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

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30 June 2014



Liquid Air
Energy
Network

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

Foreword

Feeding the world to 2050 and beyond presents a massive challenge. As the population rises inexorably towards 9 billion, and the global middle class swells by some 3 billion, it's estimated that demand for food will rise by 70% by the middle of the century. That demand cannot be satisfied sustainably by relying on the same old wasteful, resource-intensive approach. Global agriculture needs an entirely new paradigm to reconcile rising demand and the environment – and liquid air could be a vital part of it.

Modern farming has achieved huge advances in productivity, yet close to a billion people still experience hunger while 1-2 billion tonnes of food go to waste every year. In the developing world, 30-50% of perishable food rots before ever reaching a plate, meaning the land, water, fertilizer and labour used to produce it has also been squandered. All these resources could be better conserved if developing countries had a sustainable 'cold chain' of refrigerated warehousing and transport to preserve the quality of food from farm to fork.

Cold chains are rapidly expanding in the megacities of the developing world, where investment is booming to cater to the tastes of the emerging urban middle class. But these are powered by highly polluting diesel Transport Refrigeration Units, which only worsen the chronic and highly toxic smog that blankets cities like Beijing and Delhi. Outside air pollution caused 600,000 premature deaths in India alone in 2010.

This paper explores how liquid air could provide an affordable, zero-emission and sustainable cold chain for emerging economies such as Tanzania and rapidly industrialising ones like India. The paper was prepared by Lisa Kitinoja of the Postharvest Education Foundation and is published by the Liquid Air Energy Network in support of A Tank Of Cold: Cleantech Leapfrog To A More Food Secure World, a report by the Institution of Mechanical Engineers.

Liquid air has recently emerged as a new energy vector that stores renewable energy as both power and cold, which makes it particularly efficient as a refrigeration 'fuel' – providing two bangs for one buck. Liquid air is easy to store and transport, making it suitable for both static and mobile applications, which in turn means it could provide an entire cold chain from farm to fork, with no exhaust emissions from refrigeration at any point, and which could be entirely powered by renewable energy. Liquid nitrogen, which can be used in the same way as liquid air, is already widely available as a commodity industrial gas.

This paper investigates the business case for various possible applications of liquid air against a conventional cold chain powered by grid electricity – where available in the developing world - and diesel where it is not. The paper does not consider batteries, which store only power and not cold, and so do not offer the same energy density when the primary purpose is cooling.

The paper finds that liquid air cold chain technologies would in all cases reduce postharvest food losses, raise farmers' incomes and improve air quality. The competitive position of liquid air compared to diesel depends on the specific application, but liquid air is quite often cheaper than diesel – sometimes by 25% or more – meaning the environmental benefits are free. Where liquid air is the more expensive option, it is often still extremely

cheap and would repay its investment in avoided food losses many times over. In some circumstances liquid air transport refrigeration is capable of pre-cooling crops in transit, which standard diesel refrigerators cannot deliver.

Even where liquid air is more expensive than diesel today, it could easily undercut fossil fuels in future. In rapidly industrialising economies, where liquid nitrogen is already widely available, there is enormous scope for competition and technology development to reduce prices. The price of liquid air in rural regions, where it would be produced from renewable energy such as solar, depends almost entirely on the capital cost, meaning it is essentially fixed for the lifetime of the equipment – 40 years for an air liquefier. The cost of solar panels has plummeted over the past decade while the price of diesel has risen dramatically and is likely to keep on rising, driven both by the price of oil and the withdrawal of fuel subsidies.

The sheer scale of cooling demand is only now beginning to be recognised within the energy debate, and the full potential of liquid air as an economic and sustainable solution starting to be explored. Liquid air could not only provide refrigeration in an individual location or vehicle, but also a complete, end-to-end cold chain. This would not only help to expand the food supply, but could also improve health by preserving medicines; in India, inadequate cold chain means up to 70% of vaccines can be lost during distribution on certain routes

Nor is the potential of liquid air – and its combination of cold and power - limited to cold chain: other uses include food processing; power and cooling within the built environment; and transport fuel for zero-emission and 'heat hybrid' vehicles. As these applications are developed, what starts as a liquid air cold chain could develop into a much broader 'cold economy', to achieve major reductions in cost, carbon and air pollution.

The cold chain itself may seem a rather narrow and specialist corner of the environmental debate, but even here the potential human and environmental benefits are enormous. As this paper explains, halving postharvest losses in developing countries would provide East Africa with 15 million tonnes of additional food per year, and South Asia almost 73 million tonnes. The task of developing a sustainable cold chain could not be more urgent; luckily it is now in reach.



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30 June 2014

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

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30 June 2014

Executive summary

This paper was prepared by Lisa Kitinoja of the Postharvest Education Foundation and published by the Liquid Air Energy Network in support of *A Tank Of Cold: Cleantech Leapfrog To A More Food Secure World*, a report of the Institution of Mechanical Engineers.

The purpose of this ancillary paper is to demonstrate potential impacts of liquid air refrigeration technologies in cold chain applications in emerging and rapidly industrialising economies. The impacts assessed include reduced food losses; improved food security; job creation, value addition and wealth generation in the countryside; and reduced fossil fuel import dependency and urban air pollution.

The paper first evaluates the importance of refrigeration in reducing postharvest food losses and describes the range of cold chain technologies available, and then analyses the potential of liquid air through case studies of Tanzania and India.

The paper finds that liquid air cold chain technologies would in all cases reduce postharvest food losses, raise farmers' incomes and improve air quality. The competitive position of liquid air compared to diesel depends on the specific application, but liquid air is quite often cheaper than diesel – sometimes by 25% or more. Where liquid air is the more expensive option, it is often still extremely cheap and would repay its investment in avoided food losses many times over. In some circumstances liquid air transport refrigeration is capable of pre-cooling crops in transit, which standard diesel refrigerators cannot deliver.

The fuel price assumptions in this paper are conservative; no account has been taken of likely future increases in the oil price, nor of the potential to reduce liquid air or nitrogen prices through competition, technology development and economies of scale.

The paper concludes by calculating the millions of tonnes of additional food that could be provided with no extra production if postharvest losses in developing countries could be reduced from a conservatively estimated 30% to 15%.

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Much of the developing world lacks cold storage and refrigerated transport.

Introduction

Global food losses recently have been documented to be in the order of 25% to 50% of production volumes, caloric content and/or market values depending on the commodity (Lipinski et al, 2013; Gustavsson et al 2011; IIR 2009). A great number of organizations, including the Institution of Mechanical Engineers (IMechE), World Resources Institute (WRI), Rockefeller Foundation, Bill and Melinda Gates Foundation (BMGF), Alliance for a Green Revolution in Africa (AGRA), International Development Research Center (IDRC) and the UN Food and Agriculture Organization (FAO) are currently studying this enormous problem of postharvest food losses. The UN FAO launched the SAVE FOOD initiative in October 2013 (http://www.fao.org/save-food/en/) with more than 150 partner organizations. The website http://worldfoodclock.com/ provides a count of food losses per second, along with their associated losses of water and energy resources, based upon the 2013 publications FAO "Food Waste Footprint" and IMechE "Global Food Report".

Much of the developing world in general lacks access to affordable refrigeration systems for pre-cooling, refrigerated transport, cold storage, or freezing during postharvest handling and distribution of perishable foods. As a consequence, developing countries tend to lose 40 to 50% of their total production of horticultural crops, fresh fish, milk and dairy products before consumption (Gustavsson et al, 2011). These food losses occur mainly during the period from harvest to retail marketing and are due to changes in physical volume (i.e. weight loss, decayed or damaged and discarded foods) or economic value (i.e. quality losses due to poor appearance or color changes), and often result in loss of nutritional value, shorter shelf life and/or compromised food safety between the time of harvest and final retail marketing.

The use of "cold" handling and storage systems as an investment to prevent perishable food losses is widely used in developed countries and can be highly cost effective compared to continually increasing production to meet increasing demands for these foods. The use of cold technologies in the development of agricultural supply chains for meat, dairy, fish and horticultural products in the USA and EU countries began with the use of natural ice, and increased dramatically in the early 1950s along with the growth of the mechanical refrigeration industry, but cold chains are still limited in most developing countries.

For the purposes of this report, and with a liquid air refrigeration engine starting on-vehicle testing in the UK this summer and scheduled to move into low-volume manufacture by 2016, let's imagine a world in the near future where a variety of sizes of cryogenic piston engines are being manufactured. Let's also imagine – since all major economies, including India, South East Asia, have a well-developed industrial gas industry - that the energy and industrial gas sectors have the support of policy makers to develop new energy options for rural areas using a liquid air "Tank of Cold" as an energy vector. Let's further imagine – since many cities in the rapidly industrialising economies are within easy delivery distance of a liquid nitrogen plant – that a potential user of a commercial vehicle equipped with a cryogenic engine could drive up to a commercially operated fueling station and fill up their insulated storage tank with 100L of liquid air at a price that is competitive with other local energy options. And let's finally assume that farming villages around the world could install a 10,000 L liquid air storage tank to be refilled via small (30 to 75 tonnes/day) local liquefaction plants powered by renewable energy sources such as solar, wind, geothermal or hydro power. With the stage set, let's consider just a few examples of the many potential uses of liquid air based refrigeration technologies for the development and use of the cold chain.

Table 1: The Cold Chain, Food Security and Economic Development

Variable	Global	Developed countries	Developing countries
Population in 2009 (in billions of inhabitants)	6.83	1.23	5.60
Population in 2050 (forecast, in billions of inhabitants)	9.15	1.28	7.87
Refrigerated storage capacity (m^3/1000 inhabitants)	52	200	19
Food losses (all products)	25%	10%	28%
Losses of fruits and vegetables	35%	15%	40%
Losses of perishable foodstuffs due to lack of refrigeration	20%	9%	23%

Source: IIR. 2009. The role of refrigeration in worldwide nutrition (www.iifiir.org)

ADDITIONAL FOOD FROM COLD CHAIN INVESTMENT

Reducing postharvest food losses to 15% from the current 30% level with cold chain technologies could provide:

- Tanzania: 1.9 million tonnes of fresh foods each year, valued at $432 million
- India: 18.3 million tonnes of fresh foods each year, valued at $3.9 billion

Perishable foods tend to be high value compared to staple crops.

Recently a World Food Logistics Organization (WFLO) project measured postharvest losses for 26 perishable crops in 4 countries, and documented losses from 30 to 80% due to poor quality packages, poor temperature management, and delays in marketing (Kitinoja and Hassan, 2012). The International Institute of Refrigeration (IIR) calculated that 23% of perishable foods are lost in developing countries due to the lack of the use of refrigeration.

Perishable foods tend to be high in market value compared to staple food crops, and they provide important sources of off-farm jobs (in packinghouses, transport, processing and marketing), nutrients (especially vitamins and minerals) and culinary options for consumers. Protecting them from losses by keeping these foods cold often makes economic sense. However, there are many technical, logistical and investment challenges as well as economic opportunities related to the use of the cold chain.

The primary segments of an integrated cold chain include 1) packing and cooling fresh food products (as soon after harvest or collection as possible), 2) food processing (i.e. chilling or freezing of certain processed foods), 3) cold storage (short or long term warehousing of chilled or frozen foods),4) distribution (cold transport and temporary warehousing under temperature controlled conditions) and 5) marketing (refrigerated or freezer storage and displays at wholesale markets, retail markets and foodservice operations). Within each country, it is common to find at least three different types of value chains – 1) individual producers who sell surpluses on the local market (rarely using cooling or any type of refrigeration, freezing or storage), 2) groups of producers growing for domestic markets (who may combine their products and pay for pre-cooling, cold storage or cold transport for highly valued products) and 3) export marketers, who must follow international standards for packing, cooling and shipping, and so often use refrigeration and the cold chain to assist with maintaining quality and meeting required standards.

Fresh foods continue to metabolize and consume their nutrients throughout their shelf life, from harvest or slaughter through packing, distribution, marketing and sale. Carbohydrates, proteins and other nutrients are broken down into simpler compounds often resulting in reduced quality or quantity of the foods, through respiration, enzymatic breakdown and microbial degradation. All of these processes are highly dependent upon temperature.

As with all biological processes, the higher the temperature the faster these natural degradation processes will occur, leading to loss of color, flavor, nutrients and texture changes. In fact, as a general rule, most of these degradation processes double or triple their rate for each increase of 10°C (known as the Q10 quotient). Lowering temperature does have some exceptions, since some fresh horticultural perishables are susceptible to chilling injury below about 10°C (most of the tropical and sub-tropical crops) and all fresh horticultural perishables will freeze below about -1°C.

