in 2014 to 6.4 billion by 2050.[23]

The OECD analysis suggests these factors mean Asian middle class spending will reach about 60% of the world total within as little as fifteen years. China's middle class is expected to reach one billion by 2030, but youthful India should overtake ageing China as the engine of growth during the 2020s (Figure 3). India's middle class is expected to be well over one billion by 2040, when it will include 90% of the country's population – up from just 10% today.

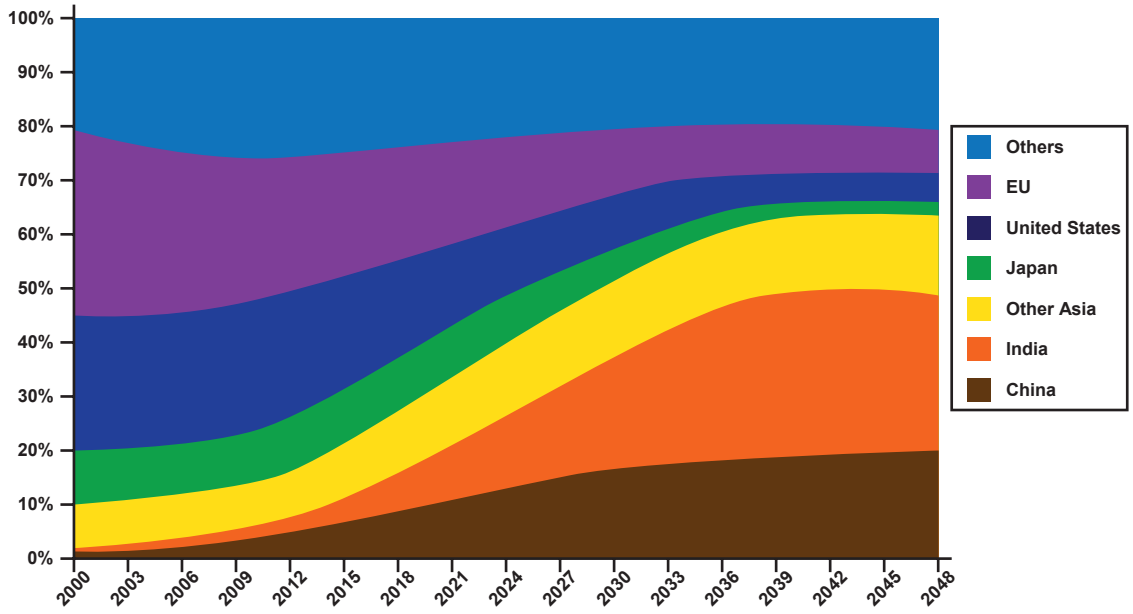


Figure 3: Regional shares of global middle class consumption, 2000-2050. Source: OECD [25]

India's Smart Cities

India's government has responded to mass urban migration with a plan to develop 100 'Smart Cities', either by upgrading existing cities or building entirely new satellite towns. Smart Cities are loosely defined as those where investment in infrastructure, transport, services and digital technologies combine to make them more sustainable and liveable. A government scoping document identifies the need for new logistics hubs, warehousing and freight terminals to support Smart Cities, and while cold chains and other forms of cooling are not mentioned specifically, they would clearly be essential for safe and efficient distribution of food and medicine.[24] The document also stresses the importance of clean air – India's cities are among the world's most polluted – implying a need for a zero-emission alternative to highly polluting diesel powered Transport Refrigeration Units (section 4). And since the government assumes an average population of 1 million per smart city, this alone implies a market for sustainable cold chains of some 100 million people.

Hunger

If the world is destined to get so much richer, it may seem odd to worry simultaneously about hunger. But although progress has been made in recent decades 200 million fewer people were chronically undernourished in 2012-14 than in 1990-92[26] – pressure on the food supply continues to grow: global demand is forecast to rise 60% by 2050.[27] In this context, technologies that reduce food wastage will become ever more vital.

The population is forecast to rise from around 7 billion today to between 9 and 10 billion in 2050, and the proportion living in urban areas to rise to 70%, from around 50% today. The booming middle classes are very likely to eat more meat and dairy, requiring far more grain to feed the livestock (intensive farming methods can require as much as 7kg of grain to produce 1kg of beef). So pressure on the food supply will intensify because there will be many more mouths to feed, and because many of those mouths will eat food that is more intensively produced.

The debate over hunger is polarised and the outcome hangs on many uncertainties: the ultimate size of the global population – one recent study found a 70% chance it would grow to 11 billion by 2100[28]; the energy content of the average diet – will it tend towards the US level (2,800 kilocalories per day) or the WHO recommended intake (2,200 kilocalories); average meat consumption; water shortage; the outlook for crop yield growth – which has fallen steadily over the last fifty years from 3.2% in 1960 to 1.5% in 2000[29]; and the impacts on food output of biofuel production and climate change. Since these are uncertainties it is always possible there could be a positive outcome, but given the range of pressures, it is not hard to imagine negative scenarios.

Rising price of food

Hunger often has less to do with the availability of food than its price. It was spiralling global prices that provoked food riots in many countries in 2008, and which prompted a report from Professor Sir John Beddington, the government's Chief Scientific Advisor, who warned of a 'perfect storm' of food, energy and water shortages emerging by 2030 unless agricultural efficiency and resource use could be improved.[30] Of course, rising prices might also stimulate innovation and increased agricultural production, but according to Professor Charles Godfray, Director of the Oxford Martin Programme on the Future of Food, "evidence shows [the market] will respond imperfectly and sometimes perversely, and with time delays that lead to hunger for many people and irreparable environmental damage in many parts of the world. The environmental 'externalities' of food production are not captured in the current market economy. Clearly, action is needed to reorient the food system in a more sustainable direction."[31]

Nor is hunger solved simply by producing enough food in total: that condition is satisfied today, yet still 1 in 6 goes hungry. Food security is regional, and according to an analysis by the Global Harvest Initiative, regional disparities are likely to widen: at current rates of productivity growth, by 2030 East Asia will be able to grow only 67% of the food it needs; India, 59%; and sub-Saharan Africa just 15%.[32] Yet India, which is currently self sufficient, loses 40% of its food after harvesting, much of it because cold chains are rudimentary or non-existent, and many other developing countries suffer similar levels of post-harvest loss.

