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CLEAN COLD AND THE **GLOBAL** GOALS

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‘COOLING IS VITAL; WITHOUT IT, THE SUPPLY OF FOOD, MEDICINE AND DATA WOULD SIMPLY BREAK DOWN. *CLEAN COLD* IS VITAL FOR SUSTAINABLE DEVELOPMENT; WITHOUT THAT, WE CANNOT ACHIEVE THE UN’S GLOBAL GOALS.’

PROFESSOR TOBY PETERS

ABOUT THE BIRMINGHAM ENERGY INSTITUTE

BIRMINGHAM ENERGY INSTITUTE

The Birmingham Energy Institute is the focal point for the University and its national and international partners, to create change in the way we deliver, consume and think about energy. The Institute harnesses expertise from the fundamental sciences and engineering through to business and economics to deliver co-ordinated research, education and the development of global partnerships.

The Midlands region is renowned for its ability to drive technology revolution and provide a nationally leading manufacturing base. It is the home of pioneers such as Watt, Boulton and Priestly, and the internationally recognised companies of Rolls-Royce and Jaguar Land Rover.

The City of Birmingham is setting the green low carbon agenda nationally. Birmingham City Council’s Green Commission launched a Vision Statement with an aim of building a leading green city and reducing CO_2 emissions by 60% by 2027 against a 1990 baseline. The UK Government is committed to facilitating a cost-effective approach to meeting the UK’s emissions by at least 80% of 1990 levels by 2050. The Birmingham Energy Institute is working with these stakeholders to realise this transition.

CLEAN COLD AND THE GLOBAL GOALS

You cannot fault the ambition: the United Nations intends to put the world to rights within fifteen years. By 2030, its Sustainable Development Goals ('Global Goals') commit the international community to abolish poverty and hunger; provide good healthcare, education, decent work, gender equality and access to clean water for all; and to promote affordable clean energy, sustainable cities, infrastructure, climate action, economic growth and responsible consumption. If the Global Goals are achieved, says the UN, 'the lives of all will be profoundly improved and our world will be transformed for the better'.[1]

But the challenge is huge. The Millennium Development Goals that expired in 2015 made enormous advances, but progress was uneven and many of the targets were missed.[2] A huge research effort is now under way into how to realise the Global Goals, much of it inter-disciplinary work on the interconnectedness of the challenges. Many of the linkages – between economic growth and pollution, for example, or water shortage and conflict – are already well understood. But one element that is critical to achieving almost all the Global Goals has been almost entirely ignored so far: **cooling.**

Until recently cooling was the Cinderella of the energy debate – but it is a pillar of civilisation. Without it, the supply of food, medicine and data would simply break down. And life in many parts of the world would be scarcely tolerable without air conditioning. Yet billions of people in developing countries live without cooling and suffer the consequences daily through hunger and ill-health. The lack of adequate 'cold chains' of refrigerated warehousing and transport causes two million vaccine preventable deaths each year, and the waste of 200 million tonnes of food – with consequences far beyond hunger and inflated food prices. Food wastage occupies a land area almost twice the size of Australia[3]; consumes 250km^3 of water per year, three times the volume of Lake Geneva; and emits 3.3 billion tonnes of CO_2, making it the third biggest emitter after the US and China.[4]

But if cooling is vital, it is also dirty. One estimate suggests that refrigeration and air conditioning cause 10% of global CO_2 emissions[5] – including both energy emissions and leaks of highly potent HFC refrigerant gases – which is three times that attributed to aviation and shipping combined.[6] Another suggests cooling emissions currently account for 7% of the total, but are growing three times faster, so cooling's share will almost double to 13% by 2030.[7] The recent global agreement to phase out HFC refrigerant gases may restrain emissions growth a little, but does nothing to tackle the 75% of cooling emissions that come from energy consumption.[8] Nor is the climate cooling's only victim: refrigerated vehicles also emit grossly disproportionate amounts of nitrogen oxides (NOx) and particulate matter (PM), the toxic pollutants that kill 3.7 people million worldwide each year. In Africa, air pollution kills more people prematurely than dirty water or childhood malnutrition.[9]

But this is just the start of the cooling pollution crisis. Demand for cooling is booming in fast growing economies such as China and India, largely driven by urbanisation and the rapid emergence of an Asian Pacific middle class – predicted to rise to 3 billion by 2030[10], whose spending power could rise to $33 trillion.[11] Their lifestyles – changing diets, improved healthcare, online data and air conditioning – will be built on cold.

Air conditioning is a case in point. Researchers at Lawrence Berkeley National Laboratory estimate the global stock of room air conditioners will rise by an additional 700 million by 2030, and 1.6 billion by 2059.[12] And according to another forecast, by the end of the century global air conditioning will consume 10,000TWh[13], about half the electricity consumed worldwide for all purposes in 2010.

