A TANK OF COLD: CLEANTECH LEAPFROG TO A MORE FOOD SECURE WORLD.

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FINDING A SUSTAINABLE SOLUTION TO MEET THE ENERGY SECURITY NEEDS OF COLD CHAIN TECHNOLOGIES IS CRUCIAL TO DEVELOPMENT AND DELIVERING A MORE FOOD SECURE WORLD.

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This report has been produced in the context of the Institution's strategic themes of Energy, Environment, Education, Manufacturing and Transport and its vision of ‘Improving the world through engineering’.

Cover image: A truck transporting bananas to market in Ethiopia.

Published June 2014.
Design: teamkaroshi.com

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FOOD SECURITY – THE 21ST CENTURY CHALLENGE

As the world's population moves towards 9.5 billion later this century, meeting future demand for food while responding to stresses placed on the food system, such as changing dietary preferences, climate change, resource competition, land-use tensions and soil nutrient degradation, will present significant challenges to engineers, as well as the public at large. Indeed, the way we farm, harvest, store, transport, process, distribute and consume food will be a major determinant in the outcome for our well-being in the 21st century.

Developing countries will need improved agricultural productivity to feed larger populations, and better connections between farmers and different market options to drive economic development. This is particularly important in sub-Saharan Africa and Asia, where the greatest growth in population is projected. In addition to meeting the food needs of an increased number of people, these countries will see the largest changes in their population demographics through urbanisation and increased affluence. The global middle class is expected to increase by about 3 billion by 2030, with much of this growth anticipated in the developing economies. The latter will require new food systems to be established that create more rural-urban supply chains, and will need to produce new types of food to meet changing consumer expectations. All of this will need to be achieved in nations that are anticipated to be simultaneously experiencing the most severe impacts of climate change.

THE WASTAGE OPPORTUNITY

Work to increase yields from the full range of agricultural activity clearly has a role to play in meeting the 21st century's food security challenge. However, working towards ensuring sustainable food security, not just increased production, is critically important. Engineers are consistently called upon to deliver more water and energy to satisfy a wide range of demands, including for food systems, and to help resolve land-use tensions. A valid question for the profession to ask therefore, is how much yield improvement is truly necessary and what alternative approaches might be more sustainable?

Much of the food produced for human consumption today does not actually reach a human stomach, as it is either 'lost' within the food supply system through spoilage, largely as a result of poor handling and inadequate infrastructure, or is discarded in the marketplace or home as 'waste' as a result of societal and consumerist behaviour. In both cases this wastage, which is estimated to be 30–50% of global production, is largely unnecessary and also represents waste of the associated water, energy and land used to produce this food. Tackling food waste requires cultural and societal change, whereas preventing produce losses is in most cases about the application of relatively basic engineering and management practice. Reducing food wastage provides an opportunity to help meet future growth in food demand while simultaneously relieving pressure on natural resources and mitigating the risks associated with environmental degradation.

PREVENTING PERISHABLE FOOD LOSSES – CRITICAL TO DEVELOPMENT

In the developing economies of sub-Saharan Africa and Asia there are high levels of post-harvest food losses, and of particular concern is the loss of perishable produce, such as fruit, vegetables, fish, meat and dairy, which currently can reach as much as 50% annually. These countries will not only experience the largest population increases, but also the largest shifts in dietary preferences which, together with increasing demand for convenience foods, will increase perishable produce demand and drive greater resource consumption. When combined with the fact that they are located in warm areas and are anticipated to experience some of the most extreme impacts of global warming, it is critical to ensure that as much of the harvested produce as possible reaches its final marketplace.

Cold is the key to tackling the loss of perishable produce. In this regard, it is estimated that around a quarter of total food wastage in developing countries could be eliminated if these countries adopted the same level of refrigeration equipment as that in developed economies. Establishing a continuous chain of temperature-controlled cold environments from the point of harvest to the marketplace and on into the home – a ‘cold chain’ – is required.

The first step in a cold chain is pre-cooling, chilling and/or freezing produce as close to the point of harvest as possible, to retain nutrients and add shelf life. Subsequent steps of cold storage and refrigerated transport continue the preservation process, boosting food safety and maintaining quality. Many mature established technologies are available to achieve all of this. The challenge is that in nearly all cases they rely on access to a reliable and affordable source of either electricity or diesel fuel, which are often lacking or virtually non-existent in developing countries, particularly in rural areas where energy security is a significant issue. In sub-Saharan Africa, 70% of the population has no access to electricity, and 80% of those are located in rural areas. In India about 350 million people are in rural off-grid villages.

The IEA predicts that by 2035 energy demand globally will increase by 40%, and 90% of this growth will be from non-OECD countries. Finding a sustainable solution to meet the energy security needs of cold chain technologies is therefore crucial to aid international development and help deliver a more food-secure world. This not only will lead to a reduction in post-harvest losses, but also has the potential to avoid additional harmful emissions of air pollutants.

A SUSTAINABLE COLD CHAIN INFRASTRUCTURE

The Institution of Mechanical Engineers has identified a pressing need in developing countries to connect local farmers with higher-value market options locally, nationally and internationally through cold chains. The challenge for the engineering profession is to do that in a way which minimises food wastage, is sustainable and avoids harmful emissions and air pollutants. In other words, we need to help establish sustainable and resilient infrastructure, fit for purpose in the local context from the beginning. There are two elements that are important; firstly, projects need to be affordable; secondly they must be safe, reliable, easy to build, operate and maintain.

For many developing communities in sub-Saharan Africa and Asia, renewable energy resources are available in abundance and the key to unlocking sustainable cold chains is to develop technology that can either utilise these directly, such as cooling through solar-driven absorption, or to power existing or new technologies through electricity generation. In many cases the costs of installing small-scale renewable infrastructure are already about the same or lower than those involved for establishing connections to a large-scale centralised electricity grid. This economic reality, combined with the substantial engineering resource needed to create a grid, means that local off-grid or micro-grid-based solutions are an attractive option.

However, in many cases the utilisation of renewable energy for power generation requires energy storage technology in order to mitigate the intermittent and seasonal nature of some of these resources, such as sun and wind. This report proposes a range of energy storage solutions that meet the criteria for use in the context of a developing economy, and are either commercially available today, or in development and close to market. One contender in this regard is cryogenic energy storage.

Using cryogenic energy storage can not only facilitate reliable electricity supply, but through the provision of direct cooling it enables a holistic systems level approach to be established. It would also avoid the use of traditional refrigerants in chilling equipment, which have environmental and health issues. The cheapest form of cryogenic energy storage is based on the use of liquid air, which involves the liquefaction of atmospheric air. Once liquefied, in addition to providing on-demand power and cooling for pre-cooling, chilling, freezing and cold storage, liquid air can deliver the energy required to drive a simple cryogenic piston engine that can form the basis of a zero-emissions refrigeration unit for transport vehicles. This is a particularly useful application, as the traditional diesel-fuelled unit not only suffers from energy security issues, due to its reliance on diesel, but also leads to environmental degradation through emissions of air-polluting nitrogen oxides and particulate matter, as well as greenhouse gases.

This report shows how by locating a cryogenic energy storage facility at an agricultural 'hub' in a rural location, effectively establishing a local 'tank of cold', sustainable power and cooling can be provided to drive all three cold chain steps. Additionally, this tank of cold could help improve a broad range of local services essential to an agricultural community. These include community electricity through micro-grid application, small-scale fertiliser production, refrigeration for vaccine storage and distribution, and cooling for value-added food processing. It also shows how existing cryogenic infrastructure in more industrialised developing economies can be utilised to begin the process of building a sustainable cold chain.

WHAT NEEDS TO BE DONE?

There is much work to be done by engineers to provide affordable, safe, reliable, easy to operate and maintain, clean technologies for cold chains in developing economies. In particular the profession must focus on delivering appropriate energy storage technologies for use in off-grid and micro-grid applications, tackle issues of equipment and plant scaling to enable a range of smaller facilities to be deployed in distributed configurations, and offer alternative technologies for the delivery of both power and cooling in rural and urban settings. Beyond the engineering however, empowering communities to implement cold chain infrastructure through access to appropriate finance mechanisms is the most critical need.

Investments in cold chains are already taking place in more industrialised developing nations, such as India's planned five-year US$15 billion commitment, and some Chinese cities subsidising up to 40% of cold store building costs. But there needs to be a concerted effort by governments of developing economies to introduce policy initiatives that offer support to clean technologies and distributed solutions, which build on existing aspirations for electricity access and energy security, ensure that the regulatory frameworks can support such investments and deployments, and encourage inward investment with a focus on adopting technology that is sustainable. The African Union has declared 2014 the Year of Agriculture and Food Security, and publication of this report provides a clear vision of a route to help deliver on these actions.

RECOMMENDATIONS

Cold chains are an essential component in establishing an efficient food supply chain, but the current deployment model is unsustainable in the developing world where in many cases energy security is completely absent. The Institution of Mechanical Engineers therefore makes the following key recommendations:

1. **Governments of newly emerging and rapidly industrialising economies must prioritise support investment in cold chain infrastructure to improve food security, underpin development and help alleviate poverty.** Providing farmers with opportunities to access higher-value market options for their produce is widely recognised as a key route to moving individuals and communities out of subsistence and poverty towards higher-level economic activity and increased well-being. For perishable produce, cold chain infrastructure is essential to ensuring that as much product as possible reaches the marketplace. Beyond this, encouraging and incentivising developments that are based on sustainable solutions, including renewable energy and clean technologies, offer opportunities for affordable routes to energy security and reduced environmental risk.
2. **Donor country governments and development NGOs must support and incentivise aid recipients to develop sustainable cold chains using renewable energy and waste cold.** Increasingly overseas aid from donor governments and NGOs is being allocated to development projects that help individuals and communities become more self-sufficient and resilient. A sustainable cold chain solution based on renewable energy, clean technologies and waste cold recycling should be encouraged and incentivised.
3. **The UK engineering community should come together to define in detail the potential opportunities a joined-up cold economy presents for the developed and developing world.** The UK has a substantial heritage in the industrial gases and broader cryogenics sectors. As a leader in the field of the industrial application of cold, as well as in renewable energy utilisation, clean technologies and energy systems integration for efficient resource use, the nation is well placed to lead on work to tackle the technical challenge of equipment scaling and explore the environmental and societal benefits of establishing cold-chain economies.

A farmer working in a vegetable field in Odisha, India.

FOOD SECURITY – ABOUT MUCH MORE THAN JUST FOOD

The world's human population is currently increasing at almost 100 million people a year and United Nations projections for future growth suggest that total numbers will peak at about 9.5 billion in the second half of this century.[1,2] It is anticipated that much of this growth will occur in the newly emerging countries of sub-Saharan Africa and rapidly industrialising nations of Asia. Some African countries are expected to see population numbers doubling or tripling in the decades ahead – Tanzania for example will see its numbers swell from 49 million – 129 million, and the continent as a whole is projected to reach about 2 billion by mid-century with 40% living in rural locations.[3] In Asia, despite a slowdown in population growth rates, another 1 billion people are anticipated in the region by the 2050s (India alone is expected to grow from 1.2 billion to 1.6 billion), taking the overall figure to about 5.3 billion[1].

This overall increase in numbers, combined with a substantial shift in global demographics as these developing countries move towards more economically affluent lifestyles, is expected to drive growing demand for the natural resources that satisfy basic human needs and support modern industrialised societies. In this regard energy demand is anticipated to increase 40% by 2035, 90% of that growth being attributed to non-OECD countries[4], and agricultural production is projected by some to double by 2050[5], leading to substantial additional requirements for water; overall human demand for water could increase 30% by 2030[1]. The potential for additional environmental degradation and increased environmental risk, such as sea-level rise and climate change, if these growing demands are not met sustainably may be substantial. In our highly connected globalised economies any resulting impacts will not be constrained by borders and are likely to be felt worldwide.

Food sits at the centre of a web of substantial resource utilisation that includes water, energy and land, and sustainable food security potentially offers a key to unlocking a successful overall outcome for humans as global population reaches a peak in the late 21st century. The production and processing of food currently accounts for 70% of the water abstracted on the planet for human use[6] and agriculture occupies nearly 50% (4.9GHa) of the productive land available for growing biomass[7]. Add to this the energy used at all stages in the food chain from initial field preparation and planting, through irrigation, cultivation, harvesting and storage, to distribution and market placement and the major impact of food on resource consumption becomes clear. Fertiliser production alone annually accounts for 3–5% of global natural gas demand[7], while agriculture as a whole is responsible for about 8.5% of 'middle distillate' oil consumption which includes diesel fuel, heating oil and small generation fuel[8]. In rural communities of developing countries these fuels are often in short supply, expensive and subject to price fluctuations yet their use in the sector can be significant, as for example in India where agriculture accounts for 13% of total diesel consumption[9]. The resulting environmental footprint of the entire global food system is therefore substantial. As global population increases in the decades ahead, finding sustainable solutions for food security is absolutely critical to the outcome for natural resources, environmental risk and human well-being.

Food security is, however, not just about having enough nutritious food to avoid hunger; it is also about much wider issues of access, human development and stability. At the individual and community level it is a key enabler to finding a route out of poverty and a mechanism to increased well-being. No country has significantly reduced the poverty of its population without achieving a higher level of agricultural productivity and connecting farmers to market options, thereby shifting from subsistence to production agriculture. Empirical evidence suggests that a 1% gain in GDP originating from agriculture generates a 6% increase in overall expenditure of the poorest 10% of the population, whereas the same increase in GDP arising from non-agricultural sectors creates zero growth in the expenditure of the poor[10]. In the case of rural communities, increased incomes to the farmer lead to reinvestment in agriculture that result in further growth, therefore enabling a continuous cycle of development gains to begin.

In the broader national context, food security is related to helping ensure the well-being of citizens, underpinning stable states and participation on a wider, often global, stage in trade, commerce and political influence. At the international level, global food security is about reducing geopolitical tensions through access to affordable, nutritious and culturally acceptable domestic food sources and imports. Working towards ensuring sustainable food security not only brings these benefits to human society, but through the high dependency relationship of food with water, energy and land-use it can also enhance water and energy security and reduce land-use tensions as well as environmental degradation and risk.

Currently approximately 842 million people on the planet (about one in eight) goes to bed hungry every night;[11] ensuring everybody has access to affordable, safe and nutritious food is a role for the combined efforts of governments, the private sector and voluntary organisations. In sub-Saharan Africa, as many as one person in three faces hunger daily and recent UN figures suggest that in 2012 about 39% of children under five in the sub-continent were stunted, the figure for southern Asia was even higher at 47%[12]. Significant progress has been made towards meeting the first Millennium Development Goal (MDG) target to reduce by half the proportion of hungry people by 2015. In this regard several African countries have met the goal[13] through exemplary leadership, including among these Ghana, Djibouti and São Tomé and Príncipe. However, with only one year remaining to achieve the first MDG much work remains to be done. According to the UN Food and Agriculture Organization (FAO), 12% of the world's population was consistently under-fed between 2011 and 2013[12], while at the same time between one third and a half of the food produced globally on an annual basis is estimated not to reach a human stomach due to food wastage.[7,14]

In the mature developed economies of the world, such as those of the North America, the EU and Australasia, food wastage is largely due to waste taking place toward the retail and consumer end of the supply chain.[15] The latter is primarily related to unhelpful retail practices, such as confused date labelling, sales promotion cultures and crop rejections on aesthetic grounds; consumer behaviour; and hospitality industry over procurement and supply. On the other hand, in developing world countries wastage occurs closer to the producers[15] and is largely an issue of food losses through poor handling of produce in harvest and inadequately engineered infrastructure for the storage, transport, distribution and marketing of food. However, although food waste through retail practices and consumer behaviour is currently relatively low in the newly emerging economies of the world, there is a growing concern that increasing affluence in the more advanced developing nations, such as China and India for example, will lead to similar levels of waste to those already experienced in the mature developed economies.[15] In particular there is already evidence of this trend in the hospitality industry where a culture of 'abundance' often results in oversupply at functions and events including weddings, banquets, celebrations and conferences.[16,17]

Food wastage is not only a tragedy for the 842 million people who currently live with hunger, but because of the high-demand relationship between food and water, energy and land-use, it is also a missed opportunity, in terms of unnecessary environmental degradation, and a waste of natural resources that could otherwise be utilised in alternative human endeavours.[7,18] The World Resources Institute (WRI)[15] estimates that the land area used to produce wasted food worldwide is as big as Mexico, and that around a quarter of the water used in food production is squandered annually through food that does not reach a human stomach. Additionally, nearly a quarter (23%) of total worldwide fertiliser use, one of the primary consumers of energy for food production, is lost unnecessarily due to food wastage. In terms of greenhouse gas emissions, if global food wastage was a country then its total emissions would place it in third position behind China and the USA.[19] The scale of the direct economic cost in global terms is also not trivial, at approximately $750 billion per year it is equivalent to the 2011 GDP of Switzerland or Turkey.[20] At the individual farm level in the emerging economies of the world the loss of income from food wastage is a substantial brake on development that would help enable a shift towards a more food secure world.