Addressing post-harvest food loss

In this context reducing the vast scale of food wastage will be increasingly important. The FAO estimates that roughly 1.3 billion tonnes or one-third of food produced for human consumption is lost between farm and fork. Much of this is 'post-harvest' food loss that could be reduced in the developing world by building modern cold chains. The International Institute of Refrigeration has calculated that if developing countries had the same level of refrigerated transport and warehousing as found in the developed world, 200 million tonnes of perishable food would be saved each year, roughly equal to 14% of the current consumption in those countries.[33] Another study found that halving food wastage could feed an extra 1 billion people[34], which is comfortably higher than the 800 million who were chronically undernourished in 2012-14.

Investing in refrigeration in developing countries could also produce major economic gains: a study by Dr Lisa Kitinoja of the Postharvest Education Institute found that cooling of vegetables can produce benefits more than 7.5 times more valuable than the initial investment.[35] And yet another paper, published by Cornell University, found that investing in infrastructure such as electricity, roads and rail to enable the reduction of post-harvest food losses would reduce food prices, increase food availability and security, and have positive economic rates of return.[36]

Every scenario studied in the paper generated benefits substantially higher than its investment cost, and resulted in substantial reductions in the price of food, particularly perishables such as meat, dairy and vegetables, by 2050 (see Table 4 below). At the same time, the population at risk of hunger would fall by 8.5-13.1% for developing countries as a whole, by as much as 18.6% for sub-Saharan Africa in one scenario. The paper compares the benefits of post-harvest loss reduction with those gained by investment in agricultural research, and concludes the two approaches to food security are complimentary.

Reducing food wastage would also conserve huge quantities of farm inputs currently used to produce food that is never eaten: it's estimated that food wastage occupies a land area the size of Mexico; consumes 250km^3 of water per year, three times the volume of Lake Geneva; and accounts for 3.3 billion tonnes of carbon dioxide emissions, the third biggest emitter after the US and China.[38]

Commodity	PL1	PL2	PL3	PL4	AR1
Beef	-11.5	-15.1	-15.3	-19.6	-11.0
Lamb	-13.9	-16.6	-19.2	-22.5	-11.3
Pork	-9.3	-14.9	-12.2	-19.2	-10.9
Poultry	-11.8	-17.0	-14.9	-21.1	-13.0
Dairy	-6.9	-9.8	-9.3	-13.0	-7.0
Eggs	-13.8	-17.2	-18.2	-22.1	-12.8
Rice	-19.8	-21.6	-10.8	-12.1	-26.3
Wheat	-12.5	-16.6	-7.2	-8.9	-20.4
Maize	-0.0	-2.7	0.8	-0.8	-3.0
Groundnuts	-18.5	-21.0	-10.7	-12.2	-25.5
Rapeseed	-8.4	-15.4	-5.1	-8.3	-19.3
Soybeans	-11.4	-16.9	-5.9	-8.6	-21.0
Fruits and vegetables	-14.0	-16.9	-19.7	-23.2	-20.7
Pulses	-14.5	-17.4	-8.3	-9.9	-21.5
Roots and Tubers	-14.3	-16.2	-7.3	-8.6	-20.1
Processed Oils	-3.4	-4.1	-2.1	-2.9	-4.7
Oil meals	0.1	1.7	1.0	3.6	0.4

Table 4: Percentage change in world food prices in 2050 as a result of investment in infrastructure to reduce postharvest losses (PL scenarios) and investment in agricultural research (AR). Source: IFPRI [37]



Cold chains in the developing world: catch-up and leapfrog

Cold chain capacity in the major developing economies is inadequate by any measure. In China, 12 million tonnes of fruit and 130 million tonnes of vegetables are damaged each year at an estimated cost of $20 billion – which is perhaps unsurprising since only 5% is transported by cold chain[39], compared to 90% in the UK.[40] In India, where less than 4% of the 104 million tonnes of fresh produce transported each year goes by cold chain[41], the value lost to wastage is $13 billion.[42]

Investment is booming, however. China's cold chain is now reported to be growing at 25% per year and projected to be worth $75 billion by 2017.[43] The Indian cold chain is also forecast to grow at 25% per year to 2017[44], when annual revenues in the sector are expected to reach $13 billion.[45] The Indian government estimates the country needs to invest $15 billion in cold chain over the next five years.[46]

Yet cold chain investment in both countries is patchy and deeply unbalanced. In both China and India there has been huge investment in cold storage but much less in refrigerated transport, meaning that often the cold 'chain' is nothing of the sort.

Growth of cold chain in India

India for example has around 31 million tonnes of cold store capacity and perhaps 9,000 refrigerated trucks, whereas in France the balance is 5 million tonnes and 140,000 (India also has 27,000 milk tankers, but these are insulated and not refrigerated). The chief executive of India's National Centre for Cold-chain Development, Pawanexh Kohli, concludes that this causes a 'major breach of the cold chain' and that there is 'in effect no integration'.[47] Mr 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.[48] By extension, making proper use of all of India's cold storage capacity would require 600,000 refrigerated trucks.

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 139,000 refrigerated vehicles, 18 times more than at present.[49] And if it had the same ratio of refrigerated trucks to population as Britain, its fleet would number more than 1.5 million.[50]

The picture in China is similarly skewed. Demand for cold chain services has been building for longer in China than in India – fridge ownership among urban households, for example, rose from 7% in 1995 to 95% in 2007 – and yet the country still has much more cold storage than refrigerated vehicle capacity.