So as the world's population heads to 9 billion by mid-century, increasing projected food demand by 60%[14], there is no question that we will need far more cooling. We will need it to conserve food, water and other resources; tackle poverty, hunger, health and climate change; and underpin growth and development. But if the new cold chains, data centres and air conditioners are cooled with conventional technologies, we will only solve one set of problems by creating another – quite possibly an environmental catastrophe.

There is an urgent need to resolve the cooling dilemma: to provide *clean* cold, through novel low carbon and zero-emission technologies such as the Dearman engine, and new approaches such as the 'cold economy' (for a full explanation see Appendix). These recent innovations mean it is finally possible to secure all the benefits of cooling whilst mitigating the downside.

Of course, clean cold is no panacea, but it is an essential pre-condition for sustainable development. And as we show in this report, it will play a fundamental role – either direct or indirect – in achieving all the Global Goals.

Professor Toby Peters
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Image courtesy of UN Sustainable Development Goals website.

GOAL 1: END POVERTY

Poverty and food wastage are intimately linked in developing countries, since most of the world's poorest work on the land[15], and food wastage both depresses farmers' incomes and raises food prices. 90% of food wastage in developing countries is caused by losses in the supply chain rather than consumers discarding edible food, and tackling food wastage in the supply chain would benefit the poorest by simultaneously raising farmers' incomes and reducing food prices.

- Food loss reduces income by at least 15% for 470 million smallholder farmers, most of whom also count among the 1.2 billion people who are food insecure.[16]

- Spending studies indicate that consumers in low income countries spend 40–50% of their incremental income on food. Food loss therefore increases poverty among consumers through higher real food prices.

  Over the long term, a sustained increase in food supply brings more people out of poverty than the income increases to farmers.[17]

- Food loss research is under-funded: US philanthropic investment in this area 2008–12 was $14 million, just 5% of the $260 million invested in agricultural research.[18]

The development of clean cold chains would reduce post-harvest food losses, which would raise small farmers' incomes by increasing the proportion of their produce that reaches market. Since this would increase the food supply, it should also reduce food prices for consumers. Access to cooling would also allow farmers to expand into processed as well as raw products, and to sell into more distant and even international markets. This would also boost local economies, generate employment and reduce the incentive to migrate to city slums.

According to India's National Centre for Cold-chain Development (NCCD), developing clean cold chains in rural areas will be a critical enabling factor in achieving the government's target of doubling farmers' income over the next five years. By breaking geographical barriers and allowing farmers to sell into distant markets, the effect would be 'transformative'.

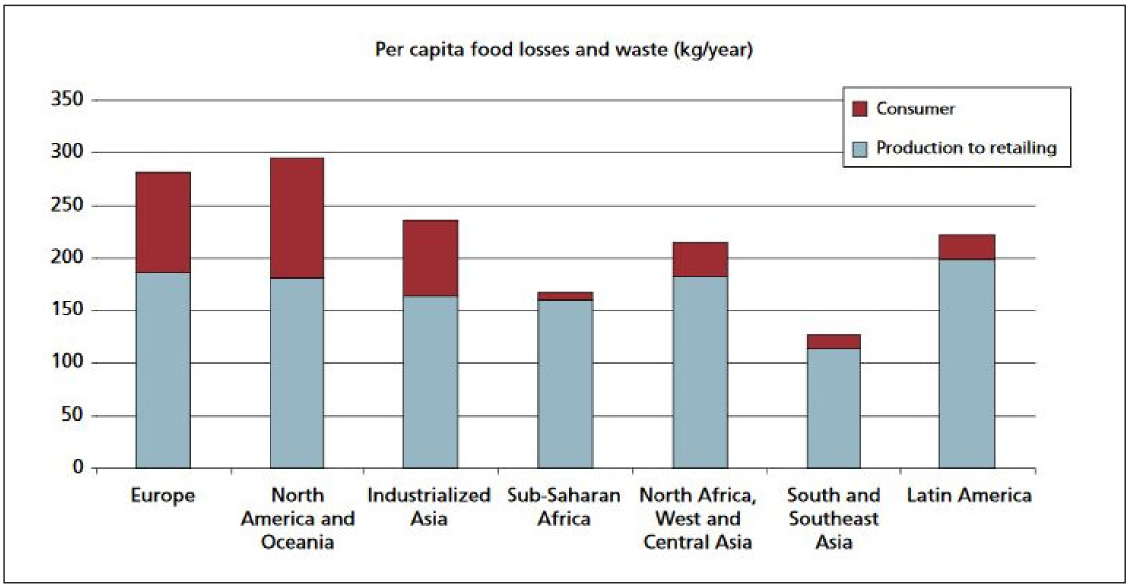


***Figure 1:** 90% of food wastage in developing countries occurs in the supply chain.*
Source: FAO[19]

GOAL 2: END HUNGER

Clean cold chains would strengthen the food supply by reducing post harvest food loss. This would reduce hunger and food insecurity by increasing the volume, quality and nutritional value of food reaching the market, and by reducing food prices and poverty. It would also promote sustainable agriculture by reducing the land, water, fertilizer and other resources currently consumed to produce food that is wasted.