THE COLD CHALLENGE

Losses of food produce from field to market in the developing world are particularly high in the case of perishables such as fruit, vegetables, fish, meat and dairy, and this is often exacerbated by temperature in the warm countries of the tropical and sub-tropical regions. In sub-Saharan Africa and India for example, losses can reach 50% annually for perishable fruit and vegetables alone.[7,21,22] Tanzania provides a case in point with up to 25% of milk production deteriorating to the point at which it becomes wastage in the food supply chain[21], and some 97% of meat sold in the country is warm, having never come into contact with refrigeration.[23] Indeed a lack of appropriate cooling within the field, store and transport vehicle, and at the point of sale, is a significant hurdle to effectively connecting farmers with market options and higher income streams in these countries.[24,25,26,27] Across Africa as a whole, the total value of lost food is US$4 billion per year,[28] and similarly in India the total is around US$4.5 billion annually.[21,22] This not only undermines both food security and food safety, as well as being an unnecessary use of scarce resources, but is likely to become of increasing concern as projected climate change impacts put greater stress on agricultural yields in these regions.[29]

Cold is the Achilles heel of the world's developing economies. In many rural areas, poor access to an appropriate technology and energy source for cooling food products from the point of harvest all the way through to the marketplace (a cold chain), leads to losses in the supply chain, holds back development and worsens poverty and hunger. Establishing cold chains is essential in these cases to help farmers, particularly those in newly emerging economies, cut produce losses, increase incomes and connect with distant, often higher value, markets both national and international. In Africa about 50% of the continents total food production is consumed by the 40% of the population who reside in cities.[13] As this proportion grows in the future through increased urbanisation, the robustness of the rural-urban food chain will become central to African food security. Indeed the UN FAO has recently called for this relationship to be recognised as at least as much of an opportunity to the continent's farmers as export markets[13] and many of these emerging chains will rely on cold for the preservation of perishable product quality en-route to its destination.

On the other hand, in the megacities of the more industrialised developing nations, such as Beijing, cold chains are booming in response to rising incomes, urban expansion and shifting dietary preferences from grain based to animal based products.[30] Since products of the latter type, such as meat and dairy, consume much higher levels of water, energy and land in their production than the former,[7] this shift has significant environmental and resource utilisation implications that make a reduction of food wastage through cold chain provision critically important.

In a stark measure of unmet demand, estimates based on figures from the International Institute of Refrigeration (IIR)[31] suggest that around one quarter of food wastage in the developing countries could be eliminated if these countries had the same level of refrigeration equipment as found in developed economies. In India for example, Agriculture and Food Processing Minister, Sharad Pawar, recently told parliament that 40% of produce is lost on the sub-continent each year, and that only by setting up more large cold stores could matters improve.[26] In response to this challenge India's investment in cold chain is forecast to total $15 billion over the next five years.[32] Similarly, China's city administrations are investing in cold storage through offering subsidies to cover up to 40% of the building costs[33] and the country's fleet of refrigerated trucks is expected to grow 12-fold to 365,000 over the next decade.[34]

What is a cold chain?

The term 'cold chain' refers to the continuous process of producing, packaging and distributing a temperature-sensitive product. The cold supply chain can be separated into three stages, as illustrated in **Figure 1**: pre-cooling/chilling/freezing; cold storage; and refrigerated transport. Pre-cooling, chilling or freezing produce at source retains more original nutrients and can add several days to the life of a product, thereby substantially reducing subsequent food losses, boosting food safety, improving product quality and increasing incomes for producers.[35] Beyond this first stage, product is placed in a cold store until it is transported onwards in refrigerated containers to markets where it is displayed for sale in chillers or temperature controlled shelving, or home delivery into domestic fridges. Maintaining end-to-end integrity of the cold chain is vital, and in most cases that means that pre-cooling/chilling/freezing techniques, cold stores and refrigerated transport networks depend on reliable energy sources.[35] The contemporary cold chain is largely fuelled by diesel and electricity, the majority of the latter being produced by fossil fuel based power generation infrastructure. Expansion in rapidly developing countries therefore has the potential to significantly increase urban air and noise pollution, strain electricity supply grids and contribute further to energy security tensions and global warming.

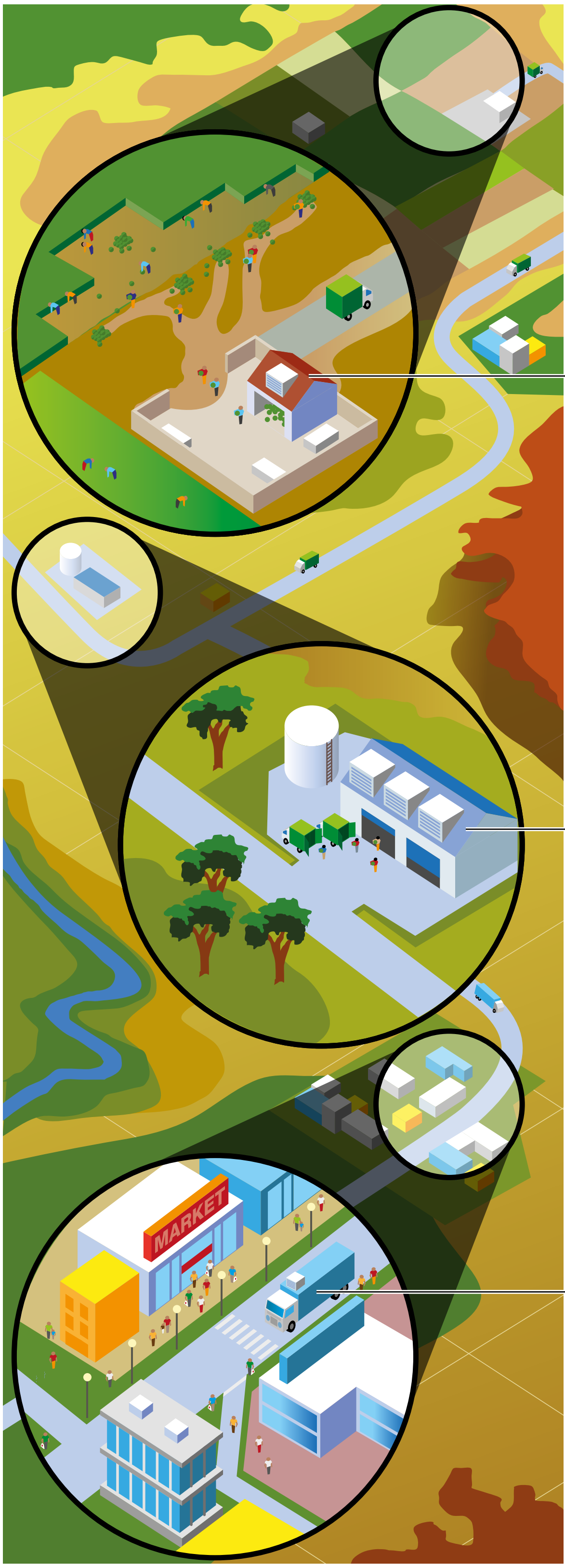

Figure 1: The three steps involved in a continuous cold chain for perishable food produce from field to market or home delivery.

Step 1: Pre-cooling/chilling/freezing as close to point/time of harvest as possible.

Step 2: Cold storage.

Step 3: Refrigerated transport to market or home delivery.

If nothing is done to change the direction of these future investments, they will default to the business-as-usual model of the developed economies, where cold chains are based largely on fossil fuel-based infrastructure. For post-harvest cooling or freezing and cold storage in industrialised countries, electricity is used to drive refrigeration (about 15% of electricity in the developed world is consumed by refrigeration and air conditioning)[36] and the bulk of this power comes from grids where a combination of coal and natural gas generation typically makes up the majority of the supply. In the absence of a reliable grid connection the default alternative is to use diesel-fuelled generator sets (gen-sets) to provide the electricity.[3,35] Similarly, highly polluting diesel powered vehicle refrigeration is largely used for product transport by road, rail or sea. In a refrigerated truck, for example, up to 20% of the diesel fuel is consumed by refrigeration[37] contributing to annual global greenhouse gas (GHG) emissions, as well as high levels of particulate matter (PM) and nitrogen oxides (NOx) leading to air pollution, environmental degradation and negative human health impacts. An analysis of regulatory standards by the consultancy E4tech shows that in Europe the separate Transport Refrigeration Unit (TRU) used by a large truck or refrigerated lorry trailer (reefer) emits six times as much NOx and 29 times as much PM as a Euro 6 lorry main engine[37] (TRUs are less strictly regulated and far more polluting than main propulsion engines for the transport vehicle itself). Compared with a Euro 6 diesel passenger car, the TRU emits almost 93 times as much NOx, and 165 times as much PM,[37] and in European cities, food deliveries by vehicles fitted with these units contributes to poor air quality that, for example, makes London the continent's NO_2 capital.[38]

The rapidly industrialising countries of the world that are reaching an advanced stage of development, such as China, are already familiar with the detrimental effects of local air pollution, not only in terms of human health and well-being impacts, but also the economic costs. Appalling smogs afflict many major Chinese cities, particularly in Hebei province where a large number of coal-fired power plants and heavy industries using fossil fuel are located.[39] Poor air quality is estimated to have caused about 1.2 million premature deaths across the country in 2010,[40] as well as shortened average life expectancy of the population by five years.[41] In economic terms this translated into a cost to the nation of $180 billion in that year.[42]

Although coal-fired power stations and industrial activity are largely responsible for the current problem, as the country's population becomes more affluent and demand increases for developed world style convenience food products[30,43] it is anticipated that high-emission vehicles associated with cold chains will increasingly contribute. By 2022 it is anticipated that middle-class China will be consuming US$3.4 trillion in goods and services[43] and this will fuel demand for convenience stores, take-aways, chilled and frozen foods, fridges and home deliveries. China's frozen food market grew 9.9% annually from 2004–2009, as a result of growing incomes and increased numbers of Chinese households owning freezers, and is expected to grow by over 30% in the next five years.[33] Similiarly, Starbucks will have 1,500 outlets in China by 2015, double what it had in 2013,[44] and international fast-food outlets such as KFC and Pizza Hut, with 3,200 and 500 restaurants respectively in 2013 across 650 Chinese cities, are established and growing in number.[43]

The E4tech comparison of EU regulatory standards suggests the refrigeration unit of a rigid refrigerated truck emits more than twice as much NOx and ten times more PM than a modern Euro 6 diesel lorry engine (the ratios for a reefer TRU are even worse, as already noted above). On this basis, if China's projected fleet within a decade of 365,000 refrigerated trucks took the business-as-usual approach, the TRUs alone would emit at least 18,000 tonnes of NOx per year. That's the NOx equivalent of putting 800,000 additional Euro 6 lorries on the road, or 40% more such vehicles than the entire UK HCV fleet in 2012. The TRUs of the Chinese refrigerated fleet would also emit more than 1,800 tonnes of PM, the PM equivalent to adding another 3.6 million Euro 6 lorries, or six times the UK HCV fleet.

Bumper to bumper traffic in the streets of Delhi, India.

The Institution of Mechanical Engineers recognises that there is an urgent need to develop cold chains in the developing countries of the world to enable farmers to connect with market options for fruit, vegetable, diary, fish and meat products; reduce perishable food losses; and increase farm incomes. Not only will this improve development outcomes and food security at the individual, community, national and international level, but through the food, water, energy and land-use nexus it will reduce unnecessary resource depletion, environmental degradation and environmental risk from food wastage. However, it is vital for both the energy security of developing communities, and local as well as global environmental degradation, that these cold chains do not follow the path taken by the developed economies, where electricity generated from fossil fuels powers chillers and cold stores, and diesel-powered refrigeration units dominate for produce transportation. These existing infrastructures in the mature economies of the world must themselves be transitioned to a cleaner more sustainable approach to cold chains, through upgrade and replacement programmes that respond to requirements for reductions in greenhouse gas emissions, tighter pollutant controls and increasing competition for fossil fuel resources.

What is required is a new model for an affordable, sustainable, clean technology (cleantech) based cold chain. In the case of newly emerging countries, the engineering task is to provide safe, reliable, simple to operate and easy to maintain mechanical based solutions that enable these nations to leapfrog over the dirty unsustainable development phase experienced by the mature economies; a 'cleantech leapfrog'. Whereas in the more industrialised countries the need is to satisfy the growing aspirations of the new middle classes in a more sustainable way. In mature economies existing infrastructure needs to transition to a sustainable replacement. This report presents innovative, practical and economically viable engineering solutions to meet these needs and thereby satisfy the demands of the world's growing populations through a smarter, more sustainable path than that followed historically in the developed world.

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THE CHALLENGE IS NOT JUST HOW TO MEET THE GROWTH IN REFRIGERATED TRANSPORT AND MANAGE EMISSIONS, BUT ALSO HOW TO DELIVER FOOD PRODUCE INTO GRID-LOCKED CITY CENTRES.

Truckload of produce ready for shipping in a refrigerated compartment, Beijing, China.

COLD CHAIN TECHNOLOGIES

The technologies that are available to establish a typical cold chain for handling perishable food products from field to market are presented in summary in **Table 1**, along with their principal applications. These can be considered in each of the three general steps that normally form the chain. Firstly, steps 1 and 2:

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IT IS ESTIMATED THAT AROUND A QUARTER OF TOTAL FOOD WASTAGE IN DEVELOPING COUNTRIES COULD BE ELIMINATED IF THESE COUNTRIES ADOPTED THE SAME LEVEL OF REFRIGERATION EQUIPMENT AS THAT IN DEVELOPED ECONOMIES.

STEP 1: PRE-COOLING/ CHILLING/FREEZING AT SOURCE

Pre-cooling/chilling/freezing involves reducing the temperature of a product at source, or as near to it as possible, because the earlier ‘field heat’ can be removed, the greater the benefit.[35] This is important for highly perishable fresh produce harvested on a warm day in the temperate mid-latitudes, and crucial in sub-tropical and tropical regions where every hour’s delay between picking and cooling can reduce shelf life by as much as one day. Since refrigerated vehicles can only maintain cool/cold temperatures once established, cooling cannot typically occur during the transit process so must be achieved in the field at harvesting. **Table 1** shows a range of technologies available to achieve this step, including evaporative forced air pre-cooling, the use of ice, hydro-cooling, forced air pre-cooling, individually quick frozen (IQF) and blast freezing, all of which need a power source, as well as the passive techniques of simple use of shade and evaporative natural cooling.

STEP 2:
COLD STORAGE

Cold storage allows food to be stored and sold days, weeks or even seasons after it was harvested, which enables several benefits to be realised by farmers, growers and customers. These include allowing farmers and growers to receive a higher average price for their produce, and to borrow against that increased value, and for customers it provides some protection against price spikes out of season.[45]

Cold chain storage technologies presented in **Table 1** include a mix of passive approaches, such as high altitude cold storage, night air ventilated storage and underground cold storage, together with those active techniques needing a power source: evaporatively cooled cold storage, small-scale and large-scale refrigerated cold storage.