In addition to physiological deterioration, foods may host micro-organisms such as bacteria and fungi which can cause molds, rots or decays and are subject to water loss which results in wilting, shriveling or darkening. Both the rate of microbial growth and the rate of water loss occur more rapidly as temperature increases. Few other interventions can so dramatically maintain the visual quality and nutritional value, and increase shelf life and ultimate market value of fresh foods as much as simply holding the foods at a lower temperature.

Cooling provides the following benefits for perishable horticultural foods:

- Reduces respiration: lessens perishability and natural senescence
- Reduces transpiration: lessens water loss, less shriveling
- Reduces ethylene production: slows ripening
- Increases resistance to ethylene action
- Decreases activity of micro-organisms
- Reduces browning and loss of texture, flavor and nutrients

In general, the Q10 coefficient (an indication of the relative rate of respiration at 10°C intervals) can be used to estimate the shelf life for fresh foods under different temperature conditions (Table 2). A perishable food product with a recommended handling temperature of 0°C will have only one third to one half of its maximum shelf life if handled at 10°C. If the handling temperature jumps to 20°C, the produce will have one quarter of its potential shelf life (Table 3).

Table 2: Theoretical relationship between temperature, respiration rate and deterioration rate of a non-chilling sensitive fresh commodity

Temperature °C	Assumed Q10	Relative shelf life	Losses per day (%)
0	-	100%	1
10	2.0 to 3.0	33 to 50%	2 to 3
20	2.0 to 2.5	13 to 25%	7 to 8
30	2.0	7 to 10%	10 to 14
40	1.5	4 to 5%	20 to 25

Developed from data available in USDA Handbook 66 (2004)

Table 3: Storage potentials for selected fresh and frozen foods

Variable	Global	Developed countries
Fresh whole fish	Less than 1 day	8 to 10 days at 0 °C
Cut fresh meats	1-2 days	3 to 4 weeks at -2°C
Minced meats (ex: ground beef)	A few hours	7 days at -2 °C
Milk	A few hours	Up to 2 weeks at 2 to 4°C
Hard Cheeses	Less than 1 week	6 months to 1 year at 0°C
Fresh green vegetables (i.e. lettuces, early cabbage)	A few days	1 month at 0°C
Potatoes	Less than 2 months	5 to 10 months at 4 to 12 °C
Tomatoes – firm ripe	Less than 1 week	1 to 3 weeks at 8 to 10 °C
Onions – pungent types	Less than 1 month	Up to 8 months at 0°C
Mangoes	Less than 1 week	2 to 3 weeks at 13°C
Apples	Less than 2 weeks	3 to 6 months at -1°C
Fresh-cut fruits	A few hours	Less than 2 weeks at 0 to 5 °C
Frozen fish	A few hours	6 months at -18°C
Frozen poultry	A few hours	4 months at -18°C
Ice cream	A few minutes	6 months at -28°C

When ambient temperatures are higher than 25°C, a common occurrence during perishable food handling in many developing countries, storage potential will be further decreased

Cold chain technologies

Cooling or use of cold in developing countries is a rare occurrence for local and domestic markets, and is often found in use only for high value foods intended for export. Smallholder farmers who lack electricity and cannot afford diesel powered generators can use shade, hydro-cooling (if clean, cold, deep well water is available and can be pumped to the site) or evaporative cooling systems (if the climate is relatively dry), but the temperatures these methods can achieve are not low enough for successful long term storage or for preventing rapid deterioration and losses in foods that need cold temperatures for maximizing shelf life.

If power sources are available, there are many options for mechanical technologies that can be used for small, medium or large scale operations (Table 4). Total construction and operating costs for refrigerated systems will vary widely depending on the capacity, costs of local materials, labor and electricity. Postharvest losses can be greatly reduced with the use of cold handling, transport and storage, but the return on investment (ROI) for any specific operation will always depend largely upon the market value of the food commodities being cooled and stored and the use efficiency of the facility (i.e. whether or not it is operated at full capacity).

Table 4: Examples of mechanical technologies available for cooling/refrigeration/freezing

Cold chain steps	Smaller scale	Larger scale
Packing and cooling Pre-cooling systems	Portable forced air cooling systems (can be set up inside a cold room) Use of ice	Vacuum cooling Forced air cold walls Hydro-cooling
Processing – chilling or freezing	Convection freezing "Direct expansion" chilling of bulk milk	"Instant" chilling of milk Blast freezing Immersion freezing IQF (individual quick frozen) Vacuum cooling of packaged meats Freeze drying
Cold Storage	Walk-in cold rooms CoolBot™ equipped cold rooms	Large cold rooms Refrigerated warehouses
Distribution Refrigerated transport	Use of gel packs (phase change materials that can be chilled or frozen) "Pack-n-Cool" trailers Refrigerated cargo van Reefer (12ft length insulated box truck)	Reefer trailers (20ft, 40ft or 53ft length) Refrigerated marine containers Refrigerated intermodal containers (for road, rail and sea shipping)
Marketing	Misting during display Use of ice	Refrigerated/frozen display cases

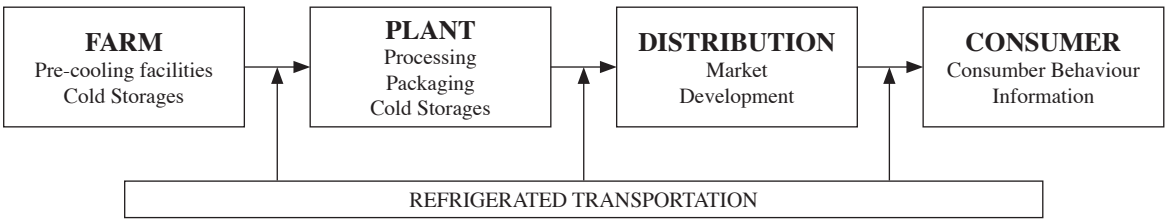


Figure 1: Typical steps of an integrated cold chain (Source: Joshi et al 2009)

Packing and Cooling

Initial **pre-cooling** refers to reducing the pulp temperature of fresh horticultural produce soon after harvest via the use of assorted means of conduction or convection. The target temperature depends upon the type of produce. Forced-air cooling (requiring 35 to 60 kWh/tonne) and hydro-cooling (requiring 100 to 110 kWh/tonne) are the most commonly used pre-cooling methods.

The initial incoming produce temperature of 30°C is an estimate based upon typical daytime temperatures in tropical regions. If the initial temperature of the produce is lower at delivery (such as for produce harvested very early in the morning and kept in the shade) pre-cooling will take somewhat less time. If the delivery temperature is higher than 30°C (such as for produce left in the sunshine or produce shipments that have been delayed for many hours after harvest before delivery to the packhouse), then pre-cooling will take longer than shown in Table 5. Pre-cooling can be expensive, so produce is typically pre-cooled to the temperature at which it has reached 7/8ths cool, which requires three ½ cooling cycles.

Table 5: Estimated Time required for Forced Air Pre-cooling

Estimated Pre-cooling Times (Forced Air Cooling Tunnels)				
Average Cooling rates	Starting Temp.	Target Temp.	1 L /sec/kg FA flow rate Estimated Hours per 1/2 cooling cycle	Estimated Hours to 7/8ths cool
Mangoes	30°	15°	1.5	4.5
Apples	30°	0°	2.5	7.5

The ideal size of a pre-cooling room with a cold wall and 2 forced air pre-cooling stations (also known as FA cooling tunnels) is 8m x 10m. The illustration here shows the layout for cooling 12 pallets per load per tunnel. A total of 24 pallets (maximum 800 kg per pallet) can be cooled at one time.

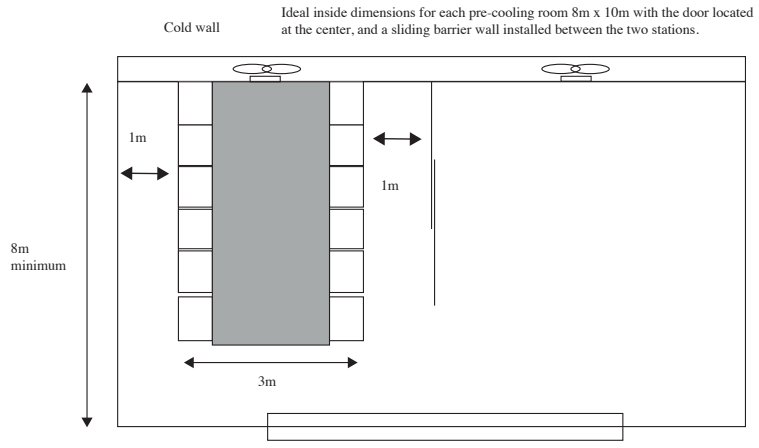


Figure 2: Illustration of a design for Forced Air pre-cooling cold room with cold wall (Kitinoja, 2013).

Vacuum pre-coolers use a special high-cost system that mechanically lowers atmospheric pressure around the produce inside a sealed chamber in order to utilize evaporation to reach temperatures as low as 1°C. Vacuum cooling is used mainly for cooling pallet loads of leafy green vegetables, which have a very large surface to volume ratio. Liquid air technologies, if combined with these traditional pre-cooling methods, have the potential to reduce operating costs and may lead to smaller versions of the equipment currently in use, which would increase access for smallholder food producers, shippers and marketers.

Crushed or slurry ice can be used for rapid pre-cooling of fish or vegetables that can tolerate water. Slurry ice is a solution of about 40% water, 60% ice and 1% salt. Ice in large pieces or blocks can be used to cool water which can then be used in shower or immersion type hydro-cooling systems. Ice is a low-tech method for providing cooling, but the cost of ice production can be very high compared to its cooling capacity (Kitinoja and Thompson, 2010), and ice melt can cause safety and sanitation problems during handling, storage, transport and marketing. If liquid air technologies could be used to produce ice for local use, the cost/benefit ratios for small scale users would improve.

Food Processing

Chilling is the rapid lowering of the temperature of fresh or processed food products to less than 8°C via various mechanical or non-mechanical means. When chilling milk, there are two systems in common use. Since the temperature of milk harvested from the dairy cow is typically 39°C and it should be stored at 2°C, the temperature must be reduced by about 37°C. To reach this temperature roughly 60 Btu of heat must be removed per pound of milk, requiring 40 kWh/tonne (1 Btu = 0.0003 kWh). For bulk liquid chilling, "direct expansion" refers to a system where the evaporator plates are incorporated in the lower portion of the storage tank in direct contact with the milk. One or more agitators move the milk over the evaporator plates for cooling. There is a limit to the size of refrigerated milk cooling and storage tanks due to structural issues. There is also a limit to the refrigerated surface area. The ability to remove heat from the milk fast enough to meet cooling requirements with high milk loading rates is not possible without reducing evaporator surface temperature to the point where freezing of milk may occur.

"Instant" chilling is where the milk cooling is completed external to the storage tank and then pumped into a storage tank. An intermediate cooling fluid, such as chilled water from an ice builder or a glycol-water mixture from a chiller is used to cool milk rapidly in a heat exchanger. Currently, there are no solutions available in the market that provide milk chilling at micro-scale, below 300 L per cycle and that run independently from the grid. Liquid air refrigeration technologies have the potential to change this.

Freezing is the drastic reduction of processed food temperature to below –18°C with the conversion of water into ice. A common method of freezing is simply indirect contact with a refrigerant that flows through shelves or belts that may touch the bottom or both top and bottom of the packages, commonly called convection freezing.

Blast freezing speeds freezing by rapidly passing cold air over packages as they move through a tunnel or when they are stacked on racks in cold rooms. This method is in most common use by refrigerated warehouses for freezing foods—either from the unfrozen state for a processor with limited freezer capacity or for bringing the temperature of still-frozen foods back to -18°C after they have been exposed to higher than optimal temperatures. For air blast freezing, the air temperature of the freezer should be -23°C or preferably lower (-34 to -40°C) and air velocity should be 305-610 m/min or higher.

The freezing process can be sped up even further by using a free flow freezing process to achieve individually quick frozen (IQF) product pieces. The unpackaged food is frozen either on belt freezers where air at -40°C blows up through a mesh belt and through a thin layer of small food product pieces or in fluidized-bed freezers where the blast of upcoming air is of sufficient velocity to partially suspend the food. The frozen food pieces are then packaged and moved into cold storage. IQF is generally used only in very large industrial food processing plants, but liquid air based freezing technologies have the potential to change this.