- 30% of global food production is lost to wastage, or 1.3 billion tonnes per year.[20] Asia and Africa account for two thirds (67%) of the food wasted worldwide.[21] 90% of food wastage in developing countries occurs in the supply chain.[22]

- If the lowest levels of wastage achieved in any region at each stage of the supply chain were replicated worldwide, global food wastage could be reduced by 50%, and this could feed an additional 1 billion people.[23] The world's population is forecast to increase by 2 billion by 2050, so in principle half the food they will need could be provided by waste reduction. Otherwise, the FAO forecasts food demand will rise 60% by 2050.[24] The figure of 1 billion people who could be fed through waste reduction is also comfortably higher than the 800 million who were chronically undernourished in 2012–14.[25]

- Cold chain infrastructure in developing countries is rudimentary to non-existent. China is thought to have 66,000 refrigerated vehicles serving a population of 1.3 billion, and India just 9,000 serving a population almost as large, whereas France has 140,000 for a population of just 66 million.[26] The International Institute of Refrigeration has estimated that if developing countries had the same level of cold chain infrastructure as developed, they could save 200 million tonnes of food each year or 14% of the food supply.[27]

- Reducing food wastage should reduce food price inflation – a key cause of poverty and hunger. Hunger has fallen from over 1 billion people in 1992 to 795 million in 2014[28], but the World Bank estimates that the food price rises between June 2010 and February 2011 alone pushed an additional 44 million people into extreme poverty and hunger.[29] Clean cold chains would reduce food price inflation by increasing the food supply, and introducing an element of storage that could mitigate seasonal shortfalls.

Reducing food wastage would improve the sustainability of agriculture by reducing the consequential wastage of valuable resources. Food wastage currently occupies a land area almost twice the size of Australia[30]; consumes 250km^3 of water per year, three times the volume of Lake Geneva; and emits 3.3 billion tonnes of CO_2, making it the third biggest emitter after the US and China.[31]

The greatest scope for waste reduction is in fruit and vegetables[32], where global wastage averages 46%, or 575 million tonnes per year. Wastage in North America and all of the developing regions exceeds 50%. In developing countries, fruit and vegetable wastage occurs overwhelmingly in the supply chain, rather than through consumer discards, and these are the countries where cold chain infrastructure is currently scant to non-existent. So developing clean cold chains is central to tackling the biggest single element of global food wastage. Greater availability of fruit and vegetables may also help reduce incidence of stunting, which affects 180 million children worldwide and can lower lifetime earnings by 22%.[33]

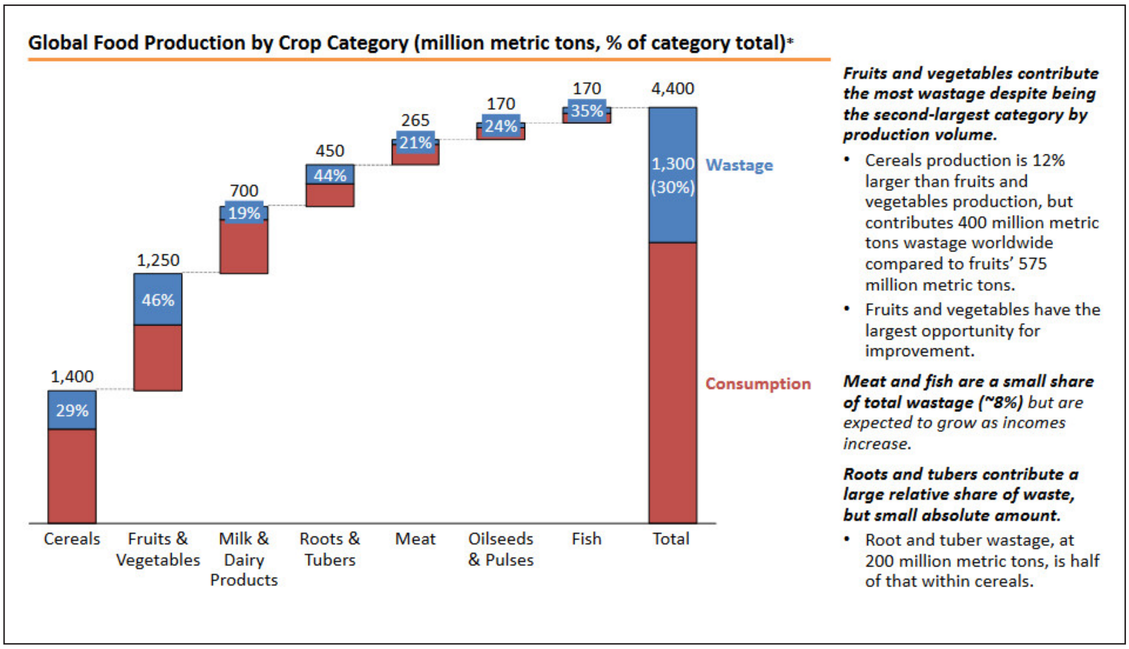


Figure 2: *Wastage of fruit and vegetables totals 575 million tonnes per year or 46% of production, the biggest single source of food wastage worldwide. Source: Rockefeller[34]; FAO.[35]*