Table 1: Summary of current widely used cold chain technologies and typical applications for pre-cooling/chilling/freezing, cold storage and transport of fresh foods and agricultural food products (Thanks to Dr Lisa Kitinoja, Founder, The Postharvest Education Foundation)

Cold chain technology	Food products	Climate and technological issues	Supporting infrastructure needed
Step 1			
Use of shade	All	Shade will provide cooling in any climate, but works best at lower relative humidity (RH)	Shade cloth, sturdy poles or structures that can handle wind
Evaporative natural cooling	All	Requires relatively low RH	Small building enclosed by porous material (eg earthenware or woven palm fronds) and water
Evaporative forced air pre-cooling	Tropical and sub-tropical fruit and vegetables	Requires relatively low RH. Stacking patterns affect rate of cooling	Needs a building and power source to circulate air (electric powered fan)
Use of ice	Fish, leafy green vegetables (green onions, broccoli)	A roughly equal solution of water and ice is pumped through holed boxes to ice wax and cool produce. Requires waterproof packages and can be used only for water tolerant food products	Source of clean ice (can be inefficient and expensive), power for pumps
Hydro-cooling	Leafy vegetables, some temperate fruits	Well water is sometimes naturally cool enough to provide a source of cold – up to five times quicker than mechanical (vapour compression) refrigeration, but more energy-intensive and has the potential to contaminate food product. Can be used only for water-tolerant food products	Source of clean water (deep well or stream) with appropriate hygiene controls. Ice or refrigeration to cool water down to 0–2°C. Power for pumps and ice
Forced air pre-cooling	Most horticultural crops	Cooling is sped up via fans. Stacking patterns and package venting patterns effect rate of cooling. Delicate produce may experience dehydration if fan speeds are too high	Needs power source to circulate air (electric powered fan) and a cold room
Individually Quick Frozen (IQF)	Fruits, vegetables in small pieces	Need to match product with freezing rate, temperature, use appropriate pre-treatments. Need appropriate packaging (can be expensive). Can utilize a direct liquid nitrogen spray as source of freezing	Source of reliable power. Requires expensive conveyor style freezing equipment
Blast freezing	All	Forced air racked pallet systems can reduce energy costs	Source of reliable power

Cold chain technology	Food products	Climate and technological issues	Supporting infrastructure needed
Step 2			
High altitude cold storage	All	Typically air temperatures decrease by 10°C for every one km increase in altitude	Roads from farms to storage sites
Night air ventilated storage	All	Effectively maintains product temperature when the outside air temperature is below the desired product temperature for 5–7 hours per night	Insulated storage structure
Underground cold storage	All	The average temperature will be similar to average surface water temperatures in local rivers or streams, or the average annual air temperature in the region	Cave or root cellar
Evaporatively cooled cold storage	Most horticultural, some dairy and fermented foods	Requires relatively low RH (best in dry regions where dew point temperature is low)	Needs water source (such as deep well), good air flow and power for fans and pumps
Small-scale refrigerated cold storage – commercial system (walk-in room)	All	Stacking patterns affect cooling effectiveness and costs	Source of reliable power
Small-scale refrigerated cold storage – CoolBot™ system (walk-in room)	All	CoolBot™ automated controller can be used with a traditional window-style air conditioning unit, reduced capital cost for cold room by 90% compared to a commercial refrigeration system. Stacking patterns affect cooling effectiveness and costs	Source of reliable power
Large-scale refrigerated cold storage warehouse	All	Stacking patterns affect cooling effectiveness and costs	Source of reliable power, back-up generators
Step 3			
Quilts and insulated blankets	All	Requires pre-cooling before packed products are covered	Source of power for pre-cooling. Return system in order to reuse expensive insulated containers
Refrigerated truck or trailer ('reefer')	All	Stacking patterns affect cooling effectiveness and costs. Traditional trucks and reefers do not have the refrigeration capacity to provide cooling (they can only maintain cold temperatures); liquid nitrogen evaporation systems have been developed to provide direct cooling of the insulated trailer compartment	Source of reefers for purchase or lease. Power to drive refrigeration units
Refrigerated marine container	All	Stacking patterns and package venting affect cooling effectiveness and costs. Typically powered via "plug-in" to electricity while at port and on ships	Source of marine containers for lease. Power to drive refrigeration units
Refrigerated rail cars	All	Stacking patterns affect cooling effectiveness and costs. Early designs used large ice banks as a source of cold	Availability of refrigerated rail cars, scheduling, routes. Power to drive refrigeration units

Apart from the passive techniques, which though often useful are limited in their application, the technologies for both steps 1 and 2 require a source of power to drive them. With about 1.3 billion people in the world (about 18% of global population) having no access to modern sources of energy[46], and most of them being located in Africa, South America or Asia, in many developing countries obtaining electricity for any use let alone supporting a cold chain is a challenge. In the countries of sub-Saharan Africa, where only 20% of the population are on the grid and 70% have no access at all to electricity, 80% of whom are in rural areas[47], the problem is exacerbated by the fact that where power grid access exists it is often unreliable[3,48]. In 2011, total installed generation capacity in sub-Saharan Africa was about the same as that of Spain, 68GW[48]. Similarly, in Asia, problems of access to modern energy are compounded by inequality of access; for example at 400 million (30% of population) India has the largest number of people without access to electricity in a single country, and 350 million of those are in rural off-grid villages.[46]

Using solar heat to cool and refrigerate

Refrigeration systems based on absorption processes are not new, but their use has been limited largely because of the success of the competing electricity powered Rankine cycle approach which has significantly greater energy efficiency. However, in the absence of a source of electricity the thermal energy of the sun can be harnessed to drive an absorption process and thereby cool a contained space. In the simple Solar-Polar application, an evacuated tube solar collector containing a heat pipe transfers thermal energy from the sun to an insulated container in which a solution is boiled to obtain ammonia. The resulting hot gas is then fed through a passive air heat exchanger to condense out pure ammonia liquid for use in the hydrogen atmosphere of an evaporator. The latent heat of evaporation is obtained from the space to be cooled through natural convective circulation of the contained air, thereby resulting in produce refrigeration. The ammonia gas that exits the evaporator is subsequently recombined with the solution in the boiling pot for reuse, hence the operation continuously cycles in a closed system without the necessity for intervention. The use of appropriate volumes of a phase-change material for energy storage in the cooled space itself mitigates against the loss of the solar source during the night.

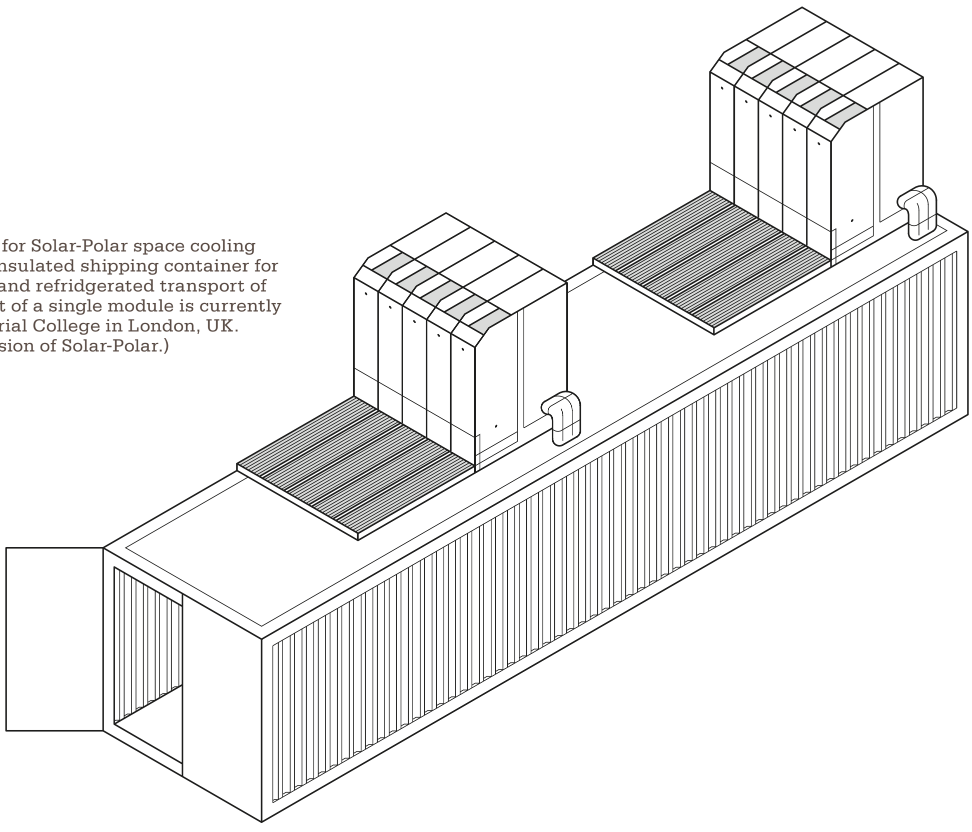
In the absence of a reliable connection to a centralised electricity transmission and distribution grid, citizens in the developing world resort to burning kerosene for light and biomass for cooking[3,49], while most farmers and growers turn to diesel gen-sets to power their electrical equipment[50,51] including that for cooling, chilling, freezing and cold store refrigeration[35]. The use of diesel makes these operations and facilities vulnerable to fuel shortages, which are common in many rural communities of developing economies, expensive to run and polluting.[35] However these energy security, affordability and environmental drawbacks could be avoided by using renewable energy either to directly drive new cold chain technologies for steps 1 and 2, such as those currently under research and development (R&D)[52,53,54] or to generate electricity to power those already available or novel solutions.

Various renewable sources, particularly solar and wind, are available in abundance in developing world countries. One new cold chain technology currently in advanced R&D that aims to capture solar for steps 1 and 2 as well as step 3, refrigerated transport, is Solar-Polar.[54] The basic concept is to use solar thermal energy to drive cooling directly through an ammonia absorption process without the need for electricity. This approach has the advantages of requiring only very basic common materials, being relatively low cost to manufacture, and operating automatically for long periods of time without the need for maintenance. The process is however low in energy efficiency, but has very low cost per watt of cooling produced, and in the context of a community with no access to electricity and unreliable diesel supply, and no other means of achieving pre-cooling, chilling and cold storage for perishable food product, this might not be the most important criterion. Practical implementation of the cooling will be in prefabricated modular form and individual units or groups of units will be mounted on the roof or walls of a cold store building exposed to the sun to provide the necessary capacity. In addition, the developers of Solar-Polar are working on an insulated shipping container-based system, **Figure 2**, which would enable pre-cooling and utilise removable modules to facilitate onward refrigerated transport (step 3) of produce to market.

Many of the technologies that use renewable energy sources to generate electricity, including geothermal and hydro-electric plant, are well established commercially across the globe. Others, such as solar panels, wind turbines and biomass plant, are reaching maturity with widespread associated cost reductions being exhibited as a result of product innovation, mass manufacture and widespread deployment. In the case of photovoltaic solar modules for example, costs have fallen dramatically in recent years:[55] more than 60% in eighteen months during 2011–2013[56]. Beyond this decrease in capital costs, the low operating costs of these power generation technologies mean they are now cheap enough to compete with oil, kerosene, diesel, and Liquified Natural Gas (LGN) in developing economies.[55] Harnessing these technologies and cost reductions for electricity production in off-grid or micro-grid applications in developing country settings is not new.[3,49,57,58] The USAID 'Powering Agriculture' programme[59] is however, specifically supporting projects in developing countries with the objective of linking renewable sources with novel cold chain technologies. These include several types of small-scale solar[60,61] and biomass[62,63] powered systems.

The principal challenge with power generation from renewable resources however is the issue of dealing with the intermittency of the prime energy source. This arises because the sun does not always shine or the wind blow with sufficient strength to produce power at the moment electricity is required, and conversely can be highly active when power demand is low. With cold store refrigeration, one way to help tackle this challenge is through adequate and effective insulation; correctly insulated stores and containers can maintain their cold temperature for a considerable time without active cooling. In developing countries, however, the necessary expertise is often lacking. For instance, many Indian cold warehouses are not properly insulated, meaning their energy consumption at times of power availability is up to three times higher than those of similar capacity in developed countries,[64] and in these cases power outages from renewables intermittency will result in rapid temperature rises within the store.

Figure 2: Concept sketch for Solar-Polar space cooling modules mounted on an insulated shipping container for pre-cooling, cold storage and refridgerated transport of produce. A pilot-scale test of a single module is currently being carried out at Imperial College in London, UK. (Reproduced with permission of Solar-Polar.)



Cold storage in standardised insulated shipping containers sidesteps the issue of poorly installed building insulation, but although useful in the absence of alternatives these are often difficult to obtain and transport to remote rural sites, as well as limited in terms of capacity and optimum storage room layout. In all cases, a reliance on insulation to tackle a power shortfall due to the intermittent nature of a renewable energy source can be for a short time only and it does not help with long term disruption or the electricity needs of the pre-cooling/chilling/freezing step.

Energy Storage – the key to unlocking clean cold

In order that electricity generated from active renewable sources at periods of low consumer demand (so called 'wrong time' energy) can be used when needed, and to protect refrigerated produce against more extended periods of (say) low wind speed or no solar (eg at night), energy storage technology is a key enabler. In the developing world context, as in the Solar-Polar system for example, in its simplest form this might mean the use of a suitable volume of phase-change material (such as ice produced when electricity is available) located within the cold store to maintain cool temperatures in the absence of refrigeration power. However, such an approach has limitations and in many cases, particularly those involving the use of renewable energy sources combined with micro-grid systems to deliver power to multiple users, more complex energy storage solutions will be required.

The Institution of Mechanical Engineers recently published a comprehensive review of energy storage technologies that are in various stages of commercial deployment, full-scale demonstration, pilot testing and research.[65] Although in many developing communities the commercially available energy storage technologies identified as in common use with electricity in the mature industrialised economies, such as pump storage and conventional batteries, could be deployed, in others they will be either geographically impractical or constrained, too expensive and/or technically demanding to build, operate, service or maintain, or a risk to health or the environment, or a combination of several of these factors. However, a number of the technologies reviewed have characteristics that make them amenable to deployment with renewable energy systems in developing economies, particularly in the case of remote rural locations, and these included flow-type batteries, pumped heat electrical storage (PHES) and cryogenic energy storage.

Flow-type batteries are an extension of conventional battery thinking in that they use the same basic principles for operation but in this technology the electrolyte is stored outside, rather than within, the battery cell in adjacent tanks.[66,67] The energy storage capacity is therefore a function of the volume (and concentration) of electrolyte stored in the tanks, while the power is a function of the size of the battery cells, which makes scaling in size for different applications relatively straightforward. The system itself is simple to construct and operate; wrong time electricity from renewable sources can be used to charge the battery and when discharge is required the reversible electrochemical reaction generates electricity. Through appropriate selection of the chemicals flow-batteries can be highly durable, with lifetimes measured in decades, require little maintenance and have no safety issues in relation to flammability, explosion or chemical disposal. REDT[67] is currently developing such a system using a reduction-oxidation (redox) reaction based on the use of vanadium and has tested a small-scale, 5kW, prototype for off-grid application in remote or stand-alone sites[68]. Further development will lead to relatively low-cost, flexible commercial units enabling sizes from 5–100kW to be achieved for small-scale wind and PV solar deployments, and beyond for larger renewable energy systems. In the case of the latter, a 250kW iron-chromium flow battery demonstration plant operating with solar is currently being tested in California by EnerVault to power an irrigation system.[66]

In terms of mechanical engineering-based solutions to energy storage that are safe, simple to operate and easy to maintain, PHES is a potential candidate for future deployment with electricity systems in newly emerging and developing economies. The concept, which is being developed for commercial production by Isentropic,[69] involves using two containers filled with locally sourced mineral particulate, such as natural sands or crushed volcanic rocks, and a highly reversible gas cycle machine that works as both an engine and a heat pump. In the charging mode, electricity is used to drive a thermodynamic cycle that creates a hot store in one vessel (500°C at 12 bar in the case of the Isentropic design) and a cold store in the other (-160°C at 1 bar). When power is required the machine reverses the process and electricity is generated as the vessels return to their previous ambient states. The Isentropic design uses well-understood, tried and tested mechanical engineering principles; and these are brought together to create a highly efficient low-cost closed system that can be manufactured in modular form using readily available materials and assembled on site without high level engineering skills. The company is currently building a prototype for testing, plans to have a commercial scale demonstration plant operating within the next three years, and foresees a storage capability in the range 2–5MW per unit.

Another potential candidate, which is also based on a thermodynamic process and uses well-established and understood mechanical engineering, is cryogenic energy storage, a concept that has been developed beyond the pilot plant stage to commercial demonstration using liquid air by Highview Power Storage.[70] Air turns to liquid when cooled to -194°C, which can be achieved by using 'wrong time' electricity to drive a chilling process, so can be conveniently stored in unpressurised insulated vessels that are a standard, relatively inexpensive component of the industrial gases sector; a 'tank of cold'. These vessels have highly efficient insulation which means that extremely low levels of temperature change occur over prolonged periods of time. Subsequent exposure to ambient temperature causes rapid regasification (boiling) of the liquid and a 700-fold expansion in volume, which can be used to drive a turbine to generate electricity at times when needed.[71] Since the boiling point of liquid air (-194°C) is far below ambient temperatures (ie it is a 'cryogen'), the environment can provide all the heat needed to make the fluid boil. However, the expansion process can be extended further, to achieve more than the 700-fold volume increase, by the addition of low grade 'waste' heat (up to +150°C) if that is available from a nearby industrial plant; such heat is generally wasted as it is often difficult to utilise in industrial processes.