A report from consultants AT Kearney in 2007 concluded that Chinese cold store capacity would need to grow twenty fold to 5 billion cubic feet by 2017, and that its fleet of refrigerated trucks would need to grow more than ten-fold to 365,000. In 2015, the warehouse capacity is on track, but the refrigerated truck fleet is estimated to be just 66,000, less than a fifth of the projected number. In both China and India, and other developing countries, as the need for integrated cold chains becomes ever more pressing, investment in refrigerated vehicles will have to increase dramatically to catch up.

Future investment in transport refrigeration

There seems little doubt that investment in transport refrigeration will accelerate, not only because of the issues of demographics, food wastage and hunger discussed above, but because it is already starting to happen. 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.[51] Yum Brands (which owns Pizza Hut, KFC and Taco Bell) also intends to triple its outlets in India to 1,000 by 2015[52], which will need the same kind of support, and Burger King opened its first restaurant in 2014. These companies have brands to protect and cannot afford not to develop and maintain reliable cold chains. More broadly the Indian fast food (or 'quick service') market – estimated at $2.5 billion in 2013 – is expected to grow to $8 billion by 2020[53]; its grocery market to be worth $566 billion by 2015[54]; and its chilled pharmaceutical market is growing at 15% per year.[55]

There are also signs that developing economies may leapfrog to the latest business models emerging in the developed economies, such as home delivery and click and collect, which depend even more heavily on transport refrigeration. Sales of fresh produce on Taobao, a Chinese eBay-style platform, almost tripled in 2013; Amazon has invested $20 million in Yummy77, a Shanghai-based fresh food e-store; and Walmart has raised its stake in Yihadodian, an online grocery, which had sales of almost $2 billion in 2013.[56] Alibaba, which owns Taobao and several other e-commerce platforms, had estimated sales of 400 billion yuan ($64 billion) in 2010.[57] The company raised $25 billion on the US stock market in September 2014 to become the largest ever IPO.[58] Roland Berger Strategy Consultancy forecasts the Chinese cold chain logistics business will grow at 25% per year until 2017, when it will be worth 470 billion yuan or $75 billion.[59]

The environmental costs of business-as-usual cold chain development

Investment in cold chains is already booming in the megacities of developing countries, and this is vital to satisfy the changing diets of the emerging middle classes, reduce postharvest food losses, and mitigate the environmental impacts of agriculture. But conventional cold chain technologies impose huge environmental penalties of their own.

One particular culprit is the transport refrigeration unit (TRU) – the secondary diesel engine that powers refrigeration on trucks worldwide. Even in developed economies, TRUs are generally unregulated and highly polluting. According to a recent report from the Liquid Air Energy Network, trailer TRUs not only consume up to 20% of the truck's fuel, but also emit six times as much nitrogen dioxide (NOx) and 29 times as much particulate matter (PM) as a modern (Euro VI) propulsion engine. These are the pollutants that cause 29,000 premature deaths in Britain each year[60]; 400,000 in the EU[61]; and 600,000 in India.[62] Since the local air pollution caused by diesel TRUs is so disproportionate, any of the cold chain forecasts discussed in section 6 would impose heavy environmental and health costs.

The pollution and health impacts of any such expansion of the diesel TRU fleet would be significant, but so would the greenhouse gas (GHG) emissions. Diesel TRUs can emit up to 50 tonnes of CO_2 per vehicle per year from diesel consumption alone[63], and the total emissions will become increasingly significant as the size of the refrigerated fleet increases. At the same time the CO_2 savings that could be achieved by replacing each diesel TRU with sustainable cooling technologies will grow as the carbon intensity of grid electricity falls in many markets. Conventional TRUs also contain refrigerants known as F-gases that have extremely high Global Warming Potential (GWP), and which tend to leak. The most commonly used F-gas has a GWP almost 4,000 times higher than CO_2, so even the small volumes thought to escape from each TRU system could equate to several additional tonnes of CO_2 per vehicle per year.

Reducing greenhouse gas emissions from TRUs

Some reductions in the environmental impacts of transport refrigeration are possible using conventional technologies. For example, manufacturers such as Carrier offer systems that replace F-gases with CO_2 as the working fluid. This eliminates the impact of leaks of high-GWP refrigerants, but has several drawbacks. To work as a refrigerant, CO_2 requires more compression than F-gases, meaning the TRU engine consumes more fuel, and therefore emits even more CO_2, NOx and PM. The TRU in any case emits far more CO_2 – up to 50 tonnes per truck per year – from burning diesel than from leaking F-gas, which at an estimated annual leakage rate of 25%[64] is likely to equate to low single digit tonnes of CO_2 per year.

As for NOx and PM, TRUs' unregulated and disproportionate emissions could be reduced by upgrading the TRU diesel engine to a lower-emitting model, but these are larger, more expensive, and may also consume more fuel. In response to a European Commission proposal to tighten emissions standards on Non Road Mobile Machinery, organisations including Transfrigoroute International, the European cold-logistics trade association, pointed out that such cleaner engines do not fit within the tight space constraints of refrigerated trailers, which are regulated by EC directive.[65]

TRUs on vans and some rigid trucks are driven from the vehicle's propulsion engine, the emissions of which are regulated in the US and EU, and it might be possible to convert more TRUs to this notionally cleaner source of power. But this would mean more propulsion engines would be left idling to provide refrigeration when the vehicle is stationary while unloading etc; and engines operating at low power tend to produce disproportionate amounts of NOx and PM.