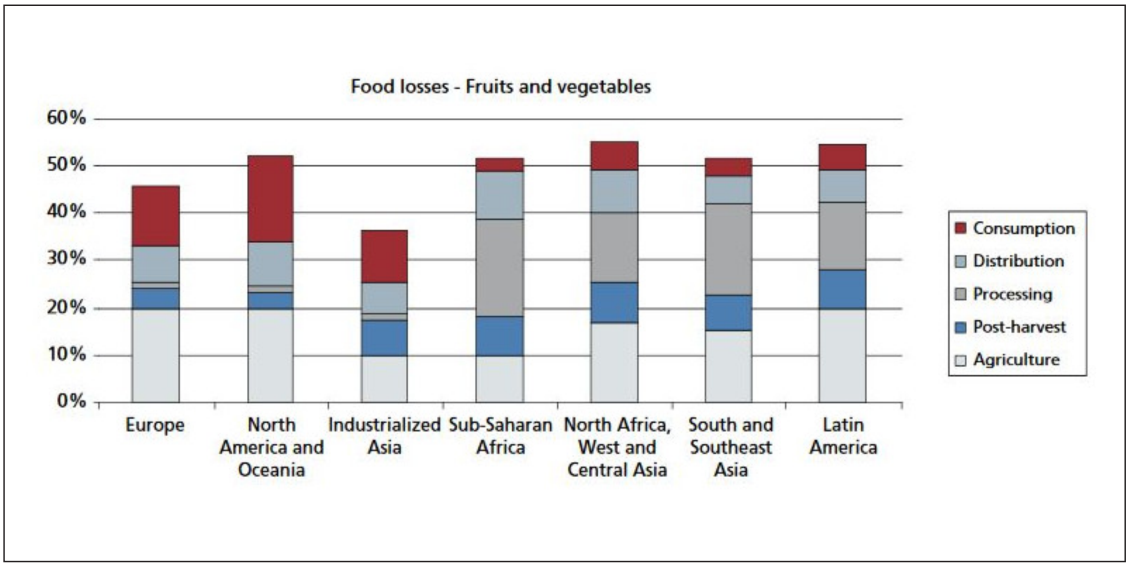


Figure 3: *Fruit and vegetable wastage exceeds 50% in the developing world, where it is overwhelmingly due to losses in the supply chain rather than wastage by consumers, and where cold chains are currently scant to non-existent. Source: FAO[36]*

GOAL 3: HEALTHY LIVES

Clean cold chains would improve health in many different ways. Direct benefits include a reduction in the 2 million vaccine preventable deaths caused each year by inadequate refrigerated distribution; a reduction of the endemic low level food poisoning in developing countries; and eliminating the grossly disproportionate emissions of toxic nitrogen oxides (NOx) and particulate matter (PM) given off by conventional diesel powered transport refrigeration units (TRUs) and diesel electricity generators (gensets). In Africa, air pollution kills more people prematurely than dirty water or childhood malnutrition.[37] [38] Indirect benefits could include a reduction in the malnutrition suffered by millions of the world's poor, which the UN's Standing Committee on Nutrition[39] identifies as the world's largest single contributor to disease.

- Vaccines need to be refrigerated until use, but 25% of all vaccines arrive damaged or degraded[40], and two million people die each year from vaccine preventable diseases simply because of inadequate refrigerated distribution.[41]