Industrial gases and liquefaction

The process of changing a substance from its gaseous to its liquid phase is called liquefaction and is achieved by condensing or cooling the gas. The development of refrigeration compression cycles in the late 19th century enabled the practical application of this process to be applied to air at low temperatures by the German engineer Carl von Linde, among others, for the production of large quantities of oxygen and nitrogen. These gases are used widely in industry for a broad range of applications such as welding, metal cutting, steelmaking, food processing, fertiliser production, electronics and aerospace: together with argon, hydrogen, acetylene, helium and carbon dioxide their production forms the basis of what is generally termed the industrial gases sector. A core technology used in the process of separating the constituent gases from air is an air separation unit (ASU), which performs distillation of the air to separate out the various components at their different cryogenic (below -150°C) boiling point temperatures. The production of liquid air however does not require this separation to be undertaken in the plant, thereby saving about 20% of the energy requirement of the overall process of producing the cryogen.

Liquefaction is a mature process and the associated engineering and technology that support it have developed over time with a focus on the delivery of large-scale centralised site-built plants. This has largely been driven by the economics of the industry which have dictated that industrial gas production is profitable at high volumes and plants, product distribution networks and equipment supply chains have become established throughout the world on this basis. However, a move towards the use of cryogenic energy storage coupled with renewables for the delivery of both power and cooling in rural developing communities will lead to a shift of emphasis towards smaller scale plants, with implications for engineering and equipment supply. The challenge to engineers is to improve the efficiency of smaller scale liquefiers, which are typically much less efficient than industrial scale plants today, and develop inexpensive factory produced plants capable of being delivered in modular form and efficiently producing just a few tonnes of liquid air per day.

Cryogenic energy storage is based on mature technology that forms the foundation of the industrial gases sector. The latter is expanding rapidly into many developing countries and is supported by a substantial global supply chain that delivers the equipment and practical know-how underpinning the industry. In common with PHES it has the advantage in a developing economy context of being constructed from readily available materials that are not exotic or unsustainable and, additionally in this case, uses a freely available and environmentally benign working fluid (ie air). However, as well as providing an energy storage solution for electricity, a cryogenic energy storage facility has the added capability to serve as a dense store of cold, effectively providing "power and cooling" and thereby opening up a wide range of possible cold chain applications in a developing community. Local power generation from solar or wind sources could drive a conventional electricity based cold store refrigeration cycle via a community level micro-grid, while simultaneously producing liquid air for energy storage in order to provide the electricity at night or on windless days. Alternatively, if co-located with the cold storage facility itself, a liquid air plant could be used to provide direct cooling of the store and to deliver an energy storage service to electricity users in the locality, distributed to them through a micro-grid. As well as providing a solution to the issue of local energy security, the use of a cryogen for direct cooling of food produce storage facilities avoids local health and environmental issues that might arise in rural communities of developing countries from the use and disposal of conventional refrigerants. If the renewable based generation capacity were built large enough, liquid air could also provide a transport refrigeration option to support step 3 of the cold chain, as described below, and thereby offer a potential route to a scaleable, holistic, system level approach to a sustainable cold chain solution, rather than a point solution to a discrete step or number of steps.

STEP 3: REFRIGERATED TRANSPORT

Refrigerated transport is essential to maintain a continuous cold chain between producer and consumer; **Table 1** shows the technologies available. In some cases small quantities of pre-cooled fresh produce can be transported short distances using the passive technique of placing product under insulated blankets or quilts, which can help keep produce cool. However, in the majority of cases a cold chain that effectively links farmers to markets will require produce to be transported in actively refrigerated spaces onboard vehicles ranging in size from small vans and trucks to large lorry trailers (reefers) or shipping containers.

Refrigerated transport today is overwhelmingly dominated by three technologies; trucks and reefers, marine shipping containers and railway wagons and all three largely use diesel fuelled refrigeration units, which are dirty and unsustainable, to provide the temperature controlled environment in which the perishable product is transported. Smaller rigid trucks, such as those typically used for 'last mile' delivery, usually run a refrigeration compressor powered by the vehicle's diesel engine while larger trucks and refrigerated reefers or containers tend to operate a separate Transport Refrigeration Unit (TRU) with its own secondary diesel engine. TRUs are effectively unregulated and emit high levels of NOx and PM as noted earlier. However, in addition to the Solar-Polar transport solution discussed previously, clean sustainable alternatives based on the use of cryogens are currently either being offered to the market, or in commercial development.

In response to increasing concerns regarding emissions from vehicle refrigeration, manufacturers and industrial gas producers have recently begun to offer systems based on liquid nitrogen evaporation (such as NatureFridge's 'ecoFridge' system),[72] a method that has been in existence for about 40 years[73]. This approach involves liquid nitrogen being either sprayed directly into the container, where it evaporates and displaces warmer air with inert cryogenic gas, or passing the fluid through a heat exchanger that cools the air in the compartment indirectly (neither approach, however, obtains any useful work from the energy available in the evaporation process). Such systems are quieter and produce zero emission at the point of use, though it should be noted that the carbon intensity of the liquid nitrogen is dependent on the energy source used for the liquefaction process (in the majority of cases today this is typically fossil fuel based infrastructure) and the economics of deployment are challenging in the absence of environmental incentives.

An alternative cryogen based refrigeration unit is currently being developed by the Dearman Engine Company (DEC)[74] that, along with delivering the zero-emissions and noise reduction benefits, potentially offers an improvement in the economics and carbon intensity of deployment[37]. In this case the unit also produces no emissions at the point of use but, since it uses liquid air or liquid nitrogen to simultaneously obtain both cooling and useful mechanical work, in the form of shaft power, it increases the return on the energy invested in the cryogen during its production. The liquid air regasifies in a heat exchanger in the cooling compartment, so cooling it down, and the resulting high pressure gas drives a piston engine. The shaft power delivered by the engine is used to drive a conventional, but smaller, refrigeration compressor and thereby delivers additional cooling. Since this approach is more efficient than simple liquid nitrogen evaporation within the refrigerated compartment itself, it will be more cost-effective and produce larger cuts in CO_2 as well as eliminate the NOx and PM emissions from the refrigeration unit.[37] A prototype of the refrigeration unit will begin on-vehicle field trials with MIRA[75] in summer 2014, with Technology Strategy Board grant funding, and the Manufacturing Technology Centre (MTC)[76] have committed to production of an initial batch of the cryogen fuelled engines for 'market seeding' purposes. The production unit is expected to have broadly the same capital costs as a conventional diesel system when manufactured commercially, but deliver significant operating cost savings.

In the context of a developing economy one advantage of this 'power and cooling' approach is that it enables pre-cooling to be delivered by the vehicle in addition to transport refrigeration, this is of particular value in the case of rural communities with no access to other reliable energy sources for steps 1 and 2 of the cold chain. Furthermore, in common with the cryogenic energy storage system described earlier for use with electricity, the cryogen-fuelled refrigeration units are relatively easy to build, simple to operate and maintain (essentially a form of simple piston engine) and use readily available materials as well as an environmentally benign working fluid.

The notion that developing economies might create sustainable cold chains based on the clean electricity, clean cold and clean 'fuel' options described in this section of the report, when the established dirty unsustainable model has been so successful to date, raises many questions however, not least of which are; how will it be funded, how practical will it be to get started and how much will it cost? Cold chain investment is already taking place in some of the more advanced and rapidly urbanising developing countries, such as India[32] and China[33], and about to begin in many newly emerging economies. There is no reason in principle that a society able to install a dirty mechanical engineering based technology should not be able to install a clean one instead. The point is to make the alternative approach more attractive from a social, political, environmental and economic perspective and catch the process early enough, before business-as-usual thinking and investment become entrenched. The key is to ensure that the alternative cleantech based sustainable solutions are reliable, readily available and, preferably, cheaper than the traditional fossil fuel based technology approach.

A tricycle rider transports vegetables to market early in the morning in Delhi, India.

INVESTMENT DECISIONS FOR COLD CHAIN TECHNOLOGIES

Investing in cold chain technologies has been shown in mature economies to be a cost-effective way to connect farmers and growers with higher value market options as well as reduce post-harvest losses of perishable produce, thereby improving incomes for producers and meeting increasing demand for food. However, the capital spending required for the deployment of these technologies can be a significant barrier in the developing world.[25] From a purely commercial perspective a positive decision to introduce cold chain technology for a given perishable product will depend largely on whether the value of the produce saved exceeds the cost of investment and operation, including pre-cooling, chilling or freezing, cold storage, cold transport and retail refrigeration. The investment is clearly more likely to be made in this way for higher value produce, such as fresh berries, snow peas, seafood and flowers, but may be difficult to justify for lower value staples without accounting for the broad societal benefits of increased well-being and health that agricultural development brings. In such cases there is a role for government intervention and subsidy to reduce the risks for early adopters and encourage deployment to a point of critical mass. In India for instance, the government currently provides subsidies of up to 50% through the National Horticulture Board (NHB) and the Ministry of Food Processing Industries (MOFPI) to help cover the upfront costs of deployment.[77] Eligible investments include plastic crates, packing houses, pre-cooling facilities, cold storage and refrigerated vehicles.

For newly emerging economies the cold chain raises the prospect not only of reducing produce losses and strengthening food security, but also of upgrading agricultural 'value chains' to underpin development. Agrarian societies will be able to increase their income by growing higher value produce for a broader range of market options, and ensuring that as much of that product as possible reaches the marketplace and consumer, thereby helping realise a shift from poverty-based subsistence farming to increased well-being founded on agricultural production. The African Union has made value addition, functioning markets to facilitate trade, and investment in agricultural value chains core areas to be addressed in the coming decade.[10] Countries in sub-Saharan Africa such as Mali and Kenya have already carved out a profitable niche supplying high value horticultural goods including mangoes and cut flowers to the mature economies of the world and poorer developing nations such as Tanzania have aspirations for similar initiatives. In this regard cold storage has already been built at Kilimanjaro Airport to facilitate horticultural exports[78] and a new container port at Bagamoyo, due to open in 2017, could increase agricultural exports to encourage development[79]. In these circumstances there is a strong case for cold chain investment through a partnership combination of overseas donor development aid (particularly 'aid for trade' investments)[80], national government subsidy and intervention, and private investment both corporate and philanthropic.

A worker with a geared compressor for air separation.

ESTABLISHING CLEAN 'POWER AND COOLING' AS A COLD CHAIN SYSTEM SOLUTION

The cryogen required to begin creating a clean 'power and cooling' based cold chain system, by starting the process of local capability and capacity building with cryogen fuelled refrigeration units for the transport step, is often already available in many developing nations. In this regard, although liquid air is not yet produced commercially, throughout the industrialised world nitrogen is as a standard output from the air separation process. The industrial gas companies potentially have large amounts of spare nitrogen production capacity available for the simple reason that the gas is more prevalent as a component of air than oxygen (78% of air by volume is nitrogen compared with only 21% oxygen) but there is significantly less commercial demand for it. Consequently the potential for nitrogen production in an ASU is often simply not utilised[37] and the amount of this latent capacity is set to increase across the developing world as industrial gas production grows along with widespread industrialisation. This surplus could in many cases be employed to support early deployment of the refrigerated transport solution,[37] in the emerging industrial centres of developing economies. Initial, conservative cost modelling presented in the Tanzanian case study of this report shows that replacing diesel with cryogen fuelled refrigeration units on cold chain road transport reefers can lead to considerable cost savings.

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IN ASIA, THE INDUSTRIAL GAS SECTOR IS GROWING FAST, AND RECENT INVESTMENT HAS LED TO THE EMERGENCE OF SIGNIFICANT SPARE NITROGEN CAPACITY.

In Asia, the industrial gas sector is growing fast, and recent investment has led to the emergence of significant spare nitrogen capacity. For example, analysts at gasworld estimate current spare nitrogen liquefaction capacity in the 'merchant' and 'onsite' trade is about 3,500 tonnes per day in India alone[81]. In principle, this amount of surplus nitrogen would be enough to fuel refrigeration units on about 29,000 delivery trucks. Additionally, many of these countries have established, or are in the process of establishing, facilities to enable the import of LNG to meet growing energy needs. The regasification of LNG provides surplus cold which in most cases is currently not used but could be recycled to help drive a liquid air plant. By 2015 China is expected to have LNG import capacity of 47 million tonnes per year[82], and the waste cold from this amount of regasification could theoretically be used to help produce 17 million tonnes of liquid air, which would be enough to fuel 390,000 cryogen fuelled refrigerated truck units. In other words, in a simple calculation, China will have the potential of wasting more cold than would be required to support the entire refrigerated fleet projected to be in place within a decade (365,000).

Recycling unpacked cold from LNG

LNG is natural gas (typically methane) which has been shrunk about 600 times in volume for ease of transport and storage by chilling to about -162°C at atmospheric pressure. This is an energy intensive process. Regasification of this cryogen requires significant amounts of energy to heat the LNG to a temperature above 0°C and this is generally achieved through a series of heat exchangers with sea water on the 'hot' (ie warm) side. In cases where the water is not of sufficient quality the heat is often supplied by burning some of the gas itself. The process of regasification gives off substantial amounts of cold that is usually rejected to the sea or vented to the environment, both of which effectively 'waste' this cold resource. In a sense, LNG is natural gas packed in cold, but that packaging is currently discarded, rather like the polystyrene in the box of a new TV set. However, this cold can be recycled and where this approach has been adopted at LNG terminals in Japan and Korea for nitrogen production the liquefier requires two thirds less electricity than a conventional unit, thereby both capturing the otherwise wasted cold and reducing the cost and carbon intensity of the cryogen product by a similar margin.

Figure 3: Artists impression of a local cold economy based on a cryogenic cold chain system building capacity in an emerging industrial centre. (Reproduced with permission of the Liquid Air Energy Network).

Existing ASU powered by grid provides nitrogen fuel for TRUs, trucks and grid balancing

Zero-emissions vehicle (ZEV) delivers chilled goods to shops

ZEV tuk-tuks refuel and collect goods for delivery to homes in the city

Air-conditioned buses refuel with liquid air

ZEV taxis refuel with liquid air

Cold warehouse for port

Liquid air production plant powered by grid and utilising waste cold from LNG regasification, provides cooling to port, transport fuel and grid balancing

Refrigerated trucks carry fish to cold warehouse in port

VISION OF A COLD ECONOMY: A 'TANK OF COLD'

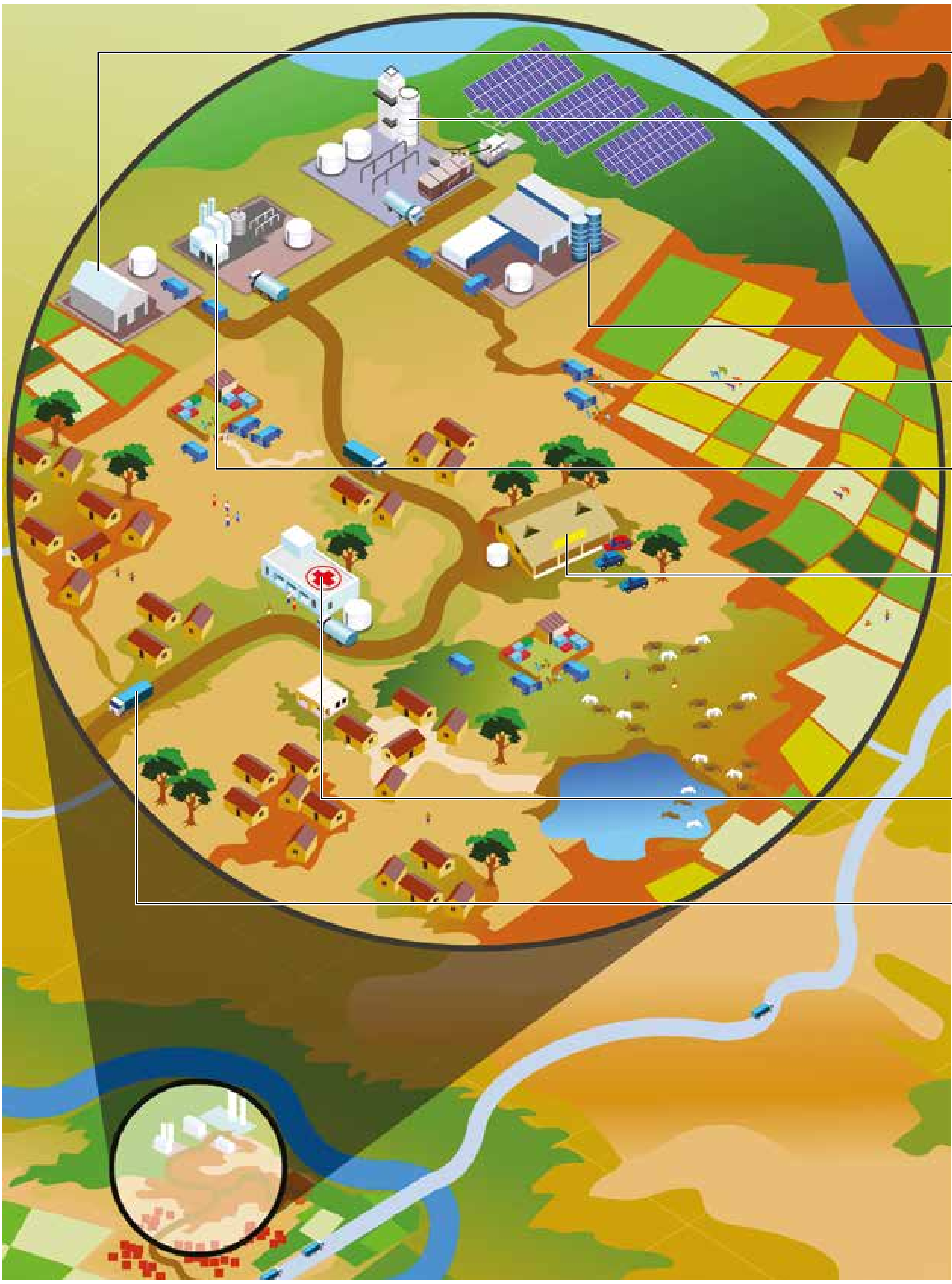
In such a capability and capacity building scenario, what starts initially as a zero emissions at point of use transport solution for the cold chain will evolve and extend to become a wide ranging cleantech leapfrog to a sustainable cold chain approach, incorporating surplus nitrogen production capacity, waste cold from LNG regasification and local production in energy storage facilities of liquid air for use as transport refrigeration unit fuel (**Figure 3**). A case study on India is provided elsewhere in this report as an example to give further details of the capabilities, capacities and opportunities available in a rapidly industrialising country to implement this scenario in practice on the ground. The study also provides an early initial cost comparison for the cleantech solution against those that would be incurred in taking a traditional fossil fuelled 'business-as-usual' infrastructure approach.