So while incremental improvements can be made using existing technologies, it is difficult to escape the conclusion that to address all the challenges of refrigerants, CO_2, and NOx and PM emissions, and make a decisive reduction in the environmental damage caused by transport refrigeration, diesel needs to be eliminated altogether.

Rapidly rising carbon emissions from transport refrigeration would be in addition to those from non-refrigerated freight, as trade expands and growing volumes of goods are transported longer distances. The International Transport Forum (ITF) of the OECD has forecast that global emissions from road freight will rise 300% by 2050 to more than 4.5 billion tonnes.[66] Emissions from all freight transport, including air and sea, will top 8 billion tonnes and exceed those of passenger traffic. The ITF has proposed a series of measures to mitigate freight emissions, but we suggest that the additional energy demands and air pollution of transport refrigeration require especially urgent attention.

Clean transport refrigeration and the Cold Economy

If the environmental cost of unbridled expansion of diesel-powered cold chains is becoming clearer, so too are some potential solutions. A range of zero tailpipe emission technologies are now being developed, although some appear more promising than others.

Battery-electric TRUs are already commercially available, as are eutectic plates that store cold in a salt solution (similar in principle to a beer cooler cold pack), both of which are quiet and, with fewer moving parts, lower maintenance. But these suffer a number of drawbacks including cost, weight and recharge times, and support only more limited duty cycles. Electric TRUs powered by hydrogen fuel cells are being piloted in California, but seem likely to face the same challenges as other hydrogen technologies, and the costs are unknown at this stage.

Refrigeration powered by evaporation of cryogenic liquids is also commercially available – around 2,000 units operate in Europe, from manufacturers including Frostcruise (Linde, UK), blueeze (Air Liquide, France), Frappa Trailers (France), and Cryotherm (Germany). Typically such systems evaporate liquid nitrogen (LIN) through a heat exchanger in the goods compartment, which removes the need for a TRU engine and compressor altogether – although power is still required for fans. Thermo King offers a system based on evaporation of CO_2, but this contains less cold per litre than LIN and so requires a bigger tank, or limits the kind of duty cycles that can be serviced.

Evaporation systems are quiet and low maintenance, but are not as efficient as they could be for two reasons. First, they run on liquid nitrogen rather than liquid air, which performs in the same way but requires 20% less energy to produce. Second, they exploit only the cooling produced by re-gasification, and not the simultaneous and massive expansion in gas volume, which can be used to drive a piston or turbine, meaning they waste around a third of the available energy.

These insights have led to the development of an innovative ‘cold and power’ approach, which is more efficient because it produces both cooling and power from the same unit of liquid air or nitrogen. First the cryogen is passed through a heat exchanger to cool the goods compartment, and then it expands through a piston engine to produce electricity to power the fans, or shaft power to drive a secondary conventional refrigeration cycle. This means it will use less fuel to produce the same amount of cooling and so reduce operating costs. The Dearman TRU is currently being tested on a vehicle at MIRA, and will go into commercial field trials in 2015 and larger-scale international trials in 2016. Further research and development is being undertaken with The University of Birmingham within the Centre for Cryogenic Energy Storage.

Mature liquid nitrogen infrastructure

Liquid air is not yet produced commercially, but liquid nitrogen, which can be used in the same way, is already widely produced for industrial purposes, such as blast freezing, fire suppression and superconducting technologies. Liquid nitrogen is widely available not only in developed economies, but also rapidly industrialising countries such as China and India. For technical reasons there is often excess nitrogen production capacity. India, for example, has about 3,500 tonnes per day of spare nitrogen production capacity, which could be used to provide cooling for zero-emission cold chains.

Liquid air and liquid nitrogen are both produced by electric-powered plants, so either could provide a solution to the intermittency of renewable generators such as wind and solar: absorbing and storing ‘wrong time’ or surplus renewable energy to use on demand in grid or transport applications. Both liquid air and nitrogen can also be produced with the help of waste cold from LNG re-gasification (see the Appendix for more detail), which reduces the electricity required, and the carbon intensity, by about two thirds, and the cost by almost half. LNG imports are growing strongly in both China and India, and we estimate the cold from projected Indian LNG imports in 2022 could in principle help produce enough liquid air to fuel half a million liquid air TRUs. Similarly, by 2030 the projected global trade of 500 million tonnes of LNG would give off enough waste cold to help produce 184 million tonnes of liquid air, enough to supply cooling for 4.2 million refrigerated delivery trucks, double the current global fleet.[67]