Very rapid freezing methods, such as using liquid nitrogen for commercial freezing are available but the technologies are extremely expensive. Shrimp, for example, can be frozen by passing them under a liquid-nitrogen spray. The shrimp are conveyed first through a cooling area where nitrogen gas from the freezing part of the process is used to cool the product. The shrimp then come into direct contact with liquid nitrogen sprays at -195°C, for less than 2 minutes. The product then equilibrates to -29°C and is ready for cold storage. This technique, commonly called conduction freezing, can be used for high value vegetables, fruits, shellfish and other food products. Liquid nitrogen systems are available for use in immersion, tunnel or batch operations (see examples marketed as Freshline ™ by Air Products -- or ColdFront™ by Praxair) but they must be used in heavily monitored closed systems to prevent worker exposure to an atmosphere that is not fit to breathe (lacks oxygen). It is envisioned that liquid air (a natural combination of 21% oxygen and 78% nitrogen) could be used more easily in any type of direct freezing operation since there would be fewer worker safety issues. Over time during storage of tanks of liquid air at ambient temperatures, nitrogen will boil off at a more rapid rate than does the oxygen, so it is still important to consider potential hazards.

Methods that produce quick freezing (IQF via immersion or liquid nitrogen sprays) result in better quality food products than do methods that provide slow freezing (traditional freezer room racking). Rapid freezing prevents undesirable large ice crystals from forming in the frozen food product because the molecules don't have time to form. Slow freezing creates large, disruptive ice crystals. During thawing, they damage the cells and break cell walls and membranes. This causes vegetables to have a mushy texture and meats to weep and lose juiciness. Quicker freezing methods, however, are currently more expensive, but liquid air has the potential to reduce these costs, since liquid air requires 20% less energy to produce than liquid nitrogen (*Liquid air in the energy and transport systems*, CLCF, May 2013) and therefore should be less costly.

Liquid air could make micro-scale, off-grid milk chilling possible for the first time.

Cold Storage

Cold storage rooms can be constructed in any size as needed, from small walk-in size to huge warehouses with racking to increase storage height, but the construction and operating costs per cubic meter increase as the size decreases. Cold storage facilities are not a stand-alone solution to the problems that arise due to surpluses of perishable produce. The actors along the entire agricultural value chain need to work together to better match production to market needs and demands for fresh and frozen foods. A lack of availability or lack of access to a needed cold chain service (such as pre-cooling or refrigerated transport) anywhere along the value chain will lead to poor results for investments in cold storage.

Recommended temperatures for cold or frozen storage vary widely by commodity, ranging from a target temperature of 15-18°C for tropical fruits, some vegetables such as sweet potatoes and tomatoes; 5 to 7°C for green beans, peppers, eggplant, melons, okra and passion fruit; 0-2°C for many temperate crops including salad greens, apples, stone fruits, herbs, carrots, cabbage, grapes; to -18°C for frozen foods. In developing countries it is quite common to see all types of produce stored together as mixed loads, and when cold rooms are in use, they are usually located in cities (where electricity is available). Due to financial constraints, they are often of smaller sizes and tend to be overfilled for their refrigeration capacity. A potential future use for liquid air refrigeration technologies would be for example, to power and cool a group of four or more individual small-scale cold rooms for use in a rural area, each of which can be set at a different target temperature. Diesel-liquid air hybrid engines ('heat hybrids') are currently under development, and could reduce diesel use in traditional cold rooms by 20% and improve refrigeration efficiency.

Distribution and Transport

Transport occurs at several points along the cold chain, to bring produce from the farm or orchard to a central location for packing and pre-cooling, from the packinghouse to cold storage or a distribution center, from there to a market or food service buyer, and finally from the marketplace to the consumer's home. In developing countries, insulated box containers permanently attached to a truck chassis are commonly used for refrigerated transport from the packinghouse and wholesale distribution center to the modern retailer or food service buyer. In some cases, the insulated box is used without refrigeration, and cold foods are loaded inside for short trips. Pallet loads can be covered with insulating materials and/or gel packs of phase change materials can be chilled and included in the load to help to maintain temperature. In rare cases, dry ice is put inside individual insulated containers to protect highly valuable products during "last mile" deliveries (most common for vaccines or expensive cuts of meats).

Most large refrigerated highway vehicles are semi tractor-trailers, with a large diesel powered engine to provide propulsion. The trailer has a self-contained small engine driven refrigeration system (5 to 15kW, depending upon load volume) that provides cold air to the insulated trailer box. Typically a 5kW diesel engine will use 5 to 6 L per hour to provide refrigeration for a pre-cooled load of perishables being transported at 2°C. Liquid air powered cryogenic engine technology is the perfect fit for this cold chain "reefer" application, since it could provide both cooling and power to drive fans without emitting air pollution.

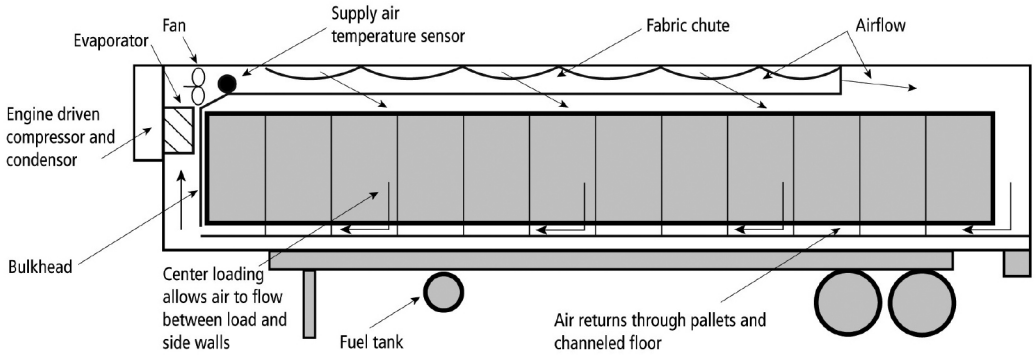


Figure 3: Refrigeration and airflow in a highway "reefer" trailer with 24 pallets (showing 12 x2). Source: Thompson 2002

Reefers also can be designed as "containers" in 20ft and 40ft lengths. A twenty foot equivalent unit (TEU) has an external length, width, and height of about 20', 8', and 8'6" respectively (6.0, 2.4, and 2.6 meters) and can hold up to 12 standard sized pallets. They have a maximum cargo load of 27 tonnes in a total volume of 27 cubic meters, however when carrying fresh produce or frozen cargo, they cannot be fully loaded since air circulation (above, below and around the load) is required for proper temperature management. These reefer containers can be utilized on the road via semi-trailer, rolled onto flat beds of trains or decks of cargo ships, or lifted by cranes to travel on trains or in cargo ships.



Figure 4: Reefer container (20 feet long or one TEU)

Typical diesel powered reefer units cannot pre-cool the load, as they are designed simply to maintain the temperature of a pre-cooled load during transport, using 3 to 6L of fuel per hour, depending on the set point temperature of the load. Average road temperatures can be up to 20°C higher than air temperatures during hot months of the year, making it even more difficult for refrigerated vehicles to maintain recommended temperatures. Transit times under these conditions should be kept as short as possible, since deterioration will increase as product temperatures increase, but it is common to see vehicles with their refrigeration units turned off or left parked in the sun during a driver's meal break. Liquid air refrigeration technologies could provide enough cooling to pre-cool a load during transit, and more easily maintain the target temperature during the journey.

Even very small insulated trailers could be equipped with a simple refrigeration system if the unit included a small cryogenic engine operating on liquid air. The only technology currently in use along these lines is the "Pack-n-Cool™" trailer developed by the University of North Carolina (USA). The 5 x 8 ft trailer is a retrofitted commercial model with added insulation, a window style air conditioner and a CoolBot™ control unit designed to over-ride the frost sensor and allow the unit to achieve temperatures of down to 2°C (at a capital cost of $3400). A cryogenic engine that could provide 5kW of refrigeration power (for operating fans and cooling) would be sufficient to power this type of small reefer trailer.



Figure 5: Pack-n-Cool™ trailer

Marketing

In developing countries most perishable foods are marketed as quickly as possible and often via open markets (outdoor marketplaces). A very small portion of fresh foods are sold in "modern retail" supermarket establishments, where display cases are used mainly for frozen foods. It is not uncommon in the capital cities of the world, to see refrigerated displays of bottled water and aseptically packaged juices (which do not require refrigeration for long term storage) while fresh fruits and vegetables are displayed nearby at ambient temperature.

Cold chain solutions and resource management

Currently available technologies for pre-cooling, cold storage, chilling, freezing and cold transport use diesel fuel, which is expensive and a source of pollution, or electric power which is often not available in rural areas. The vast majority of perishable food producers (i.e. horticultural crops, fish, milk) are smaller in scale and produce for local or domestic markets. Successful use of the cold chain requires complex management skills and supporting "best practices" such as gentle handling, use of sturdy containers (instead of the typically used baskets and sacks), pallets (to allow cold air to pass under the load in storage or during transport) and developing strong market linkages prior to planting and harvesting. As a result, to date there tends to be little if any use of cooling/cold chain in the domestic food supply chain in developing countries due to a lack of awareness, availability, access, confidence and/or perceived high cost. Liquid air / cryogenic engine technologies have the potential to change this by tapping into a virtually unpenetrated market if engineers can design equipment that is appropriate for the needs of smaller scale users.

Supporting technologies for the cold chain can all be re-imagined using liquid air and cryogenic engines.

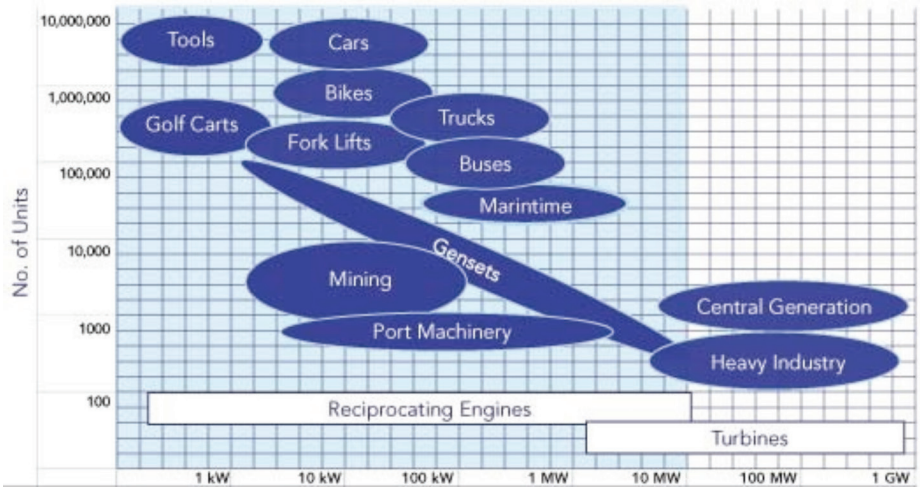


Figure 6: Market potential for technologies based on cryogenic engines
http://www.gizmag.com/dearman-zero-emissions-engine/21201/

The liquid air based technologies being developed now or being considered for the near future are already well suited for the food export sector. These include reefer trucks of various sizes and walk-in cold rooms equipped with refrigeration systems powered by cryogenic engines or hybrid diesel/liquid air engines, as well as the direct use of liquid air in freezing/IQF applications. Supporting technologies, such as the use of slurry ice or ice water for hydro-cooling, rapid cooling via forced air or hydro-cooling after heat treatments or after blanching (a common treatment used before drying or freezing to protect color and texture), can all be re-imagined using liquid air and cryogenic engine technologies. The energy requirements for these cold chain technologies range from 2 to 11 kWh/MT per day for small scale operations, and can be less than 1 kWh/MT per day for very large scale operations. The wide range of energy use for any given technology is due to differing storage volumes, target temperatures, ambient temperature differences and initial produce temperature over the course of a typical day and a typical season.

Historically, once a cold chain is developed for use for handling the higher value foods in the export sector in a given country or region, there are follow-on uses for domestic marketing. Perhaps the export window is for a period of six months of the year, and so the cold storage or reefer trucks are available for rent by others who handle perishable foods during the exporters' off season. This is the case for table grapes in Egypt and India where the harvesting and pre-cooling period is typically only 2 or 3 months long.

As a side benefit, the use of cold chains for domestic food marketing is a practical way to prevent the waste of food and well as limited natural resources. The resources required for agricultural production (i.e. land, water, fertilizers, fuels, other inputs) are becoming more scarce and costly, and 30% to 50% of the resources used to grow these foods are currently being wasted when perishable foods are lost before consumption. Investments in the cold chain prevent the loss of foods after they have been produced, harvested, processed, packaged, stored and transported to markets, which greatly reduces the need for increased production to meet the predicted growth in future demand. Reducing food losses and waste also saves the water, seeds, chemical inputs and labour needed to produce the food that is currently being lost.