In the newly emerging economies, such as those of sub-Saharan Africa, the situation is somewhat different. Here, depending on the stage of industrial development, there may be small but increasing amounts of surplus liquid nitrogen production available from industrial gas production to begin local capability and capacity building. In some cases also, depending on the individual country's emerging energy infrastructure, there might be some LNG regasification infrastructure to enable exploitation of waste cold. However, in many locations, particularly those that are rural and remote, a different capability and capacity building scenario will need to be followed. The opportunity here is to establish cryogenic energy storage as the technology of choice for off-grid and micro-grid renewable energy projects at local agricultural 'hubs'; thereby providing the potential for local liquid air production to fuel cryogen TRUs as well as delivering reliable electricity supply to cold stores and the broader community. Capacity and capability building in this scenario will open up the possibility of providing a broad range of additional local 'power and cooling' services based on a tank of cold: in effect creating a 'cold economy' from the bottom up. The Tanzanian case study included in this report explores the practical in-country potential for such an approach in a sub-Saharan Africa context and provides an early initial indication of the economics of implementation.

In developing countries that are newly emerging economies, where there is little existing infrastructure to start a cleantech leapfrog to a sustainable cold chain, the opportunity is to build a liquid air based cold economy from the ground up, powered by local renewable energy sources. In this vision, once liquid air has been established as a vehicle refrigeration unit fuel and source of energy storage for cold stores, and local capacity and capability have been built, it will then make sense to expand its use to other agricultural applications and a wider range of services for developing communities. A 'tank of cold' would then provide a substantial range of local services including off-grid and micro-grid energy storage, refrigeration, cooling, air-conditioning, transport fuel and even localised fertiliser production. The starting point here is to recognise the opportunity to solve the challenge of reliable cold storage through cryogenic energy storage, coupled with off-grid and micro-grid based electricity supply generated from abundant local renewable sources.

In sub-Saharan African nations for instance where only about 30% of the population have access to electricity,[47] power is often a luxury and in many rural areas non-existent; where it is a possibility power is often in short supply and connections are notoriously unreliable, often leading to unannounced disconnections for prolonged periods of time[48]. As an example, annual power consumption in Tanzania is currently less than 90kWh per capita[83], the equivalent of one light bulb per person for three hours per day, and 40 million people, almost 90% of the population, have no access to electricity[84]. Where a connection to an electricity supply is available, the power provided is expensive and erratic, so most rural businesses fend for themselves; the Tanzanian Horticulture Association (TAHA) reports that during five months of power rationing in 2011, a group of 18 farms spent $1 million on diesel for their generators[85].

At the same time, many of these locations have excellent renewable resources. High solar potential exists throughout sub-Saharan Africa and good wind resources are in many cases available on the coast and in the highland regions, as well as hydro and geothermal power production opportunities.[3] In these circumstances, building a conventional national electricity transmission and distribution grid infrastructure based on large-scale centralised power generation would be a substantial undertaking, in terms of both resources and costs, and it does not make economic sense. A distributed community level infrastructure based on micro-grids, stand alone off-grid solutions and local renewable sources for power generation, heat and cooling provision would be modular, more affordable, more manageable and more resilient to external shocks.[3,47,58,86]



Cold storage warehouse for crops and produce

Liquid air plant provides energy storage for electricity generation, direct cooling services, micro-grid power, fuel for trucks, ZEVs, TRUs and, with the addition of air separation (ASU), nitrogen and oxygen

Food processing with blast freezing

Trucks deliver fresh farm produce to food freezing plant

Industrial park uses nitrogen – eg small scale fertiliser production – and cooling

Hotel uses liquid nitrogen for air conditioning and back-up power

Medical centre uses liquid oxygen and nitrogen for cryogenic storage and backup power

Liquid air TRU Reefers transport frozen and chilled food to the city

Figure 4: Artists impression of a rural cold economy based on a tank of cold located at an agricultural 'hub'. (Reproduced with permission of the Liquid Air Energy Network).

In many cases, because small-scale solar equipment for electricity generation has become relatively low-cost on international markets, the costs of power sourcing from local renewables is already cheap enough to compete with oil, kerosene and diesel in many developing markets[55] and reached cost-parity or below in off-grid and micro-grid application in rural areas compared with providing centralised grid connection.[3,58,87] At the domestic level small businesses in countries such as Tanzania and India have emerged to take advantage of this economic reality and supply energy services to householders based on solar provision for lighting and mobile phone charging.[49,57] Given the positive growth prognosis for the mass production of these technologies to meet increasing global market demand for low-carbon infrastructure, economies of scale and continued innovation are expected to lead to further cost reductions making this option even more attractive in the future.

If localised off-grid and micro-grid distributed renewable generated electricity is developed, then in most cases an energy storage technology is vital both to ensure security of supply and to optimise use of the asset investment. The question we need to ask however is: should this be power only or, given the energy demand mix in sub-Saharan Africa's agricultural communities, is storing power and cooling for cold storage, air-conditioning and cold transport applications more cost-effective? Initially, a liquid air energy storage plant could be installed at a local agricultural 'hub' for the sole purpose of providing energy storage, but later its use could be extended to provide fuel for cryogen TRUs and a wider range of services (**Figure 4**). Since much of the energy required by agriculture is for cooling, liquid air could perform both functions, power and cooling, and so support a local cold economy. For example, by colocating the plant with a cold warehouse where farmers from the surrounding area could store fruit, vegetables, meat, milk or flowers, at times of low or no energy supply from intermittent renewable sources the plant could be used to provide power or cooling for the store's refrigeration and electricity to the local community through a micro-grid. Additionally the facility could produce fuel for use in the refrigeration units of the trucks collecting the produce from the local network of farmers and growers for placing in store. Onward transport to markets could be facilitated in larger vehicles with cryogen TRUs, again supplied with liquid air from the same tank of cold.

There will be many other additional benefits in having a local tank of cold, however, besides cold storage, refrigerated transport and reliable micro-grid supply. Nitrogen is required among other chemicals for the production of fertiliser, so by building an ASU into the tank of cold plant and taking off a stream of nitrogen this feedstock component could be provided to a small-scale fertiliser plant located at the 'hub' (see box). Fertiliser is a key to unlocking a potential (up to three fold) crop yield improvement across Africa, but sourcing the product from large-scale production plants remote from rural locations creates cost and logistics problems that act as barriers to agricultural development. Additionally this could provide the small amounts of liquid nitrogen needed to transport human and animal vaccines, bull semen, tissue samples and other related medical and veterinary items. The ASU can additionally supply oxygen for use in the local hospital if required. Overall, farm efficiency will be revolutionised by the local availability of the tank of cold approach, dramatically raising the proportion of produce that reaches market in good condition. It will also prompt the development of new food processing businesses in-country that require rapid cooling, such as canning, drying or freezing, further improving farmer's access to distant and overseas markets as well as allowing them to move up the value chain. At ports, a tank of cold could not only provide reliable refrigerated warehousing for produce from the interior due for export, but also transform the local fishing industry, allowing catches to be stored for longer and transported further.

The tank of cold also opens up the possibility of local ultra-low and zero-emissions transport vehicles (ZEV) powered directly by liquid air. As well as cryogen fuelled TRUs, DEC is developing a piston engine driven by the vaporisation and expansion of liquid air or nitrogen[37]. The novelty of the technology lies in the use of a heat exchange fluid that promotes extremely rapid rates of heat transfer inside the engine, allowing it to dispense with the bulky and inefficient external heat exchanger that handicapped earlier cryogenic engine designs. In common with the cryogenic energy storage system and TRUs, the vehicle engine is from a mechanical engineering perspective relatively easy to build, operate and maintain and could be used in a number of configurations:[37] on its own, as the principal engine for small vehicles, such as the ubiquitous tuk-tuk used as short distance local passenger and goods transport in many developing countries, or in combination with an internal combustion engine (ICE) to form a 'heat hybrid' for larger vehicles including trucks, lorries and buses.

Small Scale Fertiliser Production

The Haber Bosch process, which takes nitrogen from air and reacts it with hydrogen gas to produce ammonia, is responsible for the vast majority of the synthetic nitrogen fertiliser that is currently consumed around the globe. Traditionally the commercial facilities that apply this process to production are large in scale and centralised, an appoach which results in the cost of transport to remote locations being an important factor in product accessibility. Indeed, in developing countries the cost and availability of fuel such as diesel, combined with limited or inadequate transport infrastructure, often means that remote farmers with little money do not have access to this basic agricultural input. For example, in remote locations of Africa the price of a kilo of fertiliser, if available, can reach as high as six times the price charged near the country's production facilities. On the other hand, fertiliser use is known to significantly increase yields. Recent work on the Millennium Villages[88] initiative for example has shown that the application of modern farming methods in an African context, including the managed use of fertiliser, can increase average cereal grain yields from one to three tonnes per hectare[89].

Adoption of fertiliser in sub-Saharan Africa today remains low and several reasons have been suggested to explain this, including lack of access to credit, lack of information and knowledge on the appropriate fertilisers to apply and risks associated with rain-fed agriculture, as well as the availability and cost of fertiliser in local markets. Manufacturing fertiliser at small-scale has the potential to address the latter constraints, of availability and cost, and help provide the catalyst for tackling the others.

The Lenfest Center at Columbia University is developing a small-scale modular system to produce nitrogen fertiliser near the point where its application is needed using ingredients readily available in the local environment.[90] The project involves re-engineering of well-understood processes and finding ways of replacing the economies of scale with economies of mass manufacturing. In this regard the Haber Bosch chemical reaction itself is not intrinsically tied to large scales and because it occurs on surfaces and needs to shed heat the conditions appear more amenable to small rather than large systems. Recent work at Columbia has also shown that cost reductions achievable through mass producing large numbers of small units can outpace those seen from scaling-up individual unit sizes[91] and the impact can be particularly large where small-scale unit processes could result in a distributed production scheme that favours smaller operators. The focus is therefore on using cheap mass-produced components and a highly modular design where each sub-system can be easily replaced and/or substituted with an improved version at any given time. A particular challenge for engineers will be to address the scaling and costs associated with the turbo-machinery equipment in the plant. The entire system will comprise several modules that provide energy from the sun; nitrogen from the air; hydrogen generated from water; and carbon dioxide from biomass to produce nitrogen based fertiliser in the form of urea. Integrating the facility with a liquid air plant located at an agricultural 'hub' (**Figure 4**) could provide the initial nitrogen sourcing module and this is being actively explored as part of the work.

The goal of the project is to demonstrate that small-scale on-site fertiliser production is feasible, affordable and sustainable, and could support the needs of small villages and landowners. Such a change from highly centralised production will greatly benefit small farmers in remote locations through access to agricultural inputs needed for development as well as increased community resilience.

As with all clean technologies, liquid air energy storage and refrigeration fuel production utilising electricity generation from renewable energy sources would replace a low capital cost-high operating cost 'business-as-usual' fossil fuel based model with its opposite. A local communal ('hub') liquid air plant coupled with the renewable power generation equipment to drive it will incur relatively high capital costs to build, but running costs will be minimal. In a remote rural region of a developing economy, however, where there is no access to a reliable grid connection and fuel for vehicle refrigeration units, as well as local transportation, is expensive and in short supply, the case for assisted deployment funding becomes tenable, particularly given the increased human well-being and health benefits that development brings and the overall environmental benefits to be accrued from the approach. As the sub-Saharan Africa case study in this report illustrates, in countries such as Tanzania, where 18 remote farms can spend $1 million on diesel in less than six months, the commercial case could also be compelling, particularly when international development funding is likely to be available for credible renewable projects.

In developing countries that are more advanced in the industrialisation process, such as India and China, it has previously been noted that there is already substantial infrastructure in place to form the basis of a sustainable cold chain system. Here the vision entails an intervention in cold chain development as the starting point, to incentivise and guide rapid deployment of the cryogen based cleantech approach instead of the 'business as usual' model underpinned by fossil fuels, while building on opportunities to create a much broader and integrated cold economy.

Existing ASUs located in the major industrial centers can be adapted to provide fuel for vehicle refrigeration units as well as electricity grid balancing services through energy storage (**Figure 3**). The latter would improve on the reliability of electricity supply to consumers and enable successful scale-up across the grid of power generation from intermittent renewable energy sources. China has announced an intention to achieve parity of renewables with coal-fired plant in the country's grid mix by 2020[92] and India's Twelfth Five Year Plan includes the deployment of an additional 22GW of renewables based power generation on the grid by 2017. In more remote rural regions, however, grid availability, and the reliability of the connection where it does exist, will in many cases continue to be issues for sometime to come; here the local tank of cold model described above for newly emerging economies would apply for establishing a reliable, affordable and sustainable cold chain from the ground up, together with a broad ranging local clean cold economy (**Figure 4**).

As well as helping to establish clean sustainable cold chains, the anticipated growth of the number of LNG regasification terminals at ports in the rapidly industrialising world offers the potential for integration of waste cold with commercial cooling loads. The latter might include cooling for datacentres, or refrigerated warehouses used for storing perishable product destined for export, both of which could be co-located with the regasification facility to take advantage of the substantial energy savings available in recycling cold. The waste cold could also be used to produce fuel for tuk-tuks which could serve as either air-conditioned taxis or refrigerated vehicles for 'last mile' urban delivery. In such an approach, these ZEVs would shuttle produce between transfer depots on the outskirts of urban areas and shops and markets in the centre.

This approach to last mile delivery would reduce the consumption of diesel and help improve air quality in congested megacities such as Shanghai, Beijing, Mumbai and Delhi.[93] India's imports of LNG are, for example, projected to rise five-fold to about 60 million tonnes per year in 2022[94] and in principle harnessing the associated waste cold could produce almost 22 million tonnes of liquid air, enough to fuel over half a million truck refrigeration units, or 230,000 heat hybrid buses or 1 million urban tuk-tuks. The key is to think in terms of a joined-up cold economy and more details of the practical opportunities are given in the accompanying case study on India.

A Tank of Cold: Highview's 350kW pilot plant in Slough, UK.

WHAT NEEDS TO CHANGE?

The challenges of facilitating access to a range of higher value markets for farmers in developing countries and meeting the growing urban demand for food produce and related convenience food products, while addressing the issue of post-harvest loss of perishable produce through affordable and sustainable cold chain provision, require concerted action by several players, often working in coordinated partnerships. Governments, NGOs, philanthropists, aid agencies, banks, investors, commercial companies, engineers, community leaders and farmers all have an important role to play. In doing so, it is essential for a sustainable outcome that these individuals and organisations shift their thinking away from the 'business as usual' model of cold chain deployment rooted in fossil fuel sources and energy insecurity, to one based on the use of clean technologies, renewable energy and waste cold. One way forward is a model where aid donors play a catalytic role while the for-profit sector drives the economic component of sustainability. Since liquid air appears, on early initial assessment from simple modelling, to have the potential of sound economics for a holistic sustainable cold chain system, the key will be overcoming the initial fixed costs of adoption and building local capacity and capability to start implementing a cryogen infrastructure.