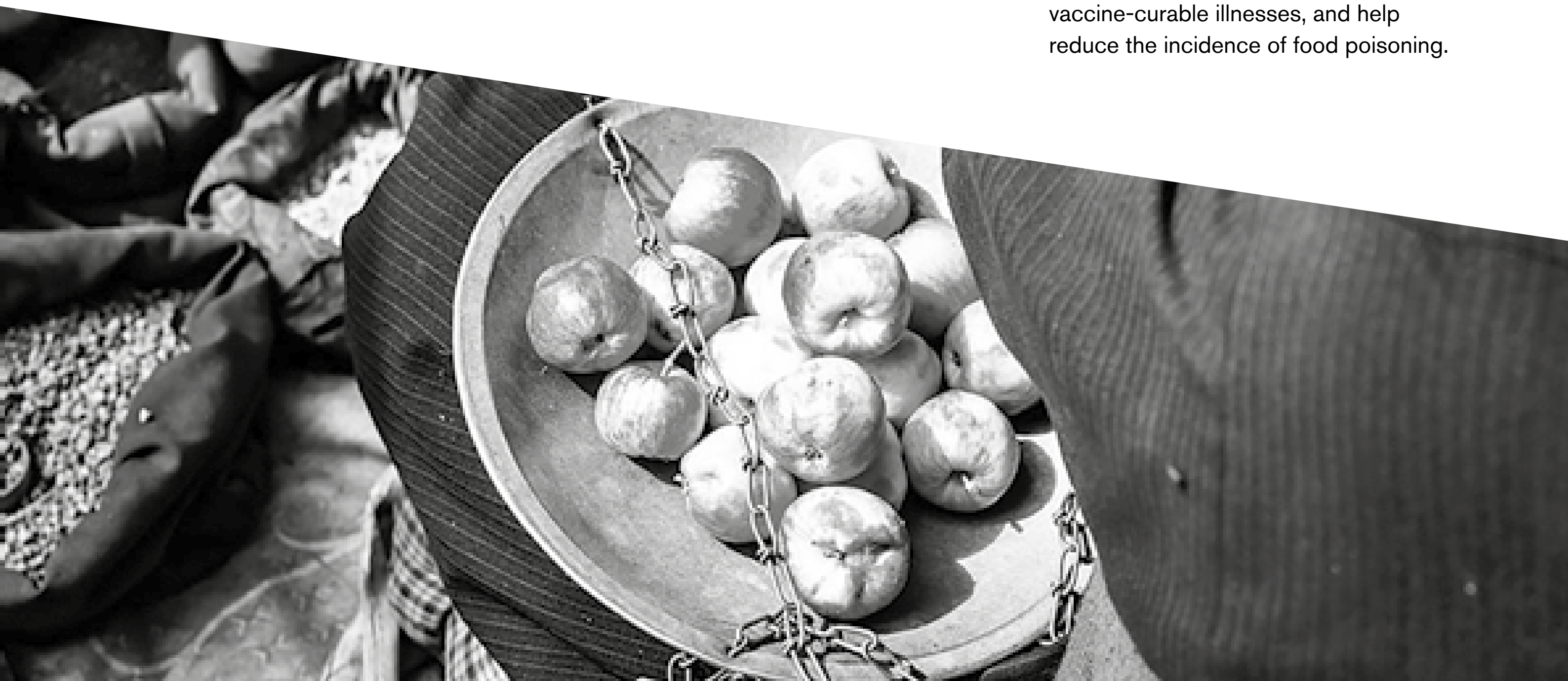
- Inadequate refrigeration contributes to endemic low level food poisoning across the developed world. An estimated 600 million – almost 1 in 10 people worldwide – fall ill after eating contaminated food and 420 000 die every year, resulting in the loss of 33 million healthy life years.[42]

- The conventional diesel powered transport refrigeration units (TRUs) that provide cooling on trucks and trailers worldwide have been shown to emit up to 6 times more NOx and 29 times more PM than the propulsion engine pulling then around.[43] These are the toxic pollutants that cause 3.7 million deaths worldwide each year. Replacing a diesel unit with a zero emission unit would reduce the combustion emissions of the entire (Euro VI) vehicle by 73% for NOx and 93% for PM.

- In Africa, air pollution causes 712,000 deaths per year, compared to 542,000 from dirty water and 275,000 from malnutrition, according to an OECD study. Deaths due to outdoor particulate matter alone rose 36% between 1990 and 2013 to 250,000, at a cost of $215 billion.[44]

- Aside from outright hunger, much of the developing world is afflicted by malnutrition, caused by diets that are deficient in crucial minerals and vitamins:
  - Malnutrition is the largest single contributor to disease in the world, according to the UN's Standing Committee on Nutrition.[45]
  - More children die from malnutrition than from AIDS, malaria and tuberculosis combined.[46]
  - Malnutrition causes mental impairment and stunting, and stunted children are more likely to have lower education levels and lifetime earnings, as well as increased risks of chronic disease and early mortality.[47]
  - Malnourished women give birth to malnourished children in a cycle that can continue for generations.

By reducing food wastage and increasing the supply of fruit and vegetables in particular (see Goal 2), clean cold chains could help reduce malnutrition and the health, social and economic damage it causes. They could also eliminate NOx and PM emissions from transport refrigeration, reduce the numbers dying unnecessarily from vaccine-curable illnesses, and help reduce the incidence of food poisoning.



GOAL 4: EDUCATION

Getting a good education is critical to improving people's lives and sustainable development, but far too many children are still prevented even from attending primary school because of hunger, poverty and conflict. By helping to solve these underlying problems (see Goals 1,2 and 16), clean cold technologies could indirectly improve children's educational and life chances.