As local and global resources become scarcer and more expensive, preventing food losses will become even more cost effective than it is at today's resource prices. Public and private sector investors need to take into consideration how investing in the use of the cold chain can generate savings due to the reduced need for constantly increasing food production to meet rising consumer demand for perishable foods. Currently the need for the use of the cold chain in developing countries may be known and even accepted as cost effective, but adoption is low due to a lack of appropriate agricultural research and development, lack of training programs for capacity building, and the absence of national organizations focusing on the cold chain. If liquid air based refrigeration technologies could be introduced at the national level, and a local, decentralized source of cooling could be generated via a "Tank of Cold" energy source at the village or small city level, some of the current impediments to the development of the cold chain could be alleviated.

Table 6: Estimated energy use for selected cold chain technologies

Cold chain technology	Typical capacity	Energy use	Estimated maximum energy use per day
Ice (330 kg required to cool 1 tonne by 28°C)	5 to 12.5 kg ice per kWh	80 to 200 kWh per tonne	1000 kWh (5 tonnes produced in a 5 hour day)
Hydro-cooling to 2°C (shower type)	3 tonnes cooled in 1 hour	240 to 330 kWh per batch	480 to 660 kWh (2 batches per day)
Forced air cooling to 2°C	3 tonnes cooled in 6 hours	165 kWh per batch	330 kWh (2 batches per day)
Forced air cooling to 13°C	3 tonnes cooled in 3 hours	105 kWh per batch	210 kWh (2 batches per day)
Small frozen storage room (20m^2) at -18°C	6 tonnes	11 kWh/MT/day	66 kWh
Small cold storage room (20m^2) at 2°C	6 tonnes	9 kWh/MT/day	54 kWh
Small cold storage room (20m^2) at 13°C	6 tonnes	4 kWh/MT/day	24 kWh
Medium sized frozen storage room (40m^2) at -18°C	12 tonnes	8 kWh/MT/day	96 kWh
Medium sized cold storage room (40m^2) at 2°C	12 tonnes	6 kWh/MT/day	72 kWh
Medium sized cold storage room (40m^2) at 13°C	12 tonnes	3 kWh/MT/day	36 kWh
Medium sized cold storage room (60m^2) at -18°C	18 tonnes	6.8 kWh/MT/day	122 kWh
Medium sized cold storage room (60m^2) at 2°C	18 tonnes	5 kWh/MT/day	90 kWh
Medium sized cold storage room (60m^2) at 13°C	18 tonnes	2.5 kWh/MT/day	45 kWh
Large frozen storage room (80m^2) at -18°C	24 tonnes	5 kWh/MT/day	120 kWh
Large cold storage room (80m^2) at 2°C	24 tonnes	4 kWh/MT/day	96 kWh
Large cold storage room (80m^2) at 13°C	24 tonnes	2 kWh/MT/day	48 kWh
20 ft reefer unit (5 kW engine) at 2°C	6 tonnes	5 L per hour	50 L (10 hour trip)
20 ft reefer unit (5 kW engine) at 12°C	6 tonnes	3 L per hour	30 L (10 hour trip)
40 ft reefer unit (12 kW engine) at 2°C	12 tonnes	7 L per hour	70 L (10 hour trip)
40 ft reefer unit (12 kW engine) at 12°C	12 tonnes	5 L per hour	50 L (10 hour trip)

Notes: 1 ton of refrigeration capacity = 3.5kW = 12,000 BTU/hour
Source: calculations by L. Kitinoja, The Postharvest Education Foundation (2014)

Supporting technologies for the cold chain can all be re-imagined using liquid air and cryogenic engines.

In one survey 56% cited lack of cold chain as the main constraint in Tanzanian horticulture.

Tanzania Case Study

Despite a variety of recent infrastructure projects in Tanzania, and a clear understanding of the importance of roads, electricity and financial support for the agricultural sector, currently only 2% of rural population has access to electricity via national grid.

In northern Tanzania there is 1) a high volume trade (tomato, cabbage and carrots) where full truckloads of a single product are traded, and 2) the trade of high value vegetables (sweet pepper, broccoli, zucchini, lettuce, cauliflower fresh beans) where smaller quantities are traded and the marketing channels are more diverse. In each case, prices fluctuate significantly, the measurements in the chain are not standardized and the actors in the chain are all prone to high risks of losses or damage (MMA 2008).

For **high volume** trade the most common value chains are:

Lushoto – Dar es Salaam (Kariakoo)

Rural wholesale marketplaces

Farmers selling directly to urban wholesale market (Kilombero in Arusha)

For **high value** trade the most common value chains are:

Usambara Lishe Trust working with farmer cooperatives selling directly to high end market

Producers contracted by exporters (Finlay's etc)

Producers contracted by hotels/tourist lodges or supermarkets

Sales via middlemen to urban shops or wholesale market

Farmers delivering directly to wholesale or retail market



Figure 7: Map of horticultural production hotspots in Tanzania. Source: MMA 2008

A recent survey of horticultural value chain actors handling higher value commodities in Tanzania found that more than 56% identified the lack of storage options, especially cold storage as their most common constraint (Chemonics 2013).

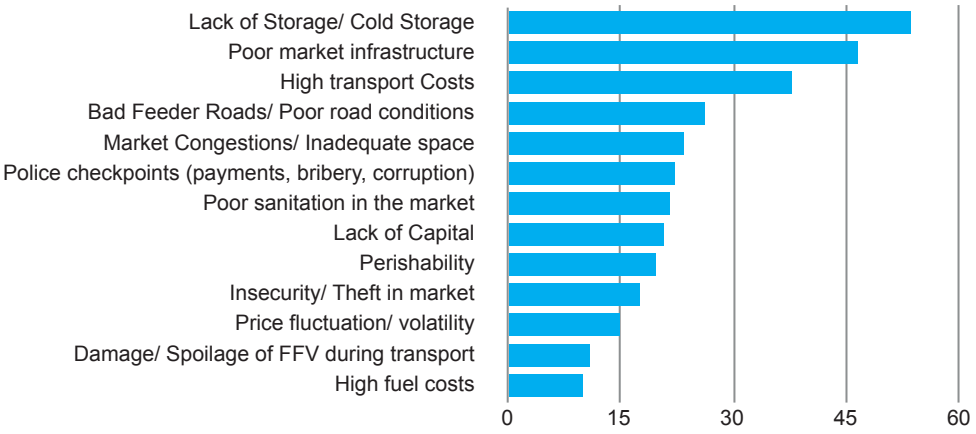


Figure 8: Most common constraints among all value chains actors (Chemonics 2013)

Several smaller scale applications can be imagined for utilization in Tanzania to reduce food losses, extend shelf life, add value and improve market access. Currently postharvest losses are 40% or higher, and the lack of the use of the cold chain limits shelf life and marketing opportunities. Even a simple technology such as using chilled or frozen gel packs in insulated containers (a practice for shipping vaccines or for keeping picnic lunches cool during a tourist outing) remains out of reach for most potential users in developing countries, since there is no easy or inexpensive way to chill or refreeze the phase change materials in rural areas.

A few examples can demonstrate the potential of value addition and/or loss reduction using liquid air based cooling/freezing technologies for various crops moving to markets in Tanzania. Mangoes and tomatoes are used in these examples, since these crops are handled in massive quantities, currently without any refrigeration. There is a lot of money to be made by those willing to make the investments in the cold chain, especially when handling higher value crops. Colored capsicum peppers, for example, can be priced at up to 10 times the value of green peppers, but unless kept cool, will have a much shorter shelf life since they are harvested at the ripe stage. Fresh green beans have a market price similar to dry beans by weight, but are 90% water, and so must be kept cool to prevent weight loss during marketing.

In each case, the technologies could be established via a variety of business models. Three examples of potential business models are: owned/operated by a group of food producers, provided as a fee for service by a local agri-business, or as a stand-alone business for a company that procured and marketed fresh foods sourced from many different producers. Each business model includes a varying set of local jobs, opportunities for investment and potential income generation.

Tanzania Scenario #1

The first example is for the use of Liquid air for IQF tunnel freezing for value addition for tropical fruits. The fresh market price for mangoes in Tanzania drops to $100 per tonne at the peak of the mango season, and IQF operating costs are estimated to be $210 to $230/tonne for electricity/liquid nitrogen or $137/tonne for a liquid air/cryogenic engine tunnel freezing system (the liquid air system is cheaper because liquid air provides both cold for freezing and power - through a cryogenic engine – to run the conveyor belt and fans, and therefore requires no grid electricity) Both tunnels use a conveyor belt and a direct spray of the cryogen to freeze small pieces of food. Using either system the wholesale market value of frozen IQF mango fruit can be increased to more than $3000/tonne. Frozen fruits have a shelf life up to 2 years at -18°C, and cold frozen storage for 6 months requires 215kW /tonne (at a cost of $22/tonne).

Coloured capiscums sell for ten times the price of green peppers, but without refrigeration have a much shorter shelf life.

Table 7: Case study details for IQF processing and frozen storage of mangoes in Tanzania

Tanzania	Commodity: MANGOES	
	Current practice	Improved practice: value addition using Liquid Air IQF processing
Value addition at the village level by freezing seasonal fruits (low to medium capacity IQF tunnel freezer)	Fresh mangoes sold immediately after harvest (Nov-March) No exports due to fruit fly pest Low season market value of "improved varieties" = Tsh 300 to 500/piece* High season (peak) price = Tsh 100/piece ($0.13/kg) Losses = 25% for buyer Market value $100/tonne	Freeze mango as chunks or pulp when market prices are low and store in local cold chamber/freezer IQF processing costs $137 /tonne Sell product during off season (April – Oct) after 1 to 6 months of cold storage Shelf life up to 2 years at -18°C Cold frozen storage cost/6 months requires 215kW /tonne (at a cost of $22/tonne) Market value $4/kg or $3400/tonne 15% waste (peels, seeds) for processor Additional potential earnings due to freezing = Market value at wholesale level – (maximum cost of freezing and cold storage) = $3400 – ($137 + $22) = $3241 /tonne
Notes	* one mango is approximately 0.5kg	Must have access to a freezer for cold storage.

Investing in liquid air cooling of tomatoes in transit could increase earnings per tonne by 10%.

FROZEN MANGOES IN TANZANIA

The fresh market price for mangoes in Tanzania drops to $100 per tonne at the peak of the mango season. Using liquid air technologies for IQF processing the wholesale market value of frozen mango fruit can be increased to more than $3000/tonne. A $50,000 investment in a small IQF line that can freeze 50kg/hour during a 10 hour day can generate more than $1500 per day in added value.

Table 8 provides some details on costs in Tanzania for this imaginary processing operation, in this case comparing options using electricity and liquid nitrogen (the current technology in use for tunnel IQF systems, requiring an energy source for 10kW/hour and 1.6L of liquid nitrogen per kg of frozen product) to the use of liquid air technology for the same purpose.

Table 8: IQF technologies via electricity /liquid nitrogen vs liquid air /cryogenic engine

	Energy cost ($)	Fuel use	large scale 400kg/hour (2.5 hours/ tonne)		small scale 50 kg/hour (20 hours/ tonne)	
IQF Freezing			electricity/ L.N2	L.Air/ cryogenic engine*	electricity/ L.N2	Liquid Air / cryogenic engine
tunnel freezer			$170,000	$170,000	$50,000	$50,000
kWh	0.10	10kW/hour	$2.50/tonne		$20/tonne	
L.N2 (L)	0.11	1.6 L/ kg of frozen product	$176/tonne		$176/tonne	
L.Air (kg)	0.11	1.25 kg/ kg of frozen product		$137/tonne		$137/tonne
*Cryogenic engine runs conveyor, fans and cooling for IQF L.Air tunnel. No grid electricity requirement.			$0.18/kg $180/tonne	$0.14/kg $137/tonne	$0.20/kg $196/tonne	$0.14/kg $137/tonne
Market value fresh mangoes $100/tonne with 25% losses for buyer						
Market value of frozen mango chunks = $4/kg or $3400/tonne after removing 15% waste (peels, seeds)						

It is possible to process a large volume of fruit per day via a liquid air powered system at a cost of less than $0.14/kg – which is 20 to 30% less than the price of the conventional technology. Typically a smaller scale processing line would add costs, but in this case it is also possible to use IQF in a much smaller scale operation even in rural areas where there is no access to electricity. A $50,000 investment in an IQF line that can freeze 50kg/hour during a 10 hour day can generate more than $1500 per day in added value.

Tanzania Scenario #2

The second example is the use of liquid air/cryogenic engine technologies to provide pre-cooling during shipping of a sub-tropical crop such as tomatoes to market. The current practice is to overload an open truck and provide no cooling. The improved practice would be to pre-cool the crop in the reefer prior to or during the 10 hour journey in a liquid air powered reefer vehicle, and deliver a fresher, higher quality product to market. Even if the market price remains the same, reduced losses would ensure a higher return.