Governments of developing countries have a significant role to play in stimulating the deployment of cold chains by creating an attractive enabling environment within which they can be built and operated. This can be achieved through policy initiatives, regulatory frameworks and financial support, which remove barriers to development and attract investment, with a particular focus on adopting technology and infrastructure that is clean and sustainable. These issues can include addressing importation and tax policy, infrastructure management and other regulations or subsidies that could either aid or undermine the adoption of new technology, as well as streamlining and standardising procedures and supporting economic modelling and local in-country commercial scale demonstration of an energy secure, sustainable approach. However, while the most pressing need for such infrastructure is in the rapidly industrialising nations of Asia and emerging economies of sub-Saharan Africa, as is common with many renewables and cleantech based solutions, the technological and engineering expertise required to deliver is largely concentrated in the mature developed economies of the world. Governments of these nations should therefore take the lead in addressing this global imbalance in cleantech knowledge by incentivising the dissemination and installation of sustainable cold chain infrastructure knowledge through programmes such as 'aid for trade'. Such an initiative does, however, need to be pursued in parallel with development of a cleantech refrigeration blueprint for the mature economies that utilises their technical expertise, access to capital and policy mechanisms so experience can continue to be accumulated and shared.

"" CRYOGENIC ENERGY STORAGE CAN NOT ONLY FACILITATE RELIABLE ELECTRICITY SUPPLY, BUT THROUGH THE PROVISION OF DIRECT COOLING IT ENABLES A HOLISTIC SYSTEMS LEVEL APPROACH.

NGOs are called upon to champion the international cause of easy to build and operate engineered solutions which reduce perishable food loss and to act as enablers to encourage investment in sustainable and reliable cold chain systems. These development focused organisations are uniquely positioned to work with local communities and the private sector to raise awareness and drive the campaign for affordable cleantech based cold chains and a reliable clean energy system, including local capability building through the provision of appropriate training, knowledge and management programmes across borders. Mechanisms for the effective development, management and transfer of knowledge and sharing of 'best practice', including the use of cryogens to provide power and cooling, in preference to diesel which provides power, heat and pollution, should be established amongst NGOs. They can also play a major role in collaborating with government and private sector to prioritise research funding for economic modelling of tank of cold solutions and to accelerate commercial scale demonstration. If NGOs can work with governments, for-profit companies and other partners, sustainable cold chain development will enable the move from aid to trade; and investment can become an economic catalyst for longer term higher revenue agricultural output. It is important in this regard to shift the focus from aid provision for yield increases alone to a more holistic approach that is inclusive of enabling market access and can create a virtuous cycle of rural reinvestment.

Secure, reliable cold chains are vital in helping minimise food losses and protecting food quality, nutritional value and safety in developing nations. Robust, affordable, easy to build, use and maintain solutions for local context must be developed by the engineering community and deployed to increase food security; thereby driving rural development in newly emerging regions and supporting the growth taking place in the rapidly industrialising countries. Further, the international engineering community must work to ensure that the governments of these nations have access to the engineering knowledge, design know-how and suitable clean technologies to enable them to maximise the opportunities for the development of wider joined-up sustainable cold economies from cold chain and tank of cold starting points.

UK engineers both academic and industrial are leaders in mechanical engineering systems thinking, cryogenics and liquid air based technologies, as exemplified by the recently established Birmingham University Centre for Cryogenic Energy Storage, the work of the UK industrial gases sector, the Dearman Engine Company, Highview Power Storage and the Liquid Air Energy Network. These engineers and engineering based organisations must work in consultation and collaboration with local and regional in-country decision makers to ensure that solutions for developing economies are carefully aligned with the technical requirements and engineering capacity specific to the region. This will require work to be done on the issues of equipment and plant scaling so that smaller facilities can be utilised in distributed operations that form part of a coherent holistic system. In addition the profession will need to engage with local providers of engineering education and training to ensure the necessary skills are developed and local capability is built. To facilitate such initiatives the creation of a technology and training deployment roadmap, from farm to fork, would be a useful first step contribution by the profession. This will involve tasks that include defining the needs for pre-cooling/chilling/freezing technology, energy storage, cold storage and refrigerated transport vehicles that use new energy vectors to harness renewable energy and sources of cold.

Finally, finance and investment are the ultimate key to realising the full potential of sustainable cold chains and in this regard international organisations such as the World Bank and regional development banks can provide long term infrastructure debt financing on terms which smaller developing countries may not otherwise be able to access. Clean technology systems based on renewable energy sources are challenging due to their financial structure, which is heavily dependent on up-front capital costs, and banks need to recognise this and play a role in offering finance appropriately structured to suit the cash flow realities of developing rural communities. International donor agencies, many of which are currently focusing attention on global food losses and waste reduction, can also provide seed money for the capital costs of piloting cold chain development efforts based on renewable energy sources and clean technologies. In both cases however banks and NGOs need to make themselves aware of the specific characteristics of the technologies they are being asked to finance so that appropriate informed financing decisions can be made. Businesses have a significant role to play here too. Retailers, particularly those operating international food supply chains that source produce in developing economies, have a responsibility to consider the sustainability of the cold chains they are investing in. More generally, businesses need to recognise the commercial opportunity of investments in off-grid and micro-grid renewable based energy systems, as well as in holistic sustainable cold chain systems based on cryogens; encouraging entrepreneurialism and unlocking further commercial development investment opportunities. In a gold rush business invests in shovels, in a cold rush it needs to invest in cold air.

An worker gives the finishing touches to solar panels at the Gujarat solar park in Charanka village, India.

RECOMMENDATIONS

The defining challenge of the 21st century will be meeting the food demands of an increasing human population undergoing substantial demographic change, while reducing environmental degradation and risk as well as global tensions over basic resources such as water, energy and land. Reducing food wastage to a minimum while simultaneously improving agricultural yields, applying clean technologies and increasing the efficiency of resource utilisation offers the route to a successful human outcome for all. Cold chains are an essential component in establishing an efficient food supply chain and are critical to development in both emerging economies and the rapidly industrialising nations. However, the current cold chain deployment model uses fossil fuel based infrastructure that is unsustainable and often completely absent in the developing world. A unique opportunity exists to instigate a cleantech leapfrog to a more sustainable model in these economies, which are also where the bulk of 21st century population growth and demographic change is projected to take place. The Institution of Mechanical Engineers therefore makes the following key recommendations:

1. **Governments of newly emerging and rapidly industrialising economies must prioritise support investment in cold chain infrastructure to improve food security, underpin development and help alleviate poverty.** Providing farmers with opportunities to access higher-value market options for their produce is widely recognised as a key route to moving individuals and communities out of subsistence and poverty towards higher-level economic activity and increased well-being. For perishable produce, cold chain infrastructure is essential to ensuring that as much product as possible reaches the marketplace. Beyond this, encouraging and incentivising developments that are based on sustainable solutions, including renewable energy and clean technologies, offer opportunities for affordable routes to energy security and reduced environmental risk.

2. **Donor country governments and development NGOs must support and incentivise aid recipients to develop sustainable cold chains using renewable energy and waste cold.** Increasingly overseas aid from donor governments and NGOs is being allocated to development projects that help individuals and communities become more self-sufficient and resilient. A sustainable cold chain solution based on renewable energy, clean technologies and waste cold recycling should be encouraged and incentivised.

3. **The UK engineering community should come together to define in detail the potential opportunities a joined-up cold economy presents for the developed and developing world.** The UK has a substantial heritage in the industrial gases and broader cryogenics sectors. As a leader in the field of the industrial application of cold, as well as in renewable energy utilisation, clean technologies and energy systems integration for efficient resource use, the nation is well placed to lead on work to tackle the technical challenge of equipment scaling and explore the environmental and societal benefits of establishing cold-chain economies.

A family subsistence farming in Tanzania, Africa.

CASE STUDY: TANZANIA

Although the economy of Tanzania has been growing at about 6% in recent years, well above the African average of 4.8% annual GDP growth from 2000–2010[13], it is one of the world's poorest countries and a major recipient of international donor funding. In common with many on the African continent, where overall 70% of people make their living from farming or growing produce[95], its population of 48 million is largely dependent on agriculture, which generates 45% of the country's GDP and 85% of exports. Indeed, four fifths of the Tanzanian workforce are employed on the land and almost all of them are engaged in that activity as subsistence smallholders.[96] Levels of malnutrition in the nation are among the highest in Africa, with 80% of one-year-olds anaemic and more than 40% of children under five stunted.[97]

Despite the fact that Tanzanians are heavily dependent on agriculture for their livelihoods, a large proportion of the country's perishable output is lost after harvesting, much of it due to an almost complete lack of cold chain infrastructure. However, as is common across much of the developing world, robust official or academic data for these post-harvest losses is severely lacking, but nevertheless it is reported that almost 60 million litres of milk are lost each year, amounting to 16% of total dairy production during the dry season and 25% in the wet season.[98] Meat losses are also anticipated to be high, since 97% is sold warm, without ever having been chilled.[23] Losses of fruit and vegetables, which deteriorate more quickly in the higher temperatures of Tanzania's arid equitorial region, could be as high as 50%, the upper estimate for Africa as a whole.[21]

The lack of cold chain has wide ramifications both for public health and economic development. Much of the food that has deteriorated to the point at which it should be discarded as unfit for human consumption is in fact eaten, often with severe unnecessary impacts on public health, which in addition to being a humanitarian issue lead to reduced workforce productivity and lost economic opportunity. Further, the fact that much of the produce that does reach the marketplace does so in a poor state means that African smallholders, such as those in Tanzania, often receive less than 20% of the potential retail value of their crops.[99] These low returns from agricultural production contribute to high rates of rural poverty and chronic under-investment in farming; as a result average crop yields are only about 50% of potential, with many farms across the continent only yielding a third of what would be possible with investment, creating a cycle that perpetuates a subsistence 'lock-in'. In Tanzania, the lack of a widespread cold chain also means that hotels and other tourist businesses often import much of their food rather than using locally sourced produce, in order to guarantee its hygiene and safety. Besides being unsustainable and imposing costs on those businesses, this missed opportunity for the country's farmers is adding to the vicious cycle.

Growth of agriculture in sub-Saharan Africa is about 11 times more effective at reducing poverty than growth in other sectors,[95] so investing in a solution to post-harvest losses should be a strong candidate for stimulating a shift out of poverty to increased well-being for many Tanzanians. One clear measure of the potential that could be unlocked for the nation by creating a reliable cold chain is the contrast between its horticultural sector and that of its northern neighbour Kenya. Horticulture in Tanzania accounts for 40% of agricultural exports and 9% of total exports but earns less than US$400 million a year.[100] Kenya's exports to the EU, by contrast, are worth almost US$2 billion per year, five times as much. Under its Kilimo Kwanza (Agriculture First) strategy, Tanzania aims to raise revenues from horticulture to US$1 billion by 2015.[101] But the Tanzania Horticulture Association (TAHA) says this target is severely challenged by the lack of cold chain technology as well as the disruption and additional costs caused by the country's chronic electricity crisis.[85]

Fewer than 14% of Tanzanians have access to electricity and in rural areas,[102] which constitute most of the country, a power grid simply does not exist and the figure is just 2%.[103] Where grid power is available, it is expensive and extremely unreliable, with customers frequently cut off through involuntary 'load shedding'. To mitigate this risk most farms and businesses maintain backup diesel generators that are not only costly to run, they are subject to fuel shortages and environmentally unfriendly. Developing access to reliable electricity supply is clearly a long-term ambition, but creating a national transmission and distribution grid infrastructure based on large-scale centralised power generation may not be the most economically viable, sustainable and resilient solution. As an alternative, in common with much of Africa[3], Tanzania has abundant renewable energy resources in the form of solar, wind and hydro which could be harnessed locally for electricity generation to form the basis of community-scale power micro-grid infrastructure. In many cases this approach will likely prove cheaper, quicker to build and more resilient than installing long distance connections to a centralised national grid.

AGRICULTURE AND MAJOR EXPORT INFRASTRUCTURE

Tanzanian agriculture has many potential advantages. The country has abundant land and water resources; is politically stable; major investments in infrastructure are beginning to happen; policy is supportive and the Tanzania Agriculture Development Bank is due to open soon. Tanzania has an estimated 44 million hectares of arable land of which about a quarter is cultivated. Smallholders work about 14 million hectares in small mixed farms of less than 2 hectares each, while about 1,000 large commercial farms occupy another 1.5 million hectares.[104]

Tanzania produces roughly 1.7 million tonnes of fruit, 660,000 tonnes of vegetables and 9,400 tonnes of flowers per year.[105] The sector is growing at about 10% but lags far below its potential. The government has identified five priority areas for horticulture development, including the northern highlands around Arusha and Kilimanjaro, the southern highlands around Iringa and Mbeya, and the coastal zone. All are within a day's travel of Dar es Salaam, the country's largest port. However, the latter has serious capacity constraints caused by high traffic growth and poor links to inland transport networks, causing a major bottleneck for the national and regional economies. To help mitigate this problem, by 2017 a new US$11 billion Chinese-funded port will open in Bagamoyo, 37 miles northwest of the capital. This port will be able to handle 20 million containers a year, 25 times more than Dar es Salaam[106], and will be better integrated into the rail and road networks. The port will help establish Tanzania's position as an East African logistics hub, and has the potential to significantly expand intra regional trade – making Tanzania the gateway to a group of African nations including Zambia, Malawi, the Democratic Republic of the Congo, Rwanda, Burundi and Uganda. To make the most of these opportunties for access to high value markets in perishable products, the Tanzanian government recognises that in parallel with these developments the nation urgently needs to stimulate the deployment of cold chain technology.

COLD CHAIN INFRASTRUCTURE

The cold chain in Tanzania today is rudimentary to non-existent, but it is beginning to develop. There is cold storage for exports at Kilimanjaro airport, for example, but none at Dar es Salaam, though TAHA is looking for land on which to construct a facility. A few big farms and co-operatives have their own refrigerated reefers, and more will follow as the government builds out a planned network of cold storage centres around the country. Bakhresa Group, the regional food and logistics company, operates cold stores and reefers, and Unicool has quotations out to establish 15 cold stores at large farms.

The key barrier to adoption of cold storage is the inadequacy of the electricity supply infrastructure, in terms of cost, reliability, reach and scale. Tanzania produced a total of just 5.3 terrawatt hours (TWh) in 2011. For context, the UK, with a population roughly 40% larger, produced 365TWh the same year, almost 70 times as much.[107] Power is frequently rationed in Tanzania through 'load shedding', forcing farmers to power their operations with diesel generators. In Arusha, for example, capacity demand for electricity is estimated at 64MW, but the available power is rated at just 40MW–55MW.[108] TAHA reports that during five months in 2011, a group of 18 farms spent US$1 million on diesel for their generators.[85] The cost of diesel in Tanzania has roughly doubled since the millenium, from US$0.73 per litre in 2000 to about US$1.40 today. The average electricity tariff is about US$0.12/kWh.[109]

The situation is complicated by continuing problems at TANESCO, Tanzania's state-owned power firm. The firm has been hampered by insufficient capital, technological capacity, management issues, logistics and corruption. In 2008 Tanzania was awarded the largest ever Millennium Challenge Compact Grant of US$698 million to fund "electricity service and coverage through the addition of new power generation, transmission and distribution capacity, as well as through much needed reinforcement of the existing network." Unfortunately, despite strong support from the Millennium Challenge Corporation (MCC) and others, progress remains slow.

'TANK OF COLD' SOLUTION

In common with many sub-Saharan Africa countries[3], Tanzania does have excellent renewable resources and already obtains over 60% of its grid electricity from these, with good potential for solar throughout the country, hydro and wind in the highlands, and wind on the coast. For example, the annual means of solar radiation (insolation) range from 4.5–6.0kWh/(m^2 day) according to ground measurements. With small-scale solar photovoltaic technology viable at around 4kWh/(m^2 day) and larger installations viable at about 5kWh/(m^2 day), almost all of Tanzania is suitable for the deployment of solar technology.[110] In many cases utilisation of these resources will either need to be coupled with energy storage or back-up gas/diesel plants to provide reliable on demand output. Assuming that a cleantech approach is desired in preference to a fossil fuel based solution, then in some cases conventional batteries, flow-type batteries or PHES will be the best form of off-grid or micro-grid energy storage for utilisation of these resources. However, in many others where the logistics, technical requirements and economics make sense, and the additional benefits of the tank of cold solution are desired, they can be coupled with a cryogenic energy storage plant.