- Hunger takes a lifelong toll on learning because it stops children going to school and limits their ability to concentrate when there.[48] Malnourishment during pregnancy permanently affects the physical and mental capacity of the child, so perpetuating poverty and hunger across generations.[49 50] 800 million people were chronically undernourished in 2012–14.[51]

- Poverty often leads to child labour, which also prevents learning. 98 million children aged 5–17 work in agriculture worldwide, some 60% of all child labourers.[52] Not only is this work among the most dangerous but a great many of those children have their education significantly disrupted as a result.[53] 57 million children worldwide do not attend school.[54]

- Poverty also restricts learning simply because of the sheer cost of education to poor families. Although many countries in Africa and developing Asia offer free primary education, the costs of uniforms, textbooks and other supplies are rarely covered. A UNESCO report found that within a sample of 50 countries, household expenditure on education was just 13% of the total for high income countries but accounted for an average of 49% among the poorest.[55] This presents a significant barrier to achieving universal primary education in the least developed economies.

- Conflict is another major barrier to education. Of the 500,000 Syrian child refugees living in Lebanon, for example, 250,000 are out of school.[56] More generally, half the world's primary school-aged children who are not enrolled live in areas affected by conflict.[57]

Clean cold technologies would reduce both poverty and hunger by reducing food wastage and prices, and by raising farmers' incomes, which should help the 60% of child labourers who work in agriculture (see Goals 1 and 2). Farmers with higher incomes would be less likely to need to put their children to work in the fields, and more likely to be able to afford to send them to school. Reducing maternal malnourishment should improve the mental ability of their children for life, and reducing hunger more generally should improve children's performance in school and educational outcomes.

Food price spikes have been implicated in the outbreak of violence and conflict – such as the Arab Spring and even the war in Syria (see Goal 16) - preventing hundreds of thousands of children from going to school. So to the extent that reducing food wastage through clean cold chains mitigates food price spikes, it may also have an indirect impact on school attendance and educational outcomes.

GOAL 5: GENDER EQUALITY

Women make up almost half the agricultural workforce in Africa, and far more in individual countries – around 70% in Kenya, Nigeria and Rwanda – yet produce less per hectare than men. This is widely attributed to the greater disadvantages women face in accessing fertilizer, labour, finance and export markets. If women worldwide had the same access to these resources as men, they could increase their output by 20–30% and global output by up to 4%. This could lift as many as 150 million people out of hunger.[58] If combined with policies to improve women farmers' access to resources, clean cold chains could benefit women disproportionately and help narrow the gender gap.

- Women are less likely to farm high value export crops than men, yet the World Bank has found that in Malawi, northern Nigeria and Uganda, when women do switch to these crops, they enjoy higher returns than men. The Bank argues that policies that exploit this advantage can therefore boost agricultural growth and improve gender equality.[59] On this basis, the development of clean cold chains would allow women farmers to move into horticultural exports and earn higher returns than men.

- Women make up almost half of the agricultural workforce in Africa, and a far higher proportion in many individual countries (see Table 1). If clean cold chains were developed, and men and women were to secure equal access to their services, this would benefit more women than men in many countries.

- Governments, donors such as USAID and multilateral organizations such as the FAO are now focussing on the gender gap. The World Bank has urged governments to reform their 'extension' policies – information and education programmes designed to increase agricultural productivity – to better serve the needs of women farmers.[60] If clean cold chains were developed alongside policies to ensure equal access for women, then the benefits to individual women and their families could be far greater, and this could help to narrow the gender gap.

Burundi	Woman constitute 55% of the agricultural labour force and do 70% of farm work.
Ghana	Woman constitute over half of the agricultural labour force and produce around 70% of the country's food.
Kenya	Woman account for 75% of the labour force in small-scale agriculture, manage 40% of small farms and play a major role in food preparation and storage.
Nigeria	Woman constitute 60–80% of the agricultural labour force and are responsible for carrying out 50% of animal husbandry and 60% of food processing.
Rwanda	Woman constitute up to 70% of agricultural labour and do 80% of the sowing, 65% of food processing, 61% of hoeing and 72% of the storage and transportation of produce.
Uganda	Woman constitute 55% of farmers. They head 26% of households in rural areas and do 85% of the planting and weeding, 55% of land preparation and 98% of food processing.
Zambia	Woman constitute around 65% of smallholder farmers. They are the main producers of food and manage, either independently or jointly, around 60% of the land under maize production.

Table 1: *The role of women farmers in seven African countries. Source: Actionaid*

GOAL 6: WATER AND SANITATION

Reducing food waste through clean cold chains would also reduce the associated waste of water, freeing up billions of cubic metres of water for drinking, sanitation and other uses.