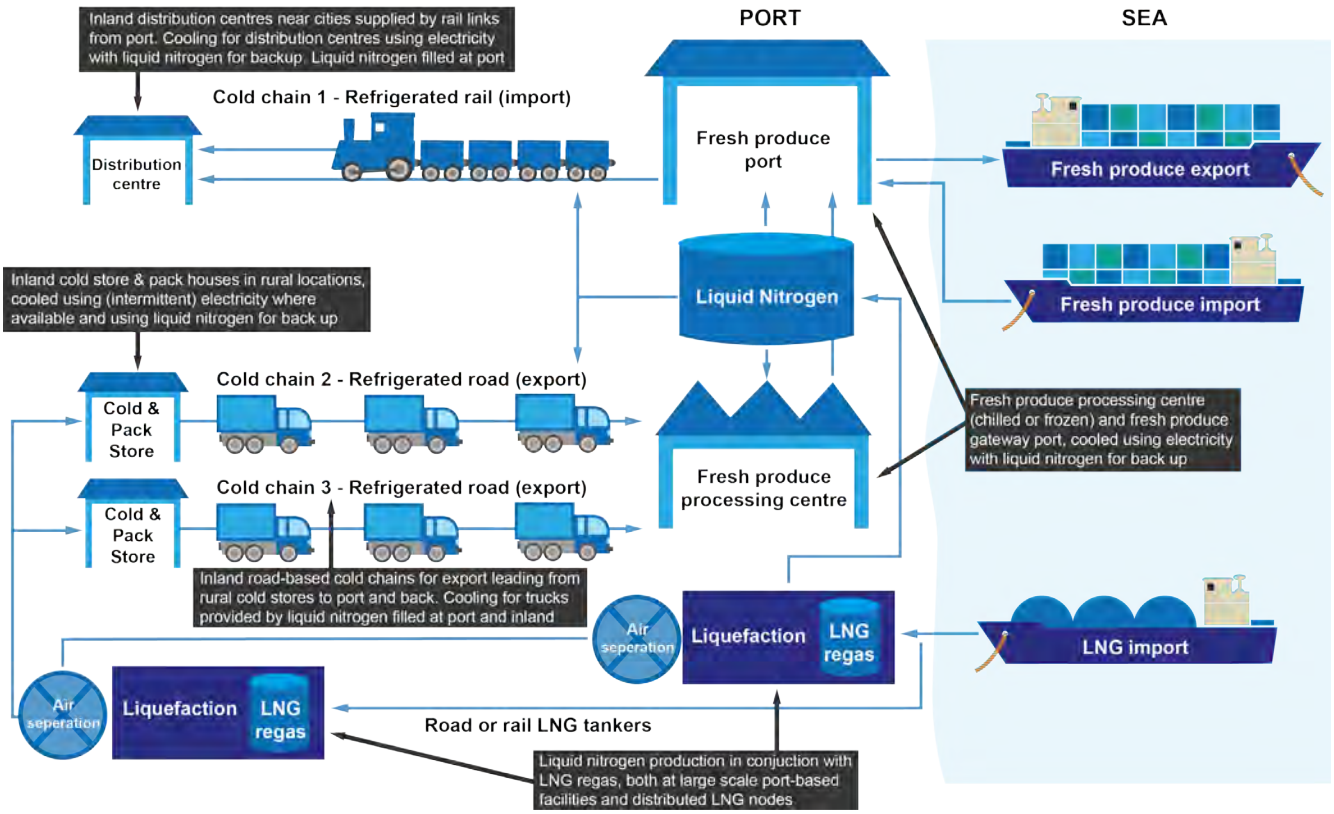


Figure 4. How waste cold from LNG re-gasification could power the 'Cold Economy' in India. Source: E4tech

Cold chains powered by LNG waste cold

The idea of developing cold chains powered by waste cold from LNG re-gasification is now being actively pursued in India, where Petronet LNG recently invited expressions of interest from companies to help it develop an integrated cold store facility at its LNG import terminal at Dahej, Gujarat. The concept has already been explored by India's National Centre for Cold-chain Development (NCCD), following a report from the IMechE and with the help of analysis from the British energy consultancy E4tech.

A study by E4tech for NCCD has shown how LNG import terminals could become the hubs of extensive import-export cold chains in developing countries (Figure 4 above), and even develop into a broader 'Cold Economy'. The report shows how a typical LNG terminal re-gasifying 7,100 tonnes of LNG per day could produce 2,600 tonnes of liquid nitrogen, enough to provide the cooling for almost 1,100 chilled and frozen refrigerated trucks operating around the clock; and peak time cooling (3 hours a day) for 7,500,000m^3 of chilled and frozen buildings, both at the port and at inland warehouses at the other end of the cold chain. For reference, the largest such facility in the world measures around 600,000m^3, and the UK has total cold store capacity of 25,000,000m^3. India has four LNG import terminals with an annual capacity of 25 million tonnes, expected to expand to 32 million tonnes, and a further 18 terminals have been proposed.

The refrigerated vehicles would be zero-emission, and would also reduce well-to-wheel carbon emissions by between 18% and 56% depending on duty cycle (chilled or frozen) and the carbon intensity of the electricity used, as shown in Table 5.

Application	Saving (2012 grid mix)	Saving (2030 grid mix)
Chilled	18%	27%
Frozen	51%	56%

Table 5: CO_2 savings of liquid air transport refrigeration with LNG assist vs diesel. Source: E4tech

Liquid air engines

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 net of capital costs, a near 75% saving 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.

The case for liquid air cold chains in developing countries is also supported by a report from Dr Lisa Kitinoja of the Postharvest Education Foundation, which found a particularly strong case for urban delivery using liquid air equipped refrigerated vans. As one example, Dr Kitinoja found that for a 1 tonne van liquid air refrigeration could be 20%-35% cheaper per kilogramme of cargo than diesel, and for a 0.5t vehicle 23%-33% cheaper (see Table 6 below).

	1 tonne capacity (small reefer van) Load market value $1,000		0.5 tonne capacity (very small reefer van) Load market value $5,000	
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

Table 6: Estimated comparative costs for refrigerated transport in India. Source: Dr Lisa Kitinoja. [63]



NCCD's clean cold vision for India

When the Government of India sanctioned the National Centre for Cold-chain Development (NCCD) as an autonomous think tank in 2012, we were expected to take a lead role in this vital sector, addressing industry concerns and providing guidance for policy-makers. A formidable task, and one I felt required a change in the way we think about cold chains.

India has an enviable cold warehousing footprint, having created almost 120 million cubic metres of cold storage space, almost 30% of this in the last decade. In contrast, we have developed only one tenth of this capacity in refrigerated transport and negligible amounts of back-end infrastructure at the farm gate. Mind you, this capacity is far from idle, and stays well occupied catering to domestic demand for potatoes, dairy products, meats and imported fruits. Yet the strategic need to use this technology as an enabler for our vast agricultural base is not fully met: clearly we need greatly to expand refrigerated transport if we are to bring seamless integration between farms and urban consumption centres.