Given the availability of such a plant based on liquid air production, the focus of initial economic feasibility assessment is to understand the cost of the refrigerated transport step in a local context. In this regard, initial conservative modelling undertaken for this report of the operational costs for such a solution in Tanzania shows a liquefier with capacity to produce 300 tonnes per day, consuming 5MW of renewable sourced electricity for just six hours of solar availability per day, would produce 75 tonnes of liquid air for US$0.11 per kg. This compares to Tanzanian grid tariffs of about US$0.12/kWh (if a reliable grid connection is available, which is largely not the case) and diesel costs of US$1.37 per litre. It also found that the quantity of liquid air required by a cryogenic TRU to refrigerate 4 tonnes of pre-cooled produce on the 11 hour trip from Mbeya to Dar es Salaam would be just under 100kg, costing around US$11. By contrast, a standard refrigeration unit would consume at least 3 litres of diesel per hour to cool the same load, at a total cost of more than US$45. In other words the zero-emissions liquid air solution would be 75% cheaper than the business-as-usual diesel refrigeration approach. In this regard it is important to note that no account has been taken in these initial calculations of the effect of inflation, or the removal of government subsidies on the price of diesel (the future liquid air costs are, on the other hand, largely fixed for a 40 year period regardless). The capital cost of the vehicles, which was ignored in the calculation, would be almost identical.

The liquid air fuelled TRU can also deliver enough cold to cool farm produce from its ambient temperature down to its target temperature after loading on-board the vehicle, whereas a diesel reefer maintains the target temperature only once it has been achieved by 'pre-cooling' in a pre-cooling facility of a cold store. In principle, the 'tank of cold' solution could therefore dispense with the need for a pre-cooling room altogether as that function could be undertaken in the reefer after loading.

Table 2 shows the comparative cost of pre-cooling 4 tonnes of produce and refrigerating it during its journey to market or port in Dar es Salaam. The data presented compares three locations with different produce against three cold chain approaches: pre-cooling using grid-sourced electricity and transport in diesel powered reefer unit; pre-cooling using diesel gen-set sourced electricity and transport in diesel powered reefer unit; and pre-cooling and transport using the tank of cold solution based on liquid air (LAIR).

In all cases the grid pre-cooling is the cheapest option, however the basic premise of taking a tank of cold approach is that reliable grid electricity is frequently not available. When compared to diesel gen-set based pre-cooling the cost of the liquid air approach is roughly 50–60% cheaper, with the added benefits of zero emissions at point of use and zero carbon intensity because it is produced from renewables. In all three examples, total liquid air consumption is less than 600kg per truckload, which is modest compared to the 75 tonnes/day production assumed in the model. If it is also assumed that, say, ten truck deliveries are made per day during the early stages of such a project, pre-cooling and transport refrigeration would consume about 5 tonnes of liquid air per day, leaving about 70 tonnes for other community uses such as energy storage.

Table 2: Comparison of operating costs for three different crops, locations and refrigeration approaches.

	Apples	Passion fruit	Snap peas
Location	Iringa	Mbeya	Arush
Travel time to Dar es Salaam (hours)	7	11	9
Target temperature (°C)	0	7–10	0
Total cost, grid elec pre-cool then diesel (US$)	48.77	61.71	57.74
Total cost, diesel pre-cool then diesel (US$)	131.52	131.52	143.85
Total cost, LAIR (US$)	76.4	64.3	81.1
LAIR required (kg)	573	473	594

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THE ROBUSTNESS OF THE RURAL-URBAN FOOD CHAIN WILL BECOME CENTRAL TO AFRICAN FOOD SECURITY.

View over the city of Dar es Salaam, Tanzania, Africa.

A FOCUS ON ARUSHA

One major agricultural centre that could benefit from the tank of cold approach is Arusha, in the northern highlands. Small farms growing mixed crops predominate in the area, as in nearly all developing countries, but there are also about 110 large commercial farms, which hire dozens to hundreds of labourers depending on the time of year. There are two rainy seasons (short rains, long rains) and a wide range of crops is produced, including many vegetables. About 20% of produce is exported, mostly via Kenya to the EU, and exported crops include snow peas, snap peas, french beans, baby squash, chilies, capsicum peppers, and cut flowers.[111] A few companies run their own reefers, and ship mostly cut flowers and fresh vegetables. The region is also a tourist destination and, as is often typical across Africa in these cases, the frozen and dairy products that are important to the trade, such as ice cream, yoghurt and butter, are shipped in by reefer from Dar es Salaam or Nairobi.

Like almost everywhere in Tanzania, the region suffers crippling electricity shortages. Estimated peak demand for electricity in Arusha is 64MW, but the available power is just 40MW–55MW. Cryogenic energy storage combined with local power generation from renewable resources offers a route to mitigation of this problem as well as enabling many other services to be delivered to Arusha. Using the same assumptions as in the transport calculations above for a liquefier with capacity to produce 300 tonnes per day, consuming 5MW of renewable sourced electricity (solar) over just six hours per day, the intial modelling undertaken for this report suggests that the liquid air solution for energy storage will be cheaper, at US$1.06/kWh, than a conventional battery at US$1.38/kWh. If the availability of cold output in addition to electricity is taken into account the economics become even more attractive. In this regard, for a plant delivering roughly the same amount of power and cooling per day (560kW of electricity for eight hours and 0.2MW of cooling 24/7, which is more than sufficient for the anticipated needs of Arusha), the liquid air plant is more than 40% cheaper than batteries and very nearly matches the current typical diesel gen-set approach (assuming diesel is available through a reliable supply). Again it is important to stress that these initial calculations are based on conservative assumptions and do not account for future diesel price increases or removal of fossil fuel subsidies.

Colocating the liquid air plant with a centralised cold store would make reliable storage available to farmers from the surrounding area for fruit, vegetables, milk or flowers. The produce could be collected from the farms by a truck with liquid air pre-cooling, stored in the warehouse, and then transported on to market, port or airport in another cryogenic TRU cooled refrigerated truck. Other lower tech approaches suitable for small-holders, such as evaporative coolers (reduce temperature of produce by 10°C to 15°C below ambient, and so extend the life of the crop by days or weeks, but cannot achieve the lower temperatures (0°C or below) required by a modern cold chain),[112] could be integrated in the liquid air based cold chain.

If an effective and economic cold chain could be established based around a local liquid nitrogen or liquid air plant, the impact could be transformational. Many more crops could be handled with better results, lower losses and improved quality and food safety. The produce currently being grown for the domestic market, including tomatoes, cabbage, lettuces, spinach, peppers, potatoes, would benefit greatly. This in turn could open up new markets, including the supermarkets, hotels, restaurants and conference centres located in the region that currently import food to ensure its safety, as well as make possible new processes such as freezing or freeze-drying to extend shelf life and increase the market value of produce.

THE NEXT STEP: ‘REPORT TO REALITY’

Tanzania has very little industrial gas production capacity, but it does have some. TOL Gases runs a 30 tonne per day liquefier in Dar es Salaam, which has surplus nitrogen capacity. The company believes that liquid nitrogen from this source could be delivered from Dar es Salaam to centres such as Arusha to support early field trials of the tank of cold approach. Additionally, the National Artificial Insemination Centre (NAIC) operates small liquefiers in the main agricultural towns, including Arusha, for liquid nitrogen supplies in veterinary uses, which also have potential for helping with small scale trials. The next step is a detailed feasibility study to assess the potential for field trials of cryogenic transport refrigeration in Arusha and Dar es Salaam. Key partners committed to the project include the Postharvest Education Foundation, TAHA, Africare, TOL Gases, Azam, World Vision, Tanzania Academy of Science and Technology, the University of Dar es Salaam and the Tanzanian Government. McLarty and DEC will pursue funding channels for the study from donors and investors; TOL Gases will supply liquid nitrogen and DEC engineers will provide technical support.

Tuk-tuks in a busy street at Hyderabad, India.

CASE STUDY: INDIA

India, the world's second most populous country and fourth biggest economy, is a study in contrasts. After almost two decades of 7% growth, the country has become a global leader in IT and business outsourcing, which occupies a third of the workforce but produces two thirds of its output, while agriculture employs more than half the workforce yet generates less than a fifth of national income. Almost 30% of the population live below the poverty line, while a growing urban middle class enjoys increasing affluence and developed economy lifestyles. Town and country are connected, or separated, by a highly inefficient supply chain that results in as much as 40% of produce being lost before ever reaching the consumer,[26] which raises retail prices while suppressing rural incomes. Rural destitution is one major cause of migration from the countryside to the cities. At the same time, investment in cold chain infrastructure is now booming to cater to the tastes of the urban middle class, but because it relies on conventional fossil fuel based energy infrastructure it is likely to worsen the already severe smogs in India's cities, with consequences for human health. The key challenge is to incentivise redirection of this investment to cleantech based sustainable cold chain infrastructure and encourage joined up thinking for a broader cold economy.

AGRICULTURE

India is the world's largest producer of milk, and second only to China in fruit and vegetables. Yet agriculture, which occupies 53% of the workforce, generates just 15% of GDP.[113] India is a huge exporter of grains, but exports very little horticultural produce: of total agricultural exports of US$37 billion, fruit and vegetables account for just US$1–1.5 billion.[114] One reason is that up to 50% of produce can be lost before reaching the consumer at a cost of some US$4.5 billion.[21,22]

Farming in India is dominated by smallholders working plots of less than 1 hectare who sell their produce through a serpentine supply chain involving many layers of middle men.[115] There are often between 6 and 8 intermediaries between an Indian farmer and the end consumer[116], with the result that the producer often receives just 30% of the price paid by the consumer[117], compared to as much as 70% in the USA.[118]

This is one reason farming incomes in India are precarious, and poverty is largely rural; two thirds of the 250 million below the poverty line live in the countryside.[119] A government inquiry in 2006 found that 40% of Indian farmers wanted to quit farming,[120] while more than 240,000 of them, mostly crippled by debt, committed suicide between 1995 and 2009.[121] Urban poverty is rising in part because of the migration of the destitute from villages to cities.[119] The government has introduced policies intended to combat rural destitution, including flagship programmes such as the National Rural Employment Guarantee, and the Rural Livelihoods Mission.

One way to help change the low income levels to farmers would be to invest in cold chain infrastructure. This should increase the food supply, reduce final prices and increase farmers' incomes by raising the proportion of their harvest to reach market. Depending on the type of crop, cold chain has been shown to save an additional 25% to 50% of the harvest. But to achieve this outcome will require government to work to resolve the multiple intermediary nature of the Indian supply chain.

Aggregating fresh produce from multiple farm gates also presents a challenge, because in hot climates, each one hour delay between the picking and cooling of highly perishable produce can shorten shelf life by as much as a day. But if creating a cold chain can help raise smallholder incomes, it might go some way towards providing the 'good' rural jobs that are needed to slow migration to the city.

COLD CHAIN INITIATIVES

The Indian government clearly recognises the value of cold chain, which it has designated a ‘sunrise sector’. Sharad Pawar, Agriculture and Food Processing Minister, recently told parliament that 40% of produce is wasted in India each year, and that only setting up more large cold stores would improve matters.[26] The government subsidises as much as 50% of the capital cost of a cold chain project[77], and grants 75% in difficult regions, up to a maximum of 10 crore rupees, approximately US$1.6 million.[122] Eligible investments include plastic crates, packing houses, pre-cooling facilities, cold storage and refrigerated vehicles.

Yet India’s cold chain falls far short of what is needed. According to the National Centre for Cold Chain Development (NCCCD), there are currently 6,488 cold stores in India with a total capacity of 30 million tonnes, which is 36 million tonnes short of estimated demand, and the market is expected to quadruple by 2020.[64] The NCCCD also estimates the country needs another 17,000 refrigerated lorries, although this number seems not to take account of likely future growth, given the huge size of the potential market.

Cold storage and refrigerated transport infrastructure is patchily distributed across the country, leaving many regions with no effective cold chain. Uttar Pradesh, one of 28 Indian states, has almost a quarter of the total cold storage facilities[123] and 75–80% of Indian refrigerated warehouses are suitable only to store potatoes, a commodity that produces only 20% of agricultural revenue. As a result only 4 million of the 104 million tonnes of fresh produce transported in India every year does so in a cold chain. This proportion, less than 4%, compares unfavourably with the developed economies, where typically between 85–90% of fresh produce is transported cold.[124] Additionally, many cold stores in India are not properly insulated, meaning their energy consumption is three times higher than those of similar capacity in the developed countries.[64]

CHALLENGE OF URBANISATION

Diets are changing rapidly in India as incomes rise and urbanisation increases. Surveys show that consumption of cereals in urban areas has fallen, while consumption of fruit, vegetables, fish, meat and milk has increased.[125] To satisfy these new tastes, companies are investing billions in gaining access to these new markets, and one major brand, Reliance Retail, is growing at 19% per year.[126] By 2016, India will become the world’s third largest grocery sector, worth $566 billion[127], and this is projected to continue to grow rapidly.[128]

Since current cold chain technologies rely on a largely fossil fuel based power grid infrastructure and diesel, their growth will increase carbon emissions and air pollution in India’s cities. PM10 levels in Delhi often reach 15 times those of Edinburgh[129], and air pollution caused 620,000 premature deaths in 2010.[130] India’s carbon dioxide emissions from transport of 185MtCO_2 in 2010 are projected to grow 10-fold by 2050.[131] So while India needs investment in cold chain to help connect producers efficiently to emerging urban market opportunities, its current deployment model will likely cause significant environmental degradation and risk. A new model is required, and one way India might develop cold chains without these drawbacks could be to invest in a holistic cryogen based solution including motorised three wheeler ZEVs for last mile delivery.

CRYOGEN – EXISTING INFRASTRUCTURE

In rapidly industrialising countries such as India, there is already extensive energy infrastructure to support the initial capability and capacity building needed for development of a cryogen based cold chain. India has a relatively large industrial gas sector, with estimated spare liquid nitrogen (LiN) production capacity of about 3,500 tonnes per day that could be used.[81] In principle 3,500 tonnes would be enough to power refrigeration on 29,000 refrigerated lorries, more than the immediate unmet need estimated by the NCCCD.

Existing ASUs are well distributed around major industrial centres, particularly New Delhi and Mumbai (see map, **Figure 5**) and, if the national surplus is also relatively evenly distributed, this could form the supply 'fuel' for an extensive cold chain. Any blast freezing facilities at food processing plants, which would already be supplied with large quantities of liquid nitrogen, could potentially extend the distribution network.

The delivered cost of liquid nitrogen in India is reported as US$0.175 per kilogramme, although this is likely to fall with bulk supply. The price of diesel in Delhi, Mumbai, Chennai and Kolkata averaged about 60 rupees per litre in early March 2014. Fuel subsidies of around Rs 8 per litre are expected to be withdrawn soon,[132] taking the likely price to about Rs 70 or US$1.15. Electricity tariffs for non-domestic users average about US$0.08/kWh.[133] Initial conservative modeling on the basis of these figures suggests refrigerated transport in India could be a third to a half cheaper than diesel based refrigeration (**Table 3**).

If the pre-cooling phase is included, it would be much cheaper to pre-cool using grid electricity whenever available rather than liquid nitrogen, but if reliable grid electricity is not available, as is often the case in rural India, and the alternative is pre-cooling powered by diesel generator, liquid nitrogen would be the cheaper option.

The delivered price of liquid nitrogen in India may currently be inflated by high distribution costs due to the country's poor road system, and these costs could be reduced if cold stores were colocated with industrial gas production plants or at least sited close to them. Costs could also be reduced in future if plants were built to produce liquid air rather than nitrogen, since this requires 20% less energy. In the meantime, however, costs could be cut substantially if liquid air production were colocated with India's LNG regasification plants, where exploiting the waste cold given off during LNG regasification would reduce the energy required for nitrogen production by two thirds.

Table 3: Cost comparison for pre-cooling and lorry transport using three different refrigeration approaches.

	Apples	**Passion fruit**	**Snap peas**
Location	Delhi	Mumbai	Hyderbad
Travel time (hours)	12	12	12
Target temperature (°C)	0	8	0
Total cost, grid elec pre-cool then diesel (US$)	65	60	66
Total cost, diesel pre-cool then diesel (US$)	131	116	135
Total cost, LiN (US$)	116	95	120
LiN required (kg)	662	544	688

SYSTEMS APPROACH IN URBAN SETTING

The tank of cold solution would look very different in a rapidly industrialising nation such as India, when compared with the newly emerging economy example of Tanzania, because the country already has so much relevant infrastructure. Developing the approach would in this case be less about starting from scratch, and more about integrating effectively with existing plant and systems. At the same time, the sheer size of a country such as India means the distance between some agricultural regions and centres of demand is challenging, while acute air pollution in cities demands an urgent response. These considerations suggest to the Institution that systems thinking and cryogen ought first to be applied to urban transport refrigeration, rather than attempting to create an end-to-end cold chain. From this starting point once capability and capacity have been built, they could then expand into an alternative 'tank of cold' delivery model that would mitigate not only air pollution but also congestion. This is not to say that a cryogen cold chain could not extend as far back as the farm gate, but that this would make more sense in regions where production of perishable crops coincides with industrial gas production such as Gujarat, Himachal Pradesh or Hyderabad.