- At least 663 million people lack access to safe drinking water; water scarcity affects 40% of the world's population and the proportion is projected to rise; over 1.7 billion already live in river basins where water use exceeds recharge; and 70% of all water extracted from rivers, lakes and aquifers is for irrigation.[62]

- The UN FAO estimates that 250km^3 of water – three times the volume of Lake Geneva – is consumed each year to produce food that is then wasted.[63] If food wastage were halved, through the introduction of clean cold chains and other measures (see Goal 2), it could in principle save 125km^3 per year, equivalent to 18 times the volume used in France for domestic purposes, or 1.8 times that in the US.[64]

- The UN's Human Right to Water and Sanitation states that every human should have access to 50–100 litres of clean water per day to ensure their most basic needs.[65] Conserving 125km^3 of water per year (342 billion litres per day) through halving food waste could in principle provide 100 litres per day to 3.42 billion people, just short of double the number living in areas of water scarcity by 2025.

- Contaminated water and poor sanitation transmit diseases such as cholera, hepatitis A, typhoid, polio, dysentery and diarrhoea. Some 842,000 people including 361,000 children die each year from diarrhoea as a result of unsafe drinking-water, sanitation and hand hygiene. Where water is not readily available, people may skip hand-washing and so increase the likelihood of diarrhoea and other diseases.[66]

- Access to clean water improves health, reduces medical expenditure, and helps people remain economically productive. Healthier children are likely to spend more time in school, with potentially life-long consequences.[67]

By reducing food wastage, clean cold chains would help liberate huge amounts of water currently used in irrigation for drinking and sanitation, with potentially significant health and economic benefits.

Cooling could also increase the fresh water supply through innovative desalination techniques that work by freezing sea water.[68] Since ice is also an effective means of storing off-peak electricity for daytime cooling[69], it is possible a single 'desalination' plant could simultaneously provide fresh water, energy storage and cooling, while reducing local air pollution and CO_2 emissions. Since most of the world's biggest cities lie on or near the coast, the initial cold for such plants could often be provided by recycling the waste cold of LNG re-gasification.

GOAL 7: AFFORDABLE CLEAN ENERGY

Until recently cooling has been largely ignored in the energy debate. This was a major oversight because making things cold is energy intensive and highly polluting, and demand for refrigeration and air-conditioning is booming, particularly in the developing world. But the environmental and economic costs of cooling could be dramatically reduced by recent innovations in clean cold technology and the 'cold economy'.

- Cooling is thought to produce around 10% of the world's CO_2 emissions[70], three times more than aviation and shipping combined.[71] In transport refrigeration, cooling is also responsible for grossly disproportionate emissions of NO_x and PM. The social costs of pollution from transport refrigeration to EU countries over the next decade are estimated at €22 billion.[72]

- Demand is booming for cooling services such as refrigeration, data centre cooling and air-conditioning, particularly in developing countries. China bought 50 million air conditioning units in 2010 alone, equivalent to half the entire US domestic air conditioner fleet.[73] Researchers at Lawrence Berkeley National Laboratory estimate the global stock of room air conditioners will rise by an additional 700 million by 2030, and 1.6 billion by 2050.[74]

- The IPCC projects that global air conditioning energy demand will grow 33-fold by 2100 to more than 10,000 TWh, which is roughly half the total electricity generated worldwide in 2010.[75] This level of demand is not sustainable.

- Demand is also booming for 'cold chain' services based on networks of refrigerated warehouses and vehicles. China's cold chain sector is reported to be growing at 25% per year and projected to be worth $75 billion by 2017.[76] Cold chain investment is also booming in India, where annual revenues from the sector are forecast to reach $13 billion by 2017.[77]