The need to develop modern cold chains is, if anything, more important in India than elsewhere. Here growing affluence has revealed the Indian preference to spend more on fresh produce rather than processed foods. This is also evident from a more than tenfold growth in fruit and vegetable imports in the last decade. The fact is, India is the world's largest concentration of vegans, and our love for fresh food is culturally ingrained. The only technology that can deliver farm fresh food across our sub-continental distances is cold-chain.

At NCCD we first set out to raise awareness that cold-chain is about motion, that it buys time to cover distance, to reach consumers safely and well within a product's saleable life span. Cold-chain is not about how long one can store, but about reaching the market in good time. For this reason we have recently undertaken a study to assess the capacity gap, to understand which transport and other components are needed to integrate our existing cold-chain assets.

NCCD also guided policy interventions to incentivise a move in the direction of seamless connectivity in the cold-chain. For the well-established pharmaceutical and frozen segments, we promoted efficiencies and the adoption of improved technology. For capacity building and training – which personally I feel should be company specific – we have a series of ongoing workshops, some in collaboration with Cemafroid of France and various domestic centres. Lastly we developed a set of minimum system standards which are now being implemented across the country.

I believe that it is vital we also pursue technologies that minimise the impact on the environment and health. India's existing cold-chain has the lowest Ozone Depleting and Global Warming Potential, largely because almost our entire cold warehousing is ammonia based. This is somewhat offset by the partial dependence on diesel fuelled electricity generators. Nevertheless, we aim to keep our cold-chain 'green', and given the desired exponential growth in reefer transport and village level pack-houses, we are keen to adopt technologies that will keep our carbon footprint low.

A significant worry is that conventional diesel-powered transport refrigeration emits large amounts of NOx and PM that can only worsen our air quality. NCCD is ardently pursuing the potential of clean energy from liquid air based cold-chains, easily fuelled by spare industrial capacity or by recovering stranded cold from LNG re-gasification. This last point also raises the possibility of developing ports as perishable import-export gateways in India. Currently four import terminals handle 25 million tonnes of LNG per year, and additional capacity of 115 million tonnes is planned, presenting the opportunity to recover vast amounts of waste cold. At NCCD, we aim to pioneer excellence and innovation in all areas of modern agri-logistics, not just traditional cold-chain.

Civilization has reached a tipping point where our capacity to feed our numbers is a matter of serious and increasing concern. Science has helped increase food production but all food is organic matter and most of it perishes before it can reach people. The science of delivering what we produce needs more attention: it has become imperative that mankind fully grasps and controls clean cold energy, so that our species can continue to thrive and prosper.

Pawanexh Kohli
Chief Advisor & CEO, National Centre for Cold-chain Development

Bottom up and top down forecasting

If there is good reason to believe the numbers and spending power of the new middles classes will surge over the next two decades, the big question is whether these factors are fully reflected in industry forecasts of demand for cold chain – the channel through which much of the new middle class consumption will be delivered. Conventional 'bottom up' forecasts are typically produced by extrapolating current population and income growth trends, but such linear forecasts may not capture the sudden and structural shifts discussed above. Conventional forecasts do generally predict much higher annual growth rates for cold chains in developing countries than in developed – 22% for India in the five years to 2017, for instance, against 13% for the world as a whole[69] – but even these higher rates may not fully reflect the scale of investment required. The Asian middle class is projected to grow six-fold by 2030; levels of cold chain coverage and service in developing economies today are far below those found in the developed; and those are in any case a moving target – the European Commission forecasts European cooling demand will rise 72% by 2030.

Top down forecasting

To explore this possibility, the strategic energy consultancy E4tech has compared the bottom up forecasting approach with a top down method that may better reflect the impending changes. For the conventional forecast, E4tech analysed the increase in Chinese consumption of food types such as meat, milk, fruit and vegetables as incomes rose over the two decades to 2011, and applied this rate to other developing economies over the next ten years. On these assumptions, the required global refrigerated truck grows almost five-fold from around 2 million today to 9.6 million in 2025.[70]

To develop a top down forecast, E4tech assumed that consumers in developing countries will aspire to lifestyles that imply the same level of cold chain service as found in the UK, and then used the growth rates of two products that have already been widely taken up in developing countries to test the rates at which this might be achieved. The products – mobile data in the Asia Pacific region, and air conditioners in China – are simply examples of goods and services that became affordable as incomes rose, and are thought to be reasonable analogues for what could happen to demand for cold chain services.