In this example, a smaller load is transported in each trip, and the fruits are packed in smaller capacity boxes. Typically both these adjustments will decrease damage during transport, but are viewed a lowering potential returns because of their cost. Even with these supplementary investments, because of the use of cooling during shipping, the financial returns are $48/tonne – or 10% – higher than the traditional practice for each 8 tonne open uncooled load. A single vehicle can make 3 round trip journeys to market per week, earning an extra margin of $864/week (approximately $5184 over a 6 week season). In a country where average cash earnings in agricultural sector jobs are reported to be $2300 per year (Tanzania National Bureau of Statistics 2013), this relatively minor use of the cold chain to reduce losses represents the economic development equivalent of 2 new full time jobs.

Table 9: Case study details for cold transport of tomatoes in Tanzania

Tanzania	Commodity: TOMATOES	
	Current practice	Improved practice: cooling during refrigerated transport
Pre-cooling during refrigerated shipping to regional or export markets (Arusha, *Ngarenanyuki, Lushoto or Iringa to Dar es Salaam) 400 to 650 km 10 hours estimated journey	8 tonnes per load 200 wooden boxes of 40 kg each on common open truck 30,000/40 kg container ($0.47 /kg) 50% losses Cost of cooling =$ 0 Maximum market value of load at wholesale level = $3750 = $469/tonne	6 tonnes per load 300 wooden boxes of 20 kg each on 20 ft reefer truck 20,000/20 kg container ($0.63 /kg) 5% losses Cost of extra boxes = $200 Cost of cooling from 30° to 18°C ($43 per tonne x 6 tonnes) = $259 Maximum market value of load at wholesale level = $3562 = $593/tonne Subtracting costs for extra boxes and cooling $3562 – 459 = $3103 = $517/tonne Additional earnings due to cooling = $48/tonne
Notes	*Ngarenanyuki ward, 50km north of Arusha, is the site of grower cooperatives that ship 50 or more 8 tonne truckloads per week	

Table 10 provides some of the details on costs, in this case comparing current options using electricity or diesel fuel and internal combustion engines (ICE) to the use of liquid air technologies for the same purpose.

Table 10: Estimated costs for pre-cooling during shipping of tomatoes in Tanzania

	Fuel cost	Fuel use	Large scale 20ft reefer (6MT)			
Reefer transport			diesel		L.Air	
Vehicle cost			$100,000		$100,000	
pre-cooling to 18°C (6 hours to 7/8th cool)			$2.50/tonne			
Via diesel engine (5kW)	$1.37/L	35kWh/ tonne	**not possible to pre-cool during transit** *requires 35kW/hour			
Pre-cooling services*	$0.03/kg		fee	$180		
Via L.Air (kg)	$0.11/kg**	250 kg/ tonne			$165	
Transit cooling (maintaining temperature of pre-cooled produce at 18°C) 10 hour trip		2kWh/ tonne	12kW in 10 hours			
diesel engine (5kW)	$1.37/L	4L/hour	40 L	$54		
L.Air (kg)	$0.11/kg	14 kg/tonne			85 kg	$9
			Total	$234	Total	$174
Cooling power of L.Air = 0.14 kWh/kg Cryogenic engine can provide cooling as well as power the fans to move cold air through the load			$0.04/kg to pre-cool and ship produce		$0.03/kg to pre-cool and ship produce	

*Requires use of a separate pre-cooling facility (not usually available in rural Tanzania)
**Assumes 300tpd liquefier powered by solar operating 6 hours per day.

PRE-COOLING DURING TRANSPORT

A typical 5kW diesel transport refrigeration unit cannot deliver pre-cooling, which requires static facilities not generally available in Tanzania. Liquid air can provide pre-cooling to 18°C in transit, and transporting 6 tonnes of tomatoes for ten hours with liquid air would be 25% cheaper than the diesel option, even if static pre-cooling facilities were available.

Conventional technologies cannot deliver pre-cooling in transit – a typical 5kW diesel transport refrigeration unit simply cannot provide enough power, and a pre-cooling room of the kind shown in Figure 2, powered by grid or diesel generated electricity, is required. Such facilities are generally not available in Tanzania, but if they were, in this example the combined cost of pre-cooling and diesel refrigerated transport would be $0.04/kg, whereas the cost using liquid air and a cryogenic engine is approximately $0.03/kg – 25% less. Actual costs per load will depend on the volume to be transported, type of container used for cooling/packing, target temperature needed (varies by crop), the distance to be traveled, and any delays.

A few more examples are provided in Table 11, which provides some details on costs for refrigerated transport, in each case comparing current options (using electricity or diesel fuel) to the use of liquid air technologies. The current unsubsidized price of diesel fuel in Tanzania is $1.37/L and the estimated delivered price of liquid air is $0.11/kg‡.

The relative cost for the small 1 tonne vehicle operated at 12°C is largely dependent upon the length of the trip. Once the produce is pre-cooled, which takes 8 hours, the cost per hour for maintaining the set temperature is about $1 for liquid air and about $2.50 for diesel fuel. Overall, the costs for using cold transport using liquid air /cryogenic engine technology range from $0.03 to 0.05 per kg, a significant investment for smallholder farmers, but a relatively small amount to pay to prevent economic losses that are often more than 1/3 of the total load value when the cold chain is not used. In the case of lower priced commodities, the cost of using the cold chain is approximately 10% of the value of the load, but if the produce was a high value crop such as dairy products, fresh green vegetables or export crops, the relative cost of cooling during transport might be as low as 5%.

Table 11: Estimated comparative costs for refrigerated transport in Tanzania depending on size of load, power source and target temperature (assume an initial temperature of 30°C, a market value of $0.60 per kg and a standard 10 hour journey)

	4 tonne capacity (typical 20 ft reefer) Load market value $2400		1 tonne capacity (small reefer van) Load market value $600	
Reefer target temperature	Diesel/ICE 5kW engine	Liquid Air / cryogenic engine	Diesel/ICE 5kW engine	Liquid Air / cryogenic engine
2°C 8 hours to 7/8ths cool	Precooling while in transit is not possible (requires 27kW/hour)	$173 to pre-cool* $12 maintain temperature Total= $185 $0.05/kg	Precooling while in transit is not possible (requires 7kW/hour)	$43 to pre-cool $3 to maintain temperature for 2 hours Total= $46 $0.05/kg
12°C 8 hours to 7/8ths cool	Precooling while in transit is not possible (requires 20kW/hour)	125 to pre-cool* $9 to maintain temperature Total = $134 $0.03/kg	$11 to pre-cool $5 to maintain temperature for 2 hours Total = $17 $0.017/kg	$31 to pre-cool $2 to maintain temperature for 2 hours Total= $33 $0.03/kg

Note* The amount of liquid air required for pre-cooling the larger capacity vehicle (1100 to 1570 kg) is likely to be too much for the vehicle to carry, so a portion of the pre-cooling could be done on the site of the loading of the vehicle

Tanzania Scenario #3

Mining companies in isolated areas of western Tanzania are currently using small diesel powered cold storages for 1) mixed loads of fresh produce (each with different temperature requirements) and 2) frozen products (where even partial thawing can lead to loss of quality and nutritional value). Small sized cold rooms are more expensive to operate than larger cold rooms. There may be additional costs in

‡ Assumes 300tpd liquefier powered by solar operating 6 hours per day.

Table 12: Estimated daily operating cost per 24 hour day for cold storage in Tanzania depending upon cold room size, refrigeration power source and set temperature

FAOSTAT 2009-2010	India				
Cold chain technology	Typical capacity (tonnes)	Energy use	Estimated maximum energy use per day	Cost using Diesel/ICE* ($1.37/L)	Cost using Liquid Air/cryogenic engine** ($0.11/kg)
Small frozen storage room (20m^2) at -18°C	6	11 kWh/MT/day	66 kWh	13.2 L $18	471 kg $51
Small cold storage room (20m^2) at 2°C	6	8 kWh/MT/day	48 kWh	9.6 L $13	343 kg $39
Small cold storage room (20m^2) at 13°C	6	4 kWh/MT/day	24 kWh	4.8 L $7	171 kg $18
Medium sized frozen storage room (40m^2) at -18°C	12	8 kWh/MT/day	96 kWh	19.2 L $26	686 kg $75
Medium sized cold storage room (40m^2) at 2°C	12	6 kWh/MT/day	72 kWh	14.4 L $20	524 kg $56
Medium sized cold storage room (40m^2) at 13°C	12	3 kWh/MT/day	36 kWh	7.2 L $10	258 kg $28
Larger sized cold storage room (60m^2) at -18°C	18	6.8 kWh/MT/day	122 kWh	24.4 L $33	871 kg $95
Larger sized cold storage room (60m^2) at 2°C	18	5 kWh/MT/day	90 kWh	18 L $25	643 kg $69
(60m^2) at 13°C	18	2.5 kWh/MT/day	45 kWh	$13	$35

* diesel fuel provides 5 kWh/L at 50% efficiency
** cooling power of L.Air or L.N2 = 0.14 kWh/kg

The cost of liquid air produced from renewable energy would be fixed for the lifetime of the equipment, while the price of diesel is likely to rise.

terms of use of diesel fuel (cost of bringing fuel to the site, plus fuel burned per 24 hours/day of operation), food losses due to mixed loads, and there may be additional problems associated with isolation such as issues with maintenance, repairs, and management of the cold rooms.

Tanzania's mining sector has had an average growth rate of 10.2% since 2000, and contributed 3.3% to GDP in 2011. In 2011 Tanzania's mineral exports were $2.3b, of which approximately 90% was gold. (http://eiti.org/Tanzania)

Table 12 provides some details on refrigeration system operating costs, in each case comparing current option (using diesel fuel) to the use of liquid air technologies. Currently diesel fuel costs $1.37 /L and the delivered cost of liquid air is estimated at $0.11 /kg. All of the options provide cold storage at reasonable cost (less than $0.005/kg per day for frozen foods, and less than $0.003 for cold storage), a bargain if compared to the cost of losing fresh foods that cost anywhere from $0.50 to $5/kg.

In this case and at the current cost of diesel fuel in Tanzania, liquid air technologies cost about three times as much to operate, but are still extremely cheap: $28 per day to keep 12 tonnes of food at 13°C, which is about $0.002 per kg. To operate the same sized cold storage at the same temperature using diesel fuel would cost only $10 per day, but a cryogenic engine would be considerably quieter and can run continuously without causing air pollution at the work site. In countries where diesel fuel prices are higher due to being landlocked (diesel prices in 2014 were $1.84/L in Burundi and $2.01/L in Malawi) or in island nations (in Madagascar diesel fuel was $1.69/L in 2014) then diesel/ICE powered refrigeration would be expected to be closer to the same cost as using liquid air. It should be noted that the cost of liquid air produced from renewable energy would depend almost entirely on its capital cost, and so would be essentially fixed for the life of the equipment – several decades - whereas diesel price is likely to rise.

Reduced postharvest losses alone could raise the value of each truckload by $900 – eight times the cost of the liquid air used to cool it. Better looking produce could also fetch a higher price.

The future of cold chain development in Tanzania

If a liquid air plant generating 75 tonnes/day were installed near the mines in eastern Tanzania, it could be used to supply the needed power for the refrigeration of perishable foods: enough to power over 140 medium sized cold rooms operating at 2°C, or 86 larger sized cold rooms operating at -18°C, and also for operating small tools and zero-emission vehicles.

If a liquid air plant generating 75 tonnes/day installed near Arusha, Tanzania were used to pre-cool and refrigerate fresh products during transport in 20ft reefers to domestic markets, each load of 4 to 6 tonnes would require a maximum of 2 tonnes of liquid air - depending upon set temperature – at a cost of $110 per tonne. The plant could supply enough liquid air per day to operate 38 reefers or up to 100 smaller trucks of 1 to 3 tonne capacity.

The direct benefits of cold transport would include postharvest loss reduction, enhanced market value per kg and longer shelf life. If postharvest losses decreased from 40% to 10% each load of 6 tonnes would result in 1800 kg more produce available for sale at the retail level. Even for lower value produce, this increase in marketable volume would improve earnings substantially. If market value was only $0.50 per kg, each 20ft reefer carrying 6 tonnes of produce would be worth $900 more - about 8 times the cost of the liquid air used to pre-cool and keep the load cold during transport.