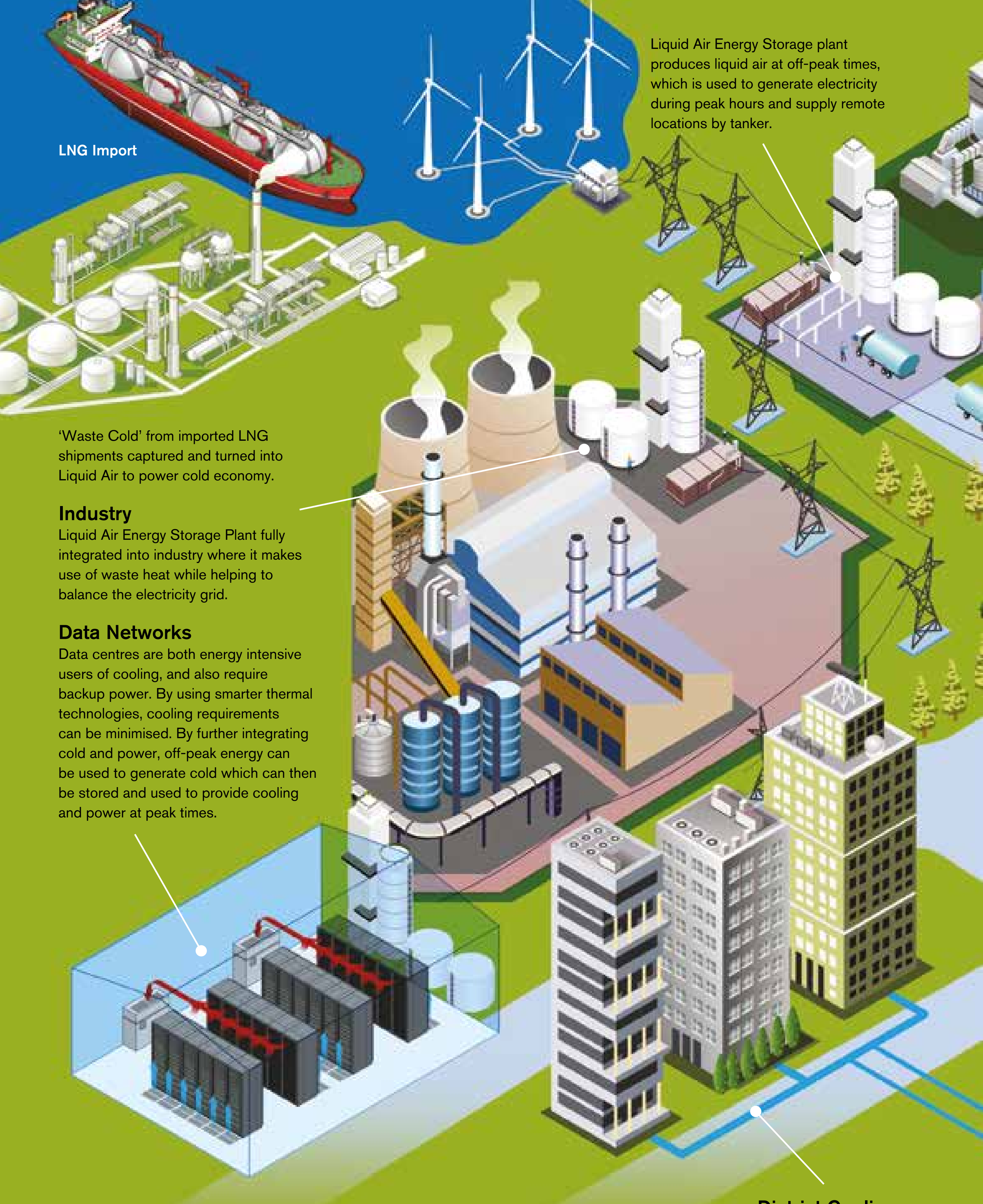
The combination of surging demand and the heavy environmental footprint of cooling conventional technologies demands a fundamental rethink of how we provide cold. Recent innovations including clean cold and power technologies such as the zero-emission Dearman engine driven by liquid air, and novel approaches such as the 'cold economy', could dramatically reduce the environmental and financial costs of cooling, while also generating sustainable economic growth (see Figure 4 and Appendix).

The cold economy is a radically new approach that applies a system-level analysis to recruit vast untapped resources of waste cold, waste heat, renewable heat, and 'wrong time' energy – such as wind or nuclear power produced at night when demand is low – to radically improve the efficiency of cooling, and reduce its environmental impact and cost. It starts by asking what service is required and then identifies the most appropriate energy carrier to meet it. Transport refrigeration units running on liquid air or nitrogen, for example, would be cheaper than highly polluting diesel TRUs, and dramatically so if the liquid air were produced with waste cold from re-gasification of liquefied natural gas at LNG import terminals, which are proliferating in developing countries.[78]

In rural areas in developing countries, the liquid air 'tank of cold' approach - explored in a recent report from the Institution of Mechanical Engineers - could allow off-grid communities to access a wide range of cold and power services all powered by renewable energy (see Figure 5 and Appendix).[79] In cities, a similar approach could be powered by grid electricity and LNG waste cold. Under Goal 7, specific targets include doubling the rate of energy efficiency improvement; substantially increasing the share of renewable energy; and ensuring 'universal access to affordable, reliable, modern energy services'.[80] All three targets would be better supported by the 'cold economy' approach given the scale of projected energy demand for cooling. Indeed, since end-to-end cold chains are a key differentiator between developed and developing countries, it is hard to see how the 'universal modern energy services' target could be achieved without the widespread introduction of clean cold.

For a full explanation of liquid air and the cold economy, please see Appendix 1.

Figure 4 (page 14): *The 'cold economy'. Source: Birmingham Policy Commission on Cold.*[81]
Figure 5 (page 16): *The 'cold economy' in developing countries. Source: Birmingham Policy Commission on Cold.*[82]



Liquid Air Energy Storage plant produces liquid air at off-peak times, which is used to generate electricity during peak hours and supply remote locations by tanker.

'Waste Cold' from imported LNG shipments captured and turned into Liquid Air to power cold economy.

Industry

Liquid Air Energy Storage Plant fully integrated into industry where it makes use of waste heat while helping to balance the electricity grid.