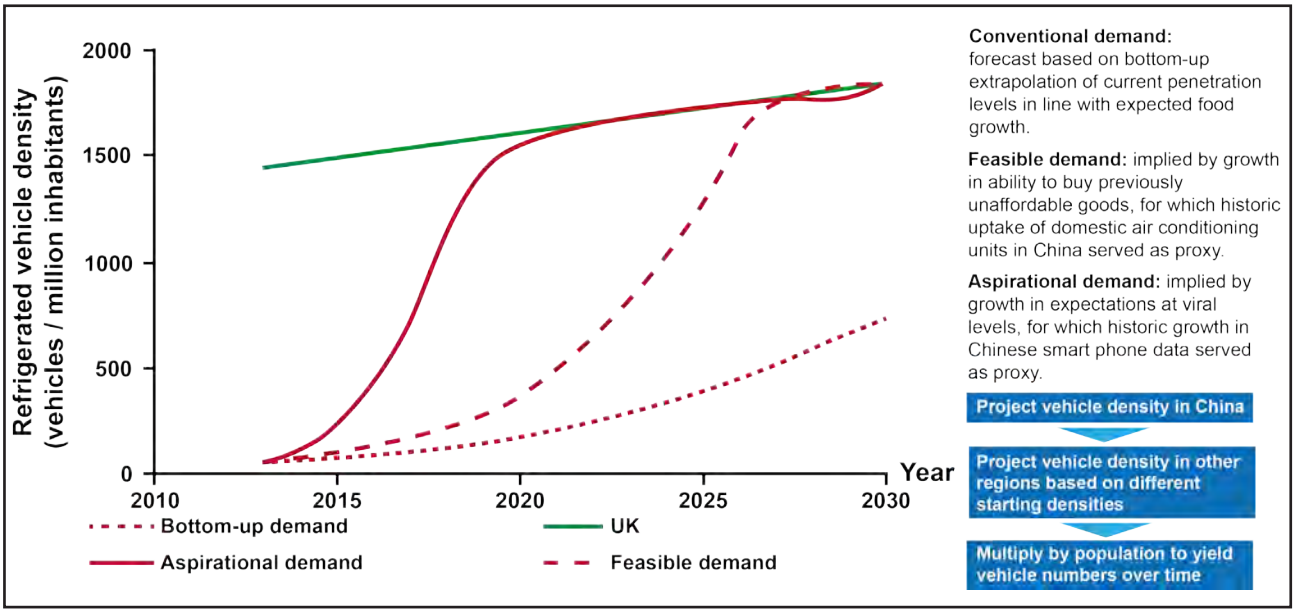
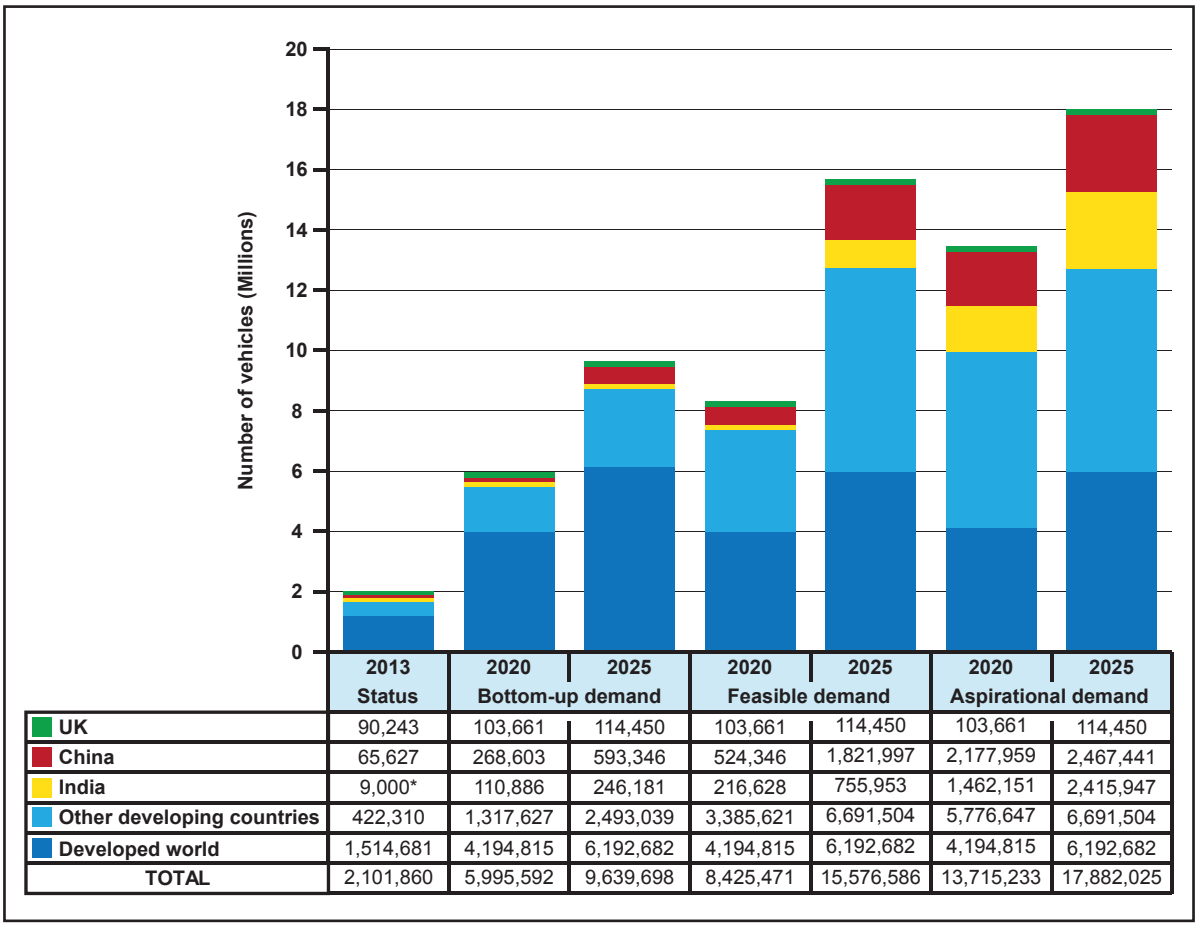


Figure 5: Potential growth rates of the Chinese refrigerated vehicle fleet to reach levels found in developed countries. Source: E4tech

In 1990, for example, less than 1% of China's urban households owned an air conditioner, but by 2003 the number had soared to 63%, and by 2010 there were about 110 air conditioning units per 100 households.[70] Mobile data usage has grown even faster, from negligible in 2011 to 1,000 petabytes per month in 2014.[72]

This data was used to develop two scenarios: 'aspirational demand', which assumes that cold chain capacity in developing countries reaches the same level per capita as in the UK; and 'feasible demand', which approximates what people in developing countries with rising incomes might be able to afford. This approach suggests that by 2025, aspirational demand in the developing world would require a global refrigerated truck fleet of 17.9 million, almost double the bottom up forecast, while feasible demand implies 15.6 million, more than 60% higher than the conventional approach. We stress that neither number is a forecast, but together they suggest the conventional forecast may be deeply conservative and that there is substantial headroom for further growth beyond it.