Pre-cooling and shipping higher value produce using liquid air cooling technology would result in even higher returns on investment. Fresh produce with excellent appearance tends to obtain a higher market price, and even a small increase in market value per kg would further add to the profitability of a refrigerated transport operation in Tanzania. Fresh cold produce and many other kinds of perishable food products could be exported, sent to domestic markets, supply nearby safari tourist sites (i.e. Ngorongoro Crater, Arusha National Park, Mount Kilimanjaro and many more), local restaurants, hotels and conference centers. In every case, the decreased losses and increased market value would pay for the cost of cold transport many times over. If the relative increase in profits was only $500 per load, it would take less than 200 loads to pay for a new $100,000 vehicle. Reefers tend to have a working life of more than 10 years, and if the vehicle was used about 4 times per week, the ROI would be less than one year. Since a used vehicle would cost much less than a new one, the ROI would be even faster. Adding a back-haul load would further enhance profitability and ROI

India Case Study

While India produces an enormous quantity of fresh fruits, vegetables, milk and dairy products (more than 230 million tonnes annually) and policy makers talk a lot about cold chain development, the use of refrigerated transport and current cold storage capacity lags behind. CII reported in 2010 that more than 80% existing of cold storage capacity is used for potatoes, and only a few facilities are used for fruit and vegetable storage.

Table 13: Fresh produce in cold storage in the states of India
Statewise Break-up of Products Stored in Cold Storages – All India

State	Potatoes	Multi-Purpose	Fruits and Vegetables	Others
Uttar Pradesh*	99%	1%	0%	0%
West Bengal	99%	1%	0%	0%
Bihar	77%	23%	0%	0%
Gujarat	67%	28%	0%	0%
Madhya Pradesh	76%	24%	0%	0%
Andhra Pradesh	0%	88%	2%	10%
Maharashtra	1%	80%	4%	16%
Rajasthan	24%	75%	0%	1%
Karnataka	0%	94%	0%	6%
Other States	53%	44%	0%	3%
Total	**81%**	**17%**	**0.2%**	**1%**

Source: Agmarknet/AFF Analysis
Note: Uttar Pradesh includes Uttranchal

The National Horticulture Board collects information on the cold storage projects it supports, and very few are using technologies for improving energy efficiency (CII, 2010).

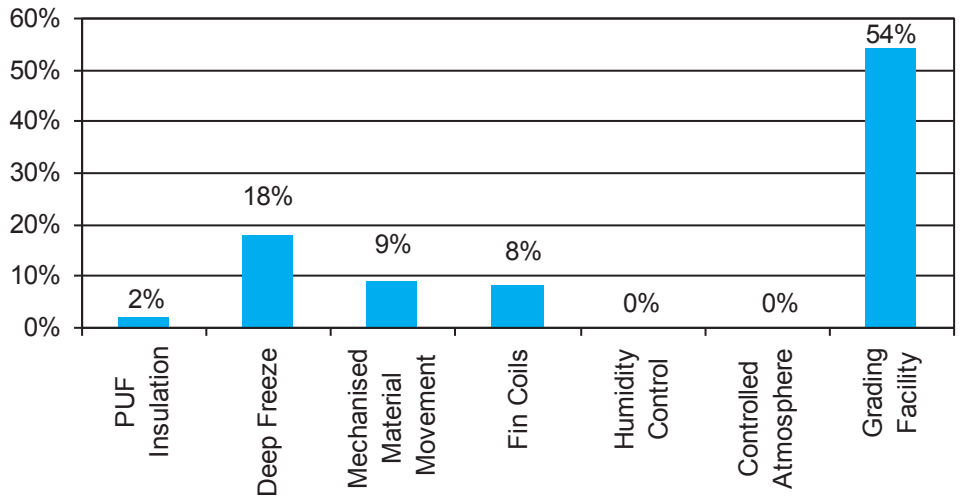


Figure 9: Current use of postharvest technologies in NHB cold storage projects in India

A lack of cold chain can lead Indian farmers to dump large amounts of produce without even sending it to market.

Existing refrigerated warehouses are poorly insulated and "woefully outdated" (Khanna and Miller Lui, 2013). A typical problem faced during peak season for lower value perishable crops in India is the lack of options for cold storage, processing to more stable forms or distant marketing via cold transport, which can lead to farmers or rural traders "dumping" (i.e. destroying) produce before it is shipped to market. Even under the best conditions, during the peak period of production, high volumes of seasonal fruits can overwhelm the transport and marketing system, leading to very high losses and waste. Temperate vegetables grown in northern mountainous regions have a ready market in the southern states, but without pre-cooling to 0° to 2°C and cold transport for traveling the 1000km distance, have an extremely short shelf life, especially during hot weather. The Government of India offers generous subsidies for cold chain development (50% matching grants), and eligible investments include plastic crates, packing houses, pre-cooling facilities, cold storage and refrigerated vehicles.

In 2011 there were only 25,000 refrigerated vehicles in all of India, and 80% are reported to handle fresh milk (Subin, 2011). By 2013, an estimated 8000 reefers were available to ship all the remaining perishables (Kohli, 2013) and serve 200 ports, plus an uncounted number of marketplaces and individual businesses. Industry estimates are that only 4 million tonnes of the 104 million tonnes of perishable foods transported between India's cities each year are shipped via refrigerated vehicles (Subin, 2011). Refrigerated vehicles (reefers) with a capacity of loads ranging from 2.5 to 20 tonnes can be found on the roads, but most are the smaller sizes.

The CII report (2010) states: "Given the lack of facilities along the transportation route and frequent hold ups at check posts and city borders, traders and farmers often face problems due to produce getting wasted and deteriorated in quality. The need of the hour, hence, is that of an effective cold chain network at these places in order to enable the transporter/ owner to store the produce in a congenial atmosphere. The provision of cool chambers and Plug in points at border areas, check posts and at frequent intervals along highways would reduce the present problems encountered in in-transit storage. This can be especially of value at key arterial routes such as the Golden Quadrilateral (GQ) covering 7,300 km of North-South East-West (NSEW) corridor connecting Delhi, Mumbai, Chennai and Kolkata. The "Green Corridor" concept of China is a good illustration of the same. China opened a 27,000-kilometer agricultural transport network that facilitates the transportation of fresh agricultural produce, including fresh vegetables, fruits, aquatic products, livestock, meat, eggs and milk. Along the network, special passages are opened for vehicles carrying perishable products."

A good number of large private companies have recently been entering the fruit and vegetable retailing sector, with big plans to find economic opportunities in these challenges. These include Reliance Industries, Ranger Farms, Bharti, ITC, Food World., Spencer, Godrej, Future group (Big Bazaar and Food Bazaar), and Aditya Birla Group. Similarly, companies such as Adani Agrifresh Ltd., Fresh and Healthy Enterprises, Harshana Naturals, Wal-Mart have entered into wholesale marketing of fresh foods (Ahmad et al, 2014). A huge barrier remains however, since even these large companies have been unwilling to make the low-level postharvest infrastructure investments, such as in pre-cooling and reefer transport, that they may initially have intended. Despite the facts showing positive returns

on investment for many crops and potential markets, the perceived costs are higher than expected returns, and there are real fears that currently positive returns may evaporate if diesel fuel prices rise suddenly if current subsidies are removed. Another concern for those investing in cold chain technologies is that there may be gaps in the cold chain that are beyond their control. Postharvest losses are therefore currently extremely high (30 to 40% is being lost depending on the crop), the shelf life and market value at retail level is lower than intended, and the quality of fresh food offered for sale to higher end consumers is only poor to fair.

Using liquid air based refrigeration technologies, it is technically possible to provide pre-cooling of freshly harvested produce inside a refrigerated truck on the way to a packinghouse or direct market buyer. The enormous cooling power provided by liquid air can reduce field heat (the natural heat being generated by the produce itself when it is removed from the plant in the field) as well as handle the heat load (due to produce respiration plus environmental heat reflecting from the road, solar radiation and friction during transport). Mobile pre-cooling combined with "just in time" supply chains could relieve the pressure on India's retail food industry to invest in stationary pre-cooling operations in farming communities and modern cold storage in the cities. A "tank of cold" mobile food handling, distribution and storage solution could decentralize agri-business opportunities for value chain actors at every scale, and help to move high volumes of high quality, lower cost fresh foods to India's cities on a daily basis.

India Scenario #1

Many companies are active in the growing refrigerated transport sector in India – these include Carrier, Denso, Fedders Lloyd, Freeze King, Haiger, Hwasung, Modiline, Sidwal and Thermo King. Clip on reefer units are sized at 5 to 6kW and require 3 to 5 L of diesel fuel per hour, depending upon target temperature. For traditional diesel powered reefer transport, the load must be pre-cooled prior to loading at a separate perishables services facility (typically at a cost of $0.03 to $0.04 /kg).

Actual costs per load will depend on the volume to be transported, type of container used for cooling/ packing, target temperature needed (varies by crop), the distance to be traveled, and any delays. A few examples are shown in Table 14, which provides some details on costs, in each case comparing current options (using electricity or diesel fuel) to the use of liquid air technologies.

Table 14: Estimated comparative costs for refrigerated transport in India depending on power source and target temperature (assume an initial temperature of 30°C, a market value of $1 per kg and a standard 10 hour journey)

	4 tonne capacity (typical 20 ft reefer) Load market value $4000	
Reefer target temperature	Diesel/ICE 5kW engine	Liquid Air /cryogenic engine
2°C 8 hours to 7/8ths cool	Precooling while in transit is not possible (requires 27kW/hour) Pre-cooling fee = $160 $58 to maintain temperature Total = $218 $0.05/kg	$283 to pre-cool (1572 kg) $20 maintain temperature Total= $303 $0.08/kg
12°C 8 hours to 7/8ths cool	Precooling while in transit is not possible (requires 20kW/hour) Pre-cooling fee = $120 $52 to maintain temperature Total = $172 $0.04/kg	$205 to pre-cool (1140 kg) $15 maintain temperature Total= $220 $0.06/kg
18°C 8 hours to 7/8ths cool	Precooling while in transit is not possible (requires 18kW/hour) Pre-cooling fee = $120 $46 to maintain temperature Total = $166 $0.04/kg	$180 to pre-cool (1000 kg) $10 maintain temperature Total= $190 $0.05/kg

‡ A newly built 300tpd liquefier running on grid electricity at $135/MWh (gasworld) could sell liquid nitrogen at $0.12/kg, including repayment of capital, 15% distribution charge and 10% margin. On the same basis, liquid air could sell for $0.10/kg.

Diesel subsidies in India are expected to be withdrawn soon, and with subsidy excluded the current price should be around $1.11/L. The price of liquid nitrogen in India today is estimated by gasworld to be $0.18/kg 'ex works' or $0.20 delivered. Our own ground up analysis suggests liquid nitrogen could in fact be produced and delivered for around half that price, and the cost of liquid air would be 20% lower again, because of its smaller energy requirement.‡ Because India has substantial spare nitrogen production capacity, we have kept $0.18/kg as the basis for our calculations below, but it should be noted this is a highly conservative assumption. We estimate the marginal cost of liquid air from a newly built plant powered by grid electricity at current prices would be just $0.7/kg.

In order to use traditional diesel powered reefers, a separate pre-cooling facility must be used prior to loading the vehicle, but these are generally not found in the rural areas of India where produce and other perishable foods are produced. If a pre-cooling facility is available locally, the fees charged for pre-cooling services generally range from $0.03 to 0.05/kg, which would add at least $120 to the cost of maintaining temperature in a traditional diesel powered 20 ft refrigerated shipment.

In this case, the amount of liquid air (or nitrogen) needed to pre-cool a 4MT load would be too large for a typical 20 ft reefer to carry (1000 to 1600 kg, requiring a 1230 to 1968 L fuel tank), so pre-cooling would need to be done at a centralized site prior to long distance transport. A liquid air plant generating 75 tonnes/day with a depot "Tank of cold" installed near any of India's major cities could be used as a fueling station for refrigerated transport/pre-cooling fresh products during shipping to the domestic markets located within a 10 to 12 hour drive. Each reefer load of 4 tonnes would require 1 to 1.5 tonnes of liquid air at a cost of $180 per tonne to pre-cool the load. The amount of liquid air needed to maintain temperature in a 4MT load would range from 55 to 110 kg for a typical reefer (requiring a 68 to 135 L fuel tank).

Costs for combined pre-cooling and cold transport in India using liquid air technologies range from $0.05 to 0.08 per kg, a significant investment for small-holder farmers, but a small amount to pay to prevent economic losses that can equal 1/3 or more of the total load when the cold chain is not used. Based on current pricing of fossil fuels in India, diesel powered options for cold transport would cost about one third less that of liquid air/cryogenic technologies.

Liquid air technologies would be a significant investment for Indian small-holders but a small price to pay to prevent losses that can equal one third of the total load.

India Scenario #2

The lack of access to pre-cooling facilities near the farm have a serious impact on the food supply, and contribute to current the high levels of postharvest losses experienced in India. It is possible to imagine a "Tank of cold" depot in each village, where each truckload of fresh produce coming from local farms could be pre-cooled before making its departure to a distant centralized packinghouse, or to an urban or suburban distribution center for a modern food retailer. Each vehicle would require 250 kg to 1500 kg of L.Air for pre-cooling, depending upon it size and target temperature for the load.