In the first instance, wherever food processors use liquid nitrogen for blast freezing food, distributing this food with LiN refrigerated transport would, from an engineering perspective, be a relatively straightforward 'bolt-on' incremental solution. It would also make sense where conventional pre-cooling and cold storage already exists in or near cities; the cost of cryogen refrigeration equipment should be almost identical, and the 'fuel' costs would be a third to a half lower than diesel. The retailer or distributor need only install a liquid nitrogen tank and refuelling pump and sign a contract for regular deliveries of cryogen.

This could be a good fit with the approach already being taken by the many retailers who are setting up 'peri-urban' food collection centres to rationalise their supply chains. In future these centres could be located within delivery distance of a nitrogen liquefier, or perhaps even co-located at the plant, to allow pre-cooling and cold-storage as well as transport refrigeration with liquid nitrogen. For example, there is a cluster of these collection centres around Vontimamidi, a village fifty km north east of Hyderabad (**Figure 5)**, where retailers such as Reliance, ITC, Spencers and Heritage have set up facilities to sort and pack up to 90 tonnes of food per day from 14,000 local farmers for delivery to stores in the city.[134] Hyderabad has a 100 tonne per day liquefier which could provide nitrogen for cooling.

This kind of approach would eliminate air pollution emissions from transport refrigeration, but increasing urban truck and lorry traffic would still be a problem in the context of Indian cities, where congestion is already severe. A report from McKinsey found that in Mumbai, for example, the number of vehicles per lane kilometre at peak times reaches 375, more than three times the recommended maximum, and that India would need to increase its urban road capacity by 50% to aleviate congestion by 2030.[135] At the same time, urban retailing around the world is shifting away from large supermarkets towards smaller convenience stores, which may need to be resupplied by last mile delivery vehicles as many as eight times per day. For Indian megacities, this suggests the potential for a new delivery as well as a refrigeration model.

If food were refrigerated or frozen at centres some distance from the city, instead of being delivered direct to large supermarkets in the city centre, it could be sent in refrigerated reefers cooled with cryogen fuelled TRUs to a distribution point on the outskirts of the urban area. Here the food could be collected by auto-rickshaw (tuk-tuk) with onboard refrigerated compartments for delivery to smaller convenience stores, and potentially individual homes. The tuk-tuks would be ZEVs both powered and refrigerated by cryogen, either liquid air or nitrogen, which could be drawn down from the main deliver lorry at the same time as collecting payload. Being smaller and faster, these tuk-tuks ought to reduce congestion compared to the conventional approach of sending trucks and lorries through city traffic. Initial calculations have shown that such vehicles fuelled with liquid nitrogen would be about US$3,000 cheaper to purchase than a battery powered model and though they are slightly more expensive to run (about US$110 per year) because refuelling could be undertaken from the food produce delivery vehicle they would not place demand on already hard pressed (largely fossil fuel based) urban electricity grid infrastructures.

Once this model were established, cryogen powered tuk-tuks could go on to have an even wider impact. Auto-rickshaw taxis are an integral part of the Indian public transport system, and the authorities see them as essential to curbing congestion.[136] In cities such as Delhi and Mumbai, auto-rickshaws are currently prohibited from the centre because of emissions and there is explosive growth of private car ownership. A cryogen powered three wheeler taxi would be zero emissions, and able to provide air conditioning effectively for free, which might encourage restrictions on their use to be lifted and transform their perception by the Indian travelling public.

This could also apply on a larger scale for buses and other forms of mass transit, which in India are massively overcrowded (the McKinsey report found that on public transport the number of people per compartment during peak times is 500, two and a half times more than the recommended maximum).[135] Clearly India needs to invest in more buses and trains, but if it does so without air conditioning, people may still prefer to negotiate traffic jams by car. Again, a bus powered by a diesel-liquid air 'heat hybrid' could provide air conditioning effectively for free while reducing diesel consumption.

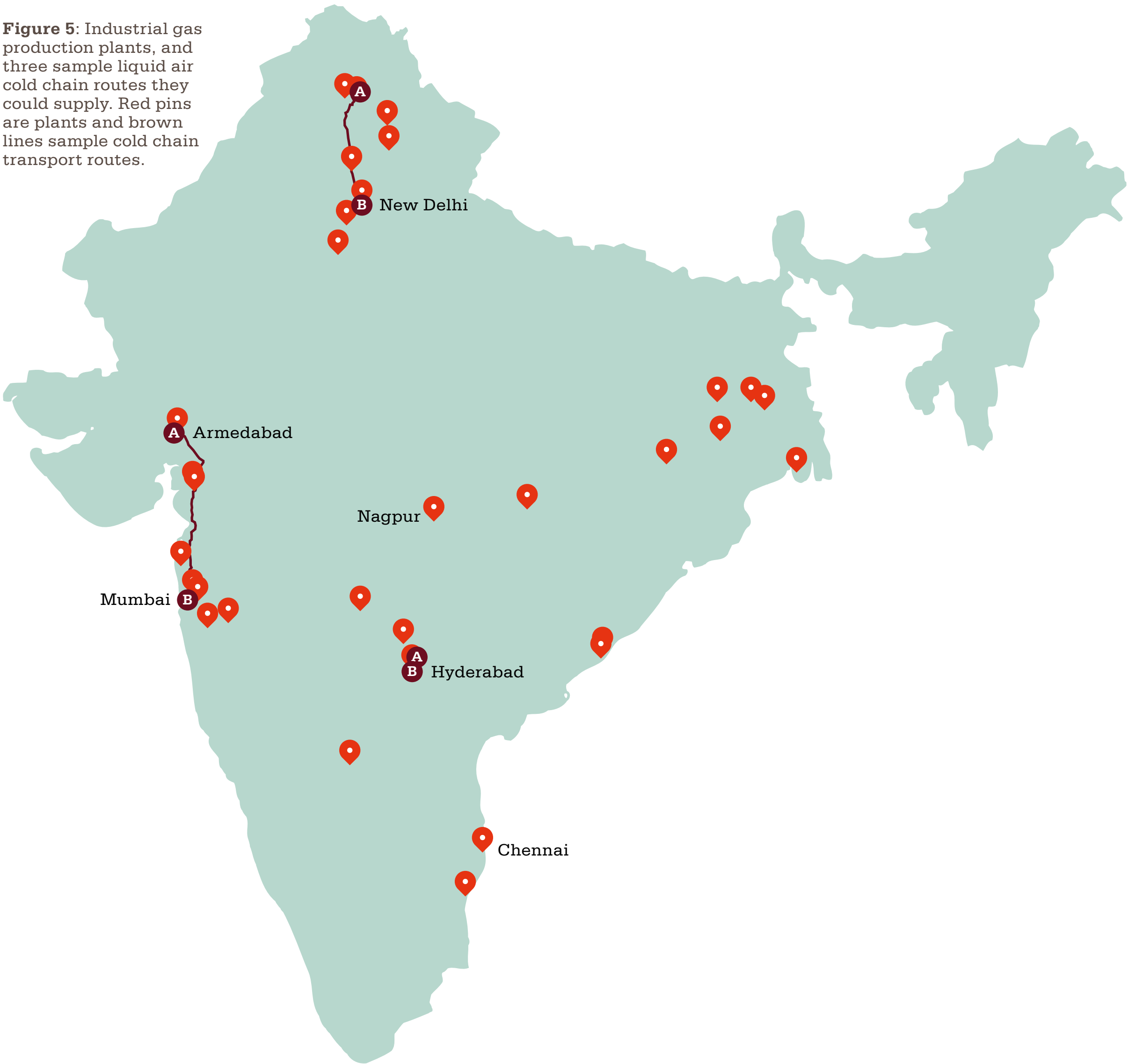
LONGER DISTANCE COLD CHAIN SYSTEM

In large and rapidly industrialising countries the tank of cold solution may, as described here, initially have an urban focus, but it could also deliver an end-to-end cold chain in regions with adequate numbers of industrial gas plants. **Figure 5** shows the distribution of nitrogen liquefaction plants (red pins) in India and two sample cold chain routes, as well as the Hyderabad example mentioned above.

The map includes only 'merchant' and 'onsite' industrial gas plants producing liquids; it excludes 'captive' plants, where a single customer consumes all of the output.

One potential route would transport apples from the orchards around Shimla in the highlands of Himachal Pradesh to market in Delhi. This trade already happens but produce is almost never refrigerated, and often carried in open loads. The trip could be made in a single day, the route is 370km and a mapping tool suggests it would take six hours, but for the case study this has been doubled to allow for local realities. The produce could be refrigerated using liquid nitrogen obtained near the start of the route. Another major fruit producing region, Gujarat[137], could supply Mumbai with mangoes, bananas, papayas and many other kinds of high value fruit, refrigerated with liquid nitrogen produced in Ahmedabad. The route is 500km long and could also be travelled in a single day.

Figure 5: Industrial gas production plants, and three sample liquid air cold chain routes they could supply. Red pins are plants and brown lines sample cold chain transport routes.



GREENHOUSE GAS EMISSIONS AND LARGE-SCALE INTEGRATION

The carbon intensity of India's electricity grid is high, at about 1.3kg $C0_2$/kWh[138], compared to about 500g/kWh in the UK, and this would inevitably be reflected in the carbon intensity of cryogen produced from it. The mix of generating technologies is unlikely to improve grid carbon in the short term: India plans to add 22GW of power generation from renewable resources by 2017 under its 12th Five Year Plan[139], but more than three times as much coal.[140] However, the carbon intensity of cryogen could still be improved by improving the efficiency of the grid, or the efficiency of liquefaction or both.

The Indian electricity grid is extremely inefficient, and loses 30% of its power during transmission on average[141], compared to about 6% in the UK. But this means improvements could be achieved: Gujarat reduced its electricity losses from 30% to 21% in just three years from 2005 to 2008, for example.[142] Clearly there are opportunities to improve efficiency both in Gujarat and throughout the country.

Perhaps more significant in the short term, the emissions from existing cryogen production can be improved not only by cutting the carbon intensity of grid electricity, but also by reducing the quantity of energy required to produce the liquid. As noted above, liquid air requires 20% less energy to produce than liquid nitrogen, and utilising the waste cold given off by LNG regasification would reduce the energy needed for air liquefaction even more significantly. If India were to use LNG waste cold for air liquefaction, the liquid air produced would have a lower carbon intensity than the liquid nitrogen currently produced in the UK, and applications such as refrigerated trailers and heat hybrid buses with air conditioning would deliver immediate though modest well-to-wheel CO_2 savings.

Where LNG import terminals are close to major cities such as Mumbai, the waste cold could be used not only to produce liquid air transport fuel, but also to provide cooling for data centers or refrigerated warehouses, which could be colocated with the LNG terminal to take advantage of the enormous energy savings. India's imports of LNG are expected to rise five-fold to around 60 million tonnes per year in 2022.[94] In principle, the regasification of 60 million tonnes of LNG would give off enough cold to produce almost 22 million tonnes of liquid air, enough to fuel over half a million truck refrigeration units, or 230,000 heat hybrid buses or 1 million tuk-tuks.

THE NEXT STEP: 'REPORT TO REALITY'

India is on the brink of a large-scale investment in cold chain infrastructure, which, if the nation pursues the business-as-usual approach, will contribute further to the country's severe urban pollution. But this need not happen. A cryogen based approach presents an opportunity to develop not only vital cleantech based sustainable cold chain infrastructure, without the inevitable drawbacks of diesel-based refrigeration, but also a much broader range of zero-emissions cold and transport services that could be described as the beginnings of a cold economy.

India has already seen the substantial impact on transport emissions from a rapidly expanding urban population. The growth in urban middle classes will lead to a major increase in demand for cold chains and urban refrigerated vehicles; not just to meet the core demand for food, but also the proliferation of convenience products and changed dietary preferences. The challenge is not just how to meet the growth in refrigerated transport and manage emissions, but also how to deliver food produce into grid-locked city centres; especially to meet the projected new demands of e-commerce, which is often time specific as to delivery. Within this, is the parallel challenge of rising land costs where city centre food warehousing cannot compete for space versus new residential, retail or office space.

A practical initial route to a successful outcome is to apply a systems approach and begin building capacity and capability for development of a cryogen based cold chain in India using existing surplus nitrogen capacity, located in industrial cities. In these deployments, reefers cooled using nitrogen fuelled TRUs will bring food into the range of the city centres where fleets of driver-owned cyrogen fuelled tuk-tuks will facilitate the last mile delivery. The next step is a detailed feasibility study to assess the potential for field trials of cryogen fuelled tuk-tuks with onboard cooling and to gain commitment from an Indian manufacturer to produce the cryogenic engines. Key partners including McLarty and DEC will carry out the assessment of the potential and practicality of the approach, as well as pursue funding channels for the project, and at least one Indian engine manufacturer has expressed an interest in producing the cryogenic units.

DEFINITIONS

ACRONYMS

ASU – air separation unit

CO_2 – carbon dioxide

GW – gigawatt

GHG – greenhouse gas

HCV – heavy commercial vehicle

kW – kilowatt

kWh – kilowatt hour

LAIR – liquid air

LiN – liquid nitrogen

LNG – liquefied natural gas

Mt – million tonnes

$MtCO_2$ – million tonnes of CO_2

MW – megawatt

MWh – megawatt hour

NGO – non-governmental organisation

NOx – mono-nitrogen oxides NO and NO_2

PHES – pumped heat electrical storage

PM – particulate matter

PV – photovoltaic

R&D – research and development

TPD – tonnes per day

TRU – transport refrigeration unit

TWh – terrawatt hour

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

ZEV – Zero-emission transport vehicle

TECHNICAL TERMS

Air separation: process in which air is cooled and the components are selectively distilled.

Ambient heat/temperature: the temperature of the air surrounding a piece of equipment or plant.

Carbon intensity: grams of carbon dioxide released per kWh of energy produced.

Cleantech: a portmanteau of ‘clean technology’. Describing an energy or process that is zero-emission or actively trying to decrease its environmental impact.

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

Cold economy: the combined, connected commercial activity that deals with cold as a commodity.

Cryogenic fluid: a fluid below –150°C, –238°F or 123K.

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

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

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

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

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

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

Micro-grid: a modern small scale localised electrical system that links distributed energy sources to consumers.

Natural capital: the stock of natural ecosystems that yield a future flow of ecosystem goods and services.

Off-grid: not being connected to a grid, often, but not always, associated with not being connected to a centralized or national electricity generation, transmission and distribution system.

Peri-urban: used to describe an area immediately adjoining an urban area, often found between the suburbs and the countryside.

Power: rate of doing work, unit is Watt (W).

Regasification: the process in which a liquid becomes a gas.

Reefer: refrigerated trailer or shipping unit.

Renewable: term used for an energy source that is naturally replenished on a human timescale (eg solar or wind power); *pl*. renewables.

Tuk-tuk: motorised three wheeled cabin rickshaw used extensively in developing countries for local transport, either as private vehicles or public transport.

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

Zero emission vehicle: a vehicle which produces no emissions such as PM or NOx.

PHRASES

Cleantech leapfrog: a low-carbon technology established as the basis for a new process or system (rather than replacing an existing technology which does the same job).

Last-mile delivery: the final stage in the delivery of produce in a supply chain, often involving transfer of goods from a transport hub to the retail outlet or home.

'Wrong-time' energy: energy produced by renewables that is not used due to lack of demand.

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The Institution of Mechanical Engineers would like to thank the following people and organisations for their assistance in developing this report:

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Tanzania – Workshop

- Africare
- Bakhresa/Azam
- Embassy of Finland
- Hortanzia
- Kiliflora Limited
- McLarty Associates
- TAHA Fresh
- Tanzania Academy of Science
- Tanzania Commission for Science and Technology
- Tanzanian Horticultural Association
- Tanzanian Prime Minister's Office/Ministry of Agriculture, Food Security and Cooperatives
- Tol Gases Limited
- Unicool
- University of Dar es Salaam
- USAID
- World Vision, Kenya
- World Vision, Tanzania

India – Workshop

- Anna University
- Automotive World
- Danfoss
- INOX AP
- Power Systems Research

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