The impact on individual countries would be dramatic. In China, for example, which has around 66,000 refrigerated trucks today, the conventional approach produces a 9 fold increase to 593,000 by 2025, whereas E4tech's feasible demand suggests a 28 fold rise to more than 1.8 million. In India, with a current fleet of just 9,000, the bottom up forecast suggests 246,000 in ten years' time, while feasible demand projects almost 1.5 million. For the rest of the developing world, the numbers are: current, 422,000; conventional, 2.5 million; and feasible, 6.7 million.



	2013 Status	2020 Bottom-up demand	2025 Bottom-up demand	2020 Feasible demand	2025 Feasible demand	2020 Aspirational demand	2025 Aspirational demand
UK	90,243	103,661	114,450	103,661	114,450	103,661	114,450
China	65,627	268,603	593,346	524,346	1,821,997	2,177,959	2,467,441
India	9,000*	110,886	246,181	216,628	755,953	1,462,151	2,415,947
Other developing countries	422,310	1,317,627	2,493,039	3,385,621	6,691,504	5,776,647	6,691,504
Developed world	1,514,681	4,194,815	6,192,682	4,194,815	6,192,682	4,194,815	6,192,682
TOTAL	2,101,860	5,995,592	9,639,698	8,425,471	15,576,586	13,715,233	17,882,025

Figure 6: World refrigerated vehicle fleet by region at various growth rate assumptions. *NB In addition to 9,000 refrigerated trucks, India has 27,000 milk tankers, which are insulated but not refrigerated, and so excluded from this analysis. Source: E4tech

Conclusion

Cold chain investment in developing countries is a vital response to profound demographic change, and also to reduce food wastage, hunger and poverty. Investment is already beginning to boom, and seems likely to accelerate far beyond conventional forecasts, because of those same demographic changes. And because the new cold chains are based on highly polluting conventional technologies, the environmental and health impacts of a business-as-usual approach would be far greater than generally expected.

If this analysis is correct, the world faces a new and largely unexpected environmental threat. We suggest the first steps to solving it should include further investigation of:

- the likely scale of cold chain demand growth to 2050;
- the environmental impacts of that demand growth if satisfied using conventional technologies;
- the pros and cons of the available or potential zero-emission cooling technologies.

To start this analysis, the University of Birmingham has recently announced the creation of a new Policy Commission on cold, entitled ‘Doing Cold Smarter’. The Commission will explore how best to develop ‘clean cold’ through new technology and infrastructure in Britain and worldwide. The Commission is chaired by Lord Teverson and will take evidence from government and experts in industry, energy and the environment, and its final report will be published in October 2015.

The Cold Commission is part of a broader and growing recognition of the importance of cold. In Britain, the University of Birmingham has secured around $20 million of government and industry funding to develop a new Centre for Cryogenic Energy Storage, whose remit includes clean cold technologies: and in India, the government has set up the National Centre for Cold-chain Development to develop sustainable cold chains. As we report above, the NCCD is investigating the possibility of developing a zero-emission, low carbon cold chain based on waste cold from LNG re-gasification. We urge other countries and organisations to take a similarly innovative approach to this little recognised but increasingly urgent challenge.



Appendix

Utilising 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 120 billion cubic metres per 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 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 half. 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 trucks, or fuel 230,000 heat hybrid buses or 1 million zero-emission autorickshaws;
- the projected global LNG trade in 2030 could provide liquid air cooling for 4.2 million refrigerated delivery trucks - double 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 truck 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 a ‘fuel’ for the Cold Economy.



The Dearman engine



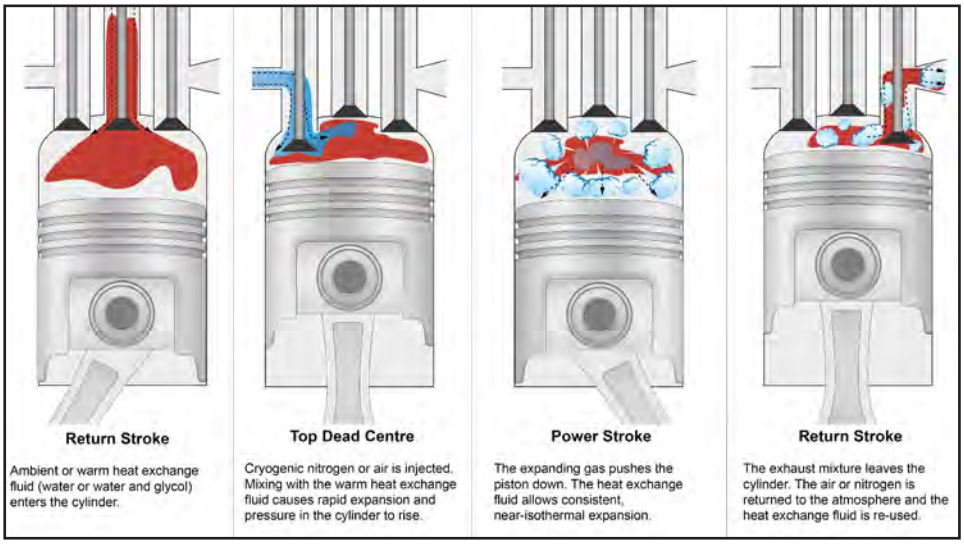
The Dearman engine is a novel piston engine powered by the phase-change expansion of liquid air or liquid nitrogen. In principle it works just like a steam engine only 300°C colder. It was invented by Peter Dearman, a classic British 'garden shed' inventor, and is being developed by the Dearman Engine Company (DEC) 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 is now in on-vehicle trials with MIRA, and will go into commercial field trials in 2015 and larger-scale international trials in 2016. 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 truck diesel consumption by 25%. A consortium including DEC, 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 while further developing and testing is being undertaken at the Birmingham Centre for Cryogenic Energy Storage.

In the 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.



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