While $0.05 to 0.08/kg is relatively a high cost for liquid air powered cold transport compared to the use of diesel powered reefers (at $0.02 to 0.06/kg), the required pre-cooling facilities are typically not found

Table 15: Estimated comparative costs for refrigerated transport in India depending on size of load, power source and target temperature (assume an initial temperature of 30°C, a market value of $1 per kg and a standard 10 hour journey)

	1 tonne capacity (small reefer van) Load market value $1000	
Reefer target temperature	Diesel/ICE 5kW engine	Liquid Air /cryogenic engine
2°C 8 hours to 7/8ths cool	Precooling while in transit is not possible (requires 7.5kW/hour) Pre-cooling fee = $40 $23 to maintain temperature Total = $63 $0.063/kg	$71 to pre-cool (393 kg) in transit $5 to maintain temperature Total= $76 $0.076/kg
12°C 8 hours to 7/8ths cool	$18 to pre-cool (16 L) $7 to maintain temperature Total= $25 $0.025/kg	$51 to pre-cool (285 kg) in transit $4 to maintain temperature Total= $55 $0.055/kg
18°C 8 hours to 7/8ths cool	$18 to pre-cool (16 L) $5 to maintain temperature Total= $23 $0.023/kg	$45 to pre-cool (250 kg) in transit $3 to maintain temperature Total= $48 $0.048/kg

in rural India. In addition, diesel powered vehicles often have trouble getting access to city centers, as many of India's large cities have begun to limit access for diesel powered vehicles. While relatively large quantities of liquid air are required for rapid pre-cooling, this could be done while the vehicle was parked and loaded, prior to beginning transport. This added cost (approximately $0.02 /kg) could be easily covered as part of a larger service fee for delivering cold, fresh foods directly to cold storage or retail distribution centres either in cities or on the outskirts.

India Scenario #3

A look at the potential for city-based home deliveries of perishable foods in India using liquid air technologies opens many possibilities for employment and new small-scale businesses. A low emission transportation option will be an important part of developing the cold chain and reducing food losses, since many of India's large cities have begun to limit access for diesel powered vehicles, and especially for the smaller motor taxis that emit particulate matter and cause air pollution.

Considering only the 1 tonne reefer van for this scenario, and assuming the vehicle would be loaded with pre-cooled foods at a distribution center or cold storage warehouse and use approximately 4 times the amount of liquid air needed to maintain temperature in a vehicle that is sealed during transit, the cost for 10 hours of local deliveries using a liquid air/cryogenic engine would be only $0.01 per kg. The vehicle storage compartment would need to be opened many times during the day to make home deliveries, which would allow the cold to escape, and require the use of more fuel to re-cool the hot ambient temperature air that enters the storage compartment, so a design with several smaller compartments would serve to help prevent the loss of cold.

In this case, for produce shipped at both 2°C (for foods that need cold) and a 12 °C (for tropical fruits, tomatoes, and other foods that are chilling sensitive), the cost for liquid air powered cold transport is only $0.1/kg, which is lower when compared to the use of diesel powered reefers (at $0.01 to 0.02/kg). In this case, for these very small vehicles, the 5kW diesel engine's standard fuel usage to operate at minimum capacity will cost more than it does to operate a cryogenic engine sized properly for the required cooling operation. The size of the "tank of cold" to carry the needed fuel for the day would be small enough to fit on the vehicles (1kg of liquid air = 1.23L). Since the required pre-cooling facilities are typically not to be found in rural India, and diesel powered vehicles often have trouble getting access to city centers, using liquid air refrigeration technologies in these small vehicles could have a quick payback for investors.

The added costs of using reefer transport in India could be easily covered as part of a larger service fee for delivering cold, fresh foods directly to the urban and suburban consumer. Individual businesses or franchised transport companies can be imagined to step forward to fulfill the need and make a nice profit. Linking distribution centers directly with consumers could solve several major food chain distribution problems all at once, since many of the new "modern retail" businesses are having trouble finding reasonably priced land in city centers, and lack of the use of the cold chain currently cuts deeply into their bottom line, as losses can often be as high as 40%.

Future potential for value addition in India

The few examples provided in Table 17 demonstrate the potential of value addition using liquid air based technologies for various crops moving to markets in India. In each case, the value addition technology could be established via a variety of business models. Three examples are: owned/operated by a group of food producers, provided as a fee for service by a local agri-business, or as a stand-alone business for a company that procured fresh foods from local

Table 16: Estimated comparative costs for refrigerated transport in India depending on size of load, power source and target temperature (assume an initial temperature of 30°C, a market value of $1 per kg and a standard 10 hour day)

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

Table 17: Examples of value addition via freezing, cold storage or cold transport in India

	Commodities		
	Tropical fruits	Onions	Fresh fruits and vegetables, milk, dairy and fish
Value addition at the village level by freezing seasonal fruits (blast freezing or IQF)	X		
Cold storage at village level to extend season and marketing windows (0°C for maximum shelf life)		X	X
Pre-cooling fresh produce during shipping from farm to market	X		X
City based home deliveries of perishable foods			X

Reduced postharvest losses alone could increase the value of each truckload by $450 or five times the cost of the liquid air needed to cool it.

producers. Each business model includes a varying set of new local jobs, opportunities for investment and potential income generation.

If a liquid air plant generating 75 tonnes/day were installed near Chandigarh in Haryana State and used for pre-cooling fresh products and refrigerated transport to domestic markets located within a 10 to 12 hour drive, each load of 6 tonnes would require about 2 tonnes of liquid air at a cost of $360. The plant could supply enough liquid air fuel per day to operate the refrigeration units on 38 reefers or 150 small trucks. Only trucks made with the insulated box and reefer unit permanently attached to the chassis are eligible for a 50% governmental subsidy in India.

The direct benefits of cold transport would include postharvest loss reduction, enhanced market value per kg and longer shelf life. In the case of home deliveries using small reefer trucks, one vehicle could deliver fresh and/or frozen foods to 50 customers per day, as compared to 50 customers driving individual passenger vehicles to shop at the food market. Some of India's governmental leaders are skeptical that postharvest losses are as high as has been reported, but even using their more conservative estimates, losses are at least 25% for most crops (Socio-Economic Research Planning Commission, no date). If using the cold chain decreased postharvest losses from 25% to 5%, each load of 3 tonnes in a small reefer van would result in 600 kg more produce available for sale at the retail level. Even for lower value produce, this increase in marketable volume will have a major positive result on earnings. If wholesale market value was only $0.75 per kg, each 12ft reefer van carrying 3 tonnes of produce would be worth $450 more (about 5 times the cost of the liquid air used to pre-cool and keep the load cool during transport).

Pre-cooling and shipping higher value produce using liquid air cooling technology would result in even higher returns on investment. If the relative increase in profits was $450 per load, it would take about 155 loads to pay for a new $70,000 vehicle. Reefer vans tend to have a working life of 7 to 10 years if the insulation in the box and refrigeration unit is well maintained, and if the vehicle was used about 3 times per week, the ROI would be less than one year. Since a used vehicle would cost less, the ROI would be even faster. Adding a back-haul load would further enhance profitability and ROI.

Fresh produce with excellent appearance also tends to obtain a higher market price (the goal of the many large companies that are jumping into the retail market space), and even a small increase in market value per kg would further add to the profitability of a refrigerated transport operation in India. Fresh cold produce and many other kinds of perishable food products handled via a cold chain could be exported, sent to domestic markets, supply nearby tourist sites (i.e. Taj Mahal, Red Fort, Dharamsala and many more), local restaurants, hotels and conference centers. In every case, the decreased losses and increased market value would pay for the cost of cold transport using liquid air technology many times over.

Potential benefits of food waste reduction

The following data is provided as an overview to determine how much value potentially could be added due to postharvest loss reduction without any increase in market value from cold chain using available statistics for crops (e.g. the FAO STAT online database). If we assume current losses of 30% (conservatively), and compare these to a target rate of 15% losses, we can anticipate a significant gain in food availability in both eastern Africa and Southern Asia without any additional production.

Halving postharvest food loss would provide Tanzania with almost 2 million tonnes of additional food worth $430 million.

Table 18: Economic value at the wholesale level of 12 of the top Tanzanian fruit and vegetable crops

FAOSTAT 2009-2010	Tanzania				
Tsh 1600 = $1	Total	Market value	Market value	Total annual market value	Economic Value of 30% losses
	Annual production (tonnes)	(Tsh/tonne)	($/tonne)	(Million $)	(Million $/year)
VEGETABLES					
Cabbage	150,000	400,000	250	$37.5	$11.3
Cassava	5,916,440	416,000	260	$1,538.3	$461.5
Onion, dry	29,595	672,000	420	$12.4	$3.7
Peas, green	6,313	1,500,000	940	$5.9	$1.8
Plantains, green	517,993	640,000	400	$207.2	$62.2
Potatoes, Irish	860,980	125,000	78	$67.2	$20.1
Sweet potatoes	1,417,200	267,000	167	$236.7	$71.0
Tomatoes	203,909	200,000	125	$25.5	$7.6
FRUITS					
Bananas	3,506,400	300,000	188	$659.2	$197.8
Citrus fruits	37,355	480,000	300	$11.2	$3.4
Mangoes	320,000	320,000	200	$64.0	$19.2
Pineapples	30,000	800,000	500	$15.0	$4.5
TOTAL	12,996,185			$2,880.1	$864.0
15% losses	1,949,428				$432.0

http://faostat3.fao.org/faostat-gateway/go/to/download/Q/*/E
http://www.theigc.org/sites/default/files/Leyaro%20and%20Morrissey%202013.pdf

Fruit and vegetables – national impacts

Table 18 presents the economic value at the wholesale level of a few of the top Tanzanian fruit and vegetable crops, selected due to high volume and/or high market value. Overall, local open markets are the primary source of food items consumed in mainland Tanzania. Households across all income groups and regions purchase at least 60% of their food from markets as opposed to home production (World Food Program, 2010).

Onions are packaged and sold in 100kg bags although they usually contain up to 140 to 150kg. They are sorted and packaged into smaller net bags which officially hold 14kg but usually contain 16-20kg. Cassava, Irish potatoes, sweetpotatoes and cooking bananas (green plantains) are considered 'non-traded' crops, but are sold locally in domestic markets and are very important foods in terms of local food security.

These 12 top crops alone account for nearly $2.9 billion/year of market value of perishable food crops in Tanzania, of which an estimated $864 million is lost before consumption. Reducing postharvest losses of just these top fresh produce crops to 15% via use of cold chain technologies could provide consumers in Tanzania with 1.95 million tonnes of additional high quality nutritious, with a market value of approximately $432 million. In a country where average cash earnings in agricultural sector jobs are reported to be $2300 per year (Tanzania National Bureau of Statistics 2013), these relatively minor improvements represent the economic development equivalent of 188,000 new full time jobs.

Turning to India, Table 19 presents the economic value at the wholesale level of a few of the top fruit and vegetable crops of India, selected due to high volume and/or high market value. Overall, local open markets are the primary source of perishable food items consumed in India.

Table 19: Economic value at wholesale level of 16 of the top fruit and vegetable crops in India

FAOSTAT 2009-2010	India				
Rs 60 =$1	Total annual production (tonnes) FAOSTAT 2009	*Market value (Rs/tonne)	Market value ($/tonne)	Total annual market value (Million $)	Economic Value of 30% losses (Million $/year)
VEGETABLES					
Cabbage	6,869,000	6320	105	$721.2	$216.4
Cauliflower & broccoli	6,531,900	11670	195	$1,273.7	$382.1
Eggplant	10,377,600	8300	138	$1,432.1	$429.6
Okra	4,528,000	14090	234	$1,059.6	$317.9
Onion, dry	12,158,800	11450	191	$2,322.3	$696.7
Peas, green	2,916,000	28230	470	$1,370.5	$411.2
Potatoes	34,390,900	10370	172	$5,915.2	$1,774.6
Sweet potatoes	1,119,700	7000	117	$131.0	$39.3
Tomatoes	11,148,800	10180	170	$1,895.3	$568.6
FRUITS					
Apples	1,985,000	57080	950	$1,885.8	$565.7
Bananas	26,469,500	10710	179	$4,738.0	$1,421.4
Citrus fruits (kinnow)	559,976	20410	340	$190.4	$57.1
Mangoes (total production includes mangosteen, guava)	12,750,000	19000	316	$4,029.0	$1,208.7
Papaya	3,913,500	11400	190	$743.6	$223.1
TOTAL	122,317,776			$25,712.8	$7,713.8
15% losses	18,347,666				$3,856.9

* http://www.nhb.gov.in/OnlineClient/MonthwiseAnnualPriceandArrivalReport.aspx
http://faostat3.fao.org/faostat-gateway/go/to/download/Q/*/E

Halving postharvest food loss would provide India with 18 million tonnes of additional food worth almost $4 billion.

Reducing postharvest losses of just these top fresh produce crops to 15% via use of cold chain technologies could provide consumers of the in India with 18.3 million tonnes of additional high quality nutritious foods, with a market value of nearly $3.9 billion. In a country where many people go hungry, investments in this long ignored sector are crying for attention. Protecting food from losses after it has been produced, harvested, and transported makes more sense than continually trying to increase production to make up for the high losses between the farmer and the consumer in India.

Fresh produce – national and regional impacts

The benefits of reducing food waste are clearly even greater if we count not only fruit and vegetables but all fresh produce, including meat, milk and dairy, and widen the assessment from individual countries to entire regions.

In 2009 in Eastern Africa, 50 million tonnes of cereals were produced, while 82 million tonnes of fresh produce (fruits, melons, root crops and vegetables) and 20 million tonnes of fish, meats milk and dairy products were produced. Reducing postharvest losses of this fresh produce from 30% to 15% via use of cold chain technologies could provide consumers of the region with 15 million tonnes of additional high quality nutritious foods.

Tanzania accounts for about 18% of the total production in East African region, while India accounts for 71% of the total product in the South Asia region. Reducing postharvest losses of this fresh produce from 30% to 15% via use of cold chain technologies in Tanzania could provide consumers of the region with more than 2.7 million tonnes of additional high quality nutritious foods, and in India the additional food available for consumption would increase by the enormous quantity of 51.8 million tonnes.

Table 20: Perishable food production in South Asia and India (FAOSTAT 2009)

	South Asia		India	
	Area harvested (Ha)	Total production (Tonnes)	Area harvested (Ha)	Total production (Tonnes)
Citrus fruits	1,422,717	14,717,100	939,080	8,623,080
Other fruits	8,829,479	94,385,117	6,177,443	68,975,172
Vegetables and Melons	8,832,873	122,717,815	6,751,140	90,634,815
Root and Tuber crops	3,621,743	61,541,128	2,232,800	45,133,600
Fish		10,806,862		6,646,244
Meats		12,417,766		6,015,611
Milk		164,467,846		115,868,000
Dairy products		4,363,951		3,176,550
TOTAL PRODUCED		485,417,585		345,073,072
30% losses (currently experienced)		145,625,276		103,521,922
Amount available for consumption (Total – 30%)		339,792,310		241,551,150
Additional food available if losses were reduced to 15%		72,812,638		51,760,961

According to the Euromonitor (2013), the vast majority of India's perishable foods are handled and marketed in their fresh state. In 2010, onions accounted for 60% of India's vegetable crops exports, an increase from 50% in 1999 (Ministry of Commerce, 2011). Proper cold storage and cold transport of fresh produce and onions intended for export in India could reduce the current high level of postharvest losses.

Tanzania's current cold storage capacity of 0.02 million cubic meters compares to 24.65 million cubic meters in Great Britain (IARW 2012). The total population of Tanzania in 2012 was 45 million (Tanzanian National Bureau of Statistics) compared to 53.5 million people in England (UK Office for National Statistics).

Dar es Salaam seaport currently handles over 9 million tonnes of cargo per year which is about 95% of all Tanzania's import and export volumes. There is no cold storage facility at the Dar es Salaam port at present, however, Tanzania International Container Terminal Services (TICTS) has 92 reefer plug-in points for refrigerated containers (www.logcluster.org/ops/som11a). The overall cost of moving a tonne of freight along East Africa's key trade routes is $200-$300, estimates the World Bank, and takes between 200 and 600 hours. The extensive dwell-times in ports and in Customs clearance accounts for about 80% of the time (The East African May 11 2013 http://www.theeastafrican.co.ke/-/2456/2456/-/1bxxmm/-/index.html).



Figure 10: Map showing the size of Tanzania in relation to the size of the UK (Google 2014).

Scheduled for completion in 2017, the Bagamoyo port, now under construction (via an $11 billion deal with China), will have the capacity to handle twenty times more cargo that of Dar es Salaam, which is currently the country's largest port. The new mega-port "… will be built with a draft sufficient to accommodate higher capacity container vessels up to 10,000 TEU and beyond, as well as possess specialised roll-on roll-off berths and other cargo berths. The overall scale of the planned development is such that it will provide a highly competitive solution to Kenya's port expansion plans in Mombasa and Lamu which, as well as catering for national trade, are focused

on meeting the needs of surrounding landlocked countries such as Uganda, Rwanda and Burundi." The Bagamoyo port will have the capacity to handle 20 million containers a year (55,000 Twenty foot Equivalent Units or TEUs per day) compared to the Dar es Salaam port which handles only 500,000 to 800,000 containers per year.

If only 5% of this cargo was refrigerated, an estimated 2740 TEUs/day could be used for handling export crops shipped from farming communities via future liquid air/cold chain technologies. The crops could be sourced year around from collectively managed packinghouses serving diverse Tanzanian farming communities including Mbeya/Iringa, Morogoro/ Mgeta, Tanga/Lushoto and Arusha/Moshi.

Conclusion

While the scenarios presented have focused on East Africa and South Asia, there is no reason to expect the economic outcomes to be much different in other locations where postharvest food losses are high and the cold chain is not currently in common use. Policy makers in the agriculture, energy, education and food sectors must work together to promote the use of appropriate cold chain technologies, improve logistics, maintenance, services, infrastructure, education and management skills, and create sustainable markets for the design, use and funding of cold chains for reducing perishable food losses.

Potential side benefits from the use of reasonably priced liquid air technology for cold chain development simply abound for rural areas in Africa, India and other developing countries -- expected results include the creation of more jobs, enhanced food safety, new marketing options, and more wealth generation from the agricultural sector as value addition and short term cold storage can be introduced at the village level. Impacts from these changes would include less urban migration, less air pollution, less dependence on imported fossil fuels, and the opening of a wide range of new opportunities in rural food handling (i.e. providing rapid cooling after heat treatments, which are required for export of certain fruit crops that are susceptible to fruit flies), food processing industries (small scale IQF and freeze drying), home refrigerators, phase change materials, rapid chillers, small zero-emission vehicles (ZEVs), and mini-electric generation plants at the village level. A rural community with its own solar or wind powered liquid air 1MW to 5 MW electricity generation plant could support a wide array of small businesses and village level industries. The ultimate potential of the uses of liquid air technologies can be limited only by our collective imagination.

References and for further information

Ahmad, Md. Shamsher, Md. Abu Nayyer, Ahmar Aftab, Basant Nayak, and Md. Wasim Siddiqui. 2014. Quality Prerequisites of Fruits for Storage and Marketing. Journal of Postharvest Technology 02 (01): 107-123.

Chemonics International 2013. The fresh fruit and vegetable markets of East Africa. http://www.competeafrica.org/Files/FFV_Markets_of_East_Africa_final_approved_and_compressed_July_17_2013.pdf

CII, 2010. CII /Min of Ag Report of Task Force on Cold Chain Development in India 2008-09. (198 p. draft)

ColdFront™ http://www.praxair.com/industries/food-and-beverage/cryogenic-freezing-and-chilling

GizMag 2012. Another zero-emissions powerplant emerges - the Dearman Engine runs on liquid air. Accessed online March 2014, http://www.gizmag.com/dearman-zero-emissions-engine/21201/

GHI. 2010. The Global Harvest Initiative 2010 GAP Report: Measuring Global Agricultural Productivity.

Gustavsson, J. et. al. 2011. Global Food Losses and Food Waste: Extent, Causes and Prevention. UN FAO: Rome http://www.fao.org/fileadmin/user_upload/ags/publications/GFL_web.pdf

FAOSTAT 2009. online database http://faostat3.fao.org/faostat-gateway/go/to/download/Q/*/E Accessed during March 2014.

Freshline™ http://www.airproducts.com/products/gases/nitrogen/industry/product-list/other-products/freezing-other-products.aspx?itemId=BF54159EC22F44078DD542740B10E060&segId=CB5DAA7863C34E77A3866AD9B7028573

IARW 2012. IARW Global Cold Storage Capacity Report (proprietary document).

IIR. 2009. The role of refrigeration in worldwide nutrition. 5th Informatory Note on Refrigeration and Food. http://www.iifiir.org/userfiles/file/publications/notes/NoteFood_05_EN.pdf

Joshi, R., D K Banwet, R Shankar, (2009) "Indian cold chain: modeling the inhibitors", British Food Journal, Vol. 111, Issue: 11, pp.1260 – 1283 http://www.emeraldinsight.com/journals.htm?articleid=1822173

Khanna, A. and Miller Lui, T. 2013. Incredible India. Cool insights from the Global Cold Chain Alliance. http://foodlogistics.epubxp.com/i/174477/15

Kitinoja, L. 2013. Use of cold chains for reducing food losses in developing countries. PEF White Paper No. 13-03 La Pine, Oregon (USA): The Postharvest Education Foundation. 16pp. http://postharvest.org/Use%20of%20cold%20chains%20PEF%20white%20paper%2013-03%20final.pdf

Kitinoja, L. and AlHassan, H. A. (2012). Identification of Appropriate Postharvest Technologies for Improving Market Access and Incomes for Small Horticultural Farmers in Sub-Saharan Africa and South Asia. Part 1: Postharvest Losses and Quality Assessments. Acta Hort (IHC 2010) 934: 31-40.

Kohli, P. 2010. Future of Cold Chain – India. (powerpoint presentation)

http://www.slideshare.net/Adrienna/india-cold-chain-opportunity-challenges-2013

Lipinski, B., C. Hanson, R. Waite, L. Kitinoja, T. Searchinger, J. Lomax. 2013. Creating a Sustainable Food Future, Installment Two: Reducing Food Loss and Waste. World Resources Institute Working Paper: June, 2013. http://www.wri.org/publication/reducing-food-loss-and-waste

MMA, 2008. High Value and Fresh Vegetables for Local Market Sub Sector Analysis Tanzania.

Ministry of Commerce, India. 2011. Export Import Data Bank Version 6.0 – TRADESTAT, Department of Commerce, Ministry of Commerce and Industry, Govt. of India, data accessed from http://commerce.nic.in/eidb/default.asp, in March 2014

Pack-n-Cool™ A full set of plans for construction of an insulated trailer equipped with the CoolBot™ has recently been developed by scientists at North Carolina State University and is available online for free download http://plantsforhumanhealth.ncsu.edu/2012/08/20/pack-n-cool/

Socio-Economic Research Planning Commission, India. no date. Estimation Loss of Horticulture Produce due to Non-availability of Post Harvest & Food Processing Facilities in Bihar & UP. 36p.

Subin, R. 2011. India's cold chain industry. IACC India. US Commercial Service. https://www.iaccindia.com/userfiles/files/India's%20Cold%20Chain%20Industry.pdf

Tanzania National Bureau of Statistics 2013. http://www.kazi.go.tz/documents/takwimu/Employment-and-Earning-Survey-Report-2012-.pdf

Thompson, J.F., P.E. Brecht, and T. Hinsch. 2002. Refrigerated trailer transport of perishable products. University of California, Agriculture and Natural Resources Publication 21614, 28 pp

USDA Handbook 66. 2004. Commercial storage of fruits, vegetables and nursery stocks. http://www.ba.ars.usda.gov/hb66/

Winrock International. 2009. Empowering agriculture: energy solutions for horticulture. USAID Office of Infrastructure and Engineering and the Office of Agriculture; 79p. Available online: http://ucce.ucdavis.edu/files/datastore/234-1386.pdf

Notes: Fuel prices

Island nations have much higher electricity prices per kWh, landlocked countries often pay higher diesel fuel prices

http://dx.doi.org/10.1016/j.apenergy.2013.12.043
http://cleantechnica.com/2012/02/19/us-virgin-islands-launches-15-year-energy-initiative-to-reduce-fossil-fuel-use-60/

to-swap-diesel-power-for-renewable-sources.html?_r=0

ABOUT THE LIQUID AIR ENERGY NETWORK

Working with the Birmingham Centre for Cryogenic Energy Storage (BCCES) and the Centre for Low Carbon Futures (CLCF), the Liquid Air Energy Network (LAEN) was founded to explore the potential of liquid air as an energy vector, and to ensure Britain maintains its lead in this promising new technology and secures the full energy, environmental and economic benefits. Its research is conducted in collaboration with technology developers, industry, universities and partner organisations. This is the first report in a series of policy and technology guides. For more information please visit www.liquidair.org.uk.

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June 2014

978-0-9927328-9-9

Liquid Air Energy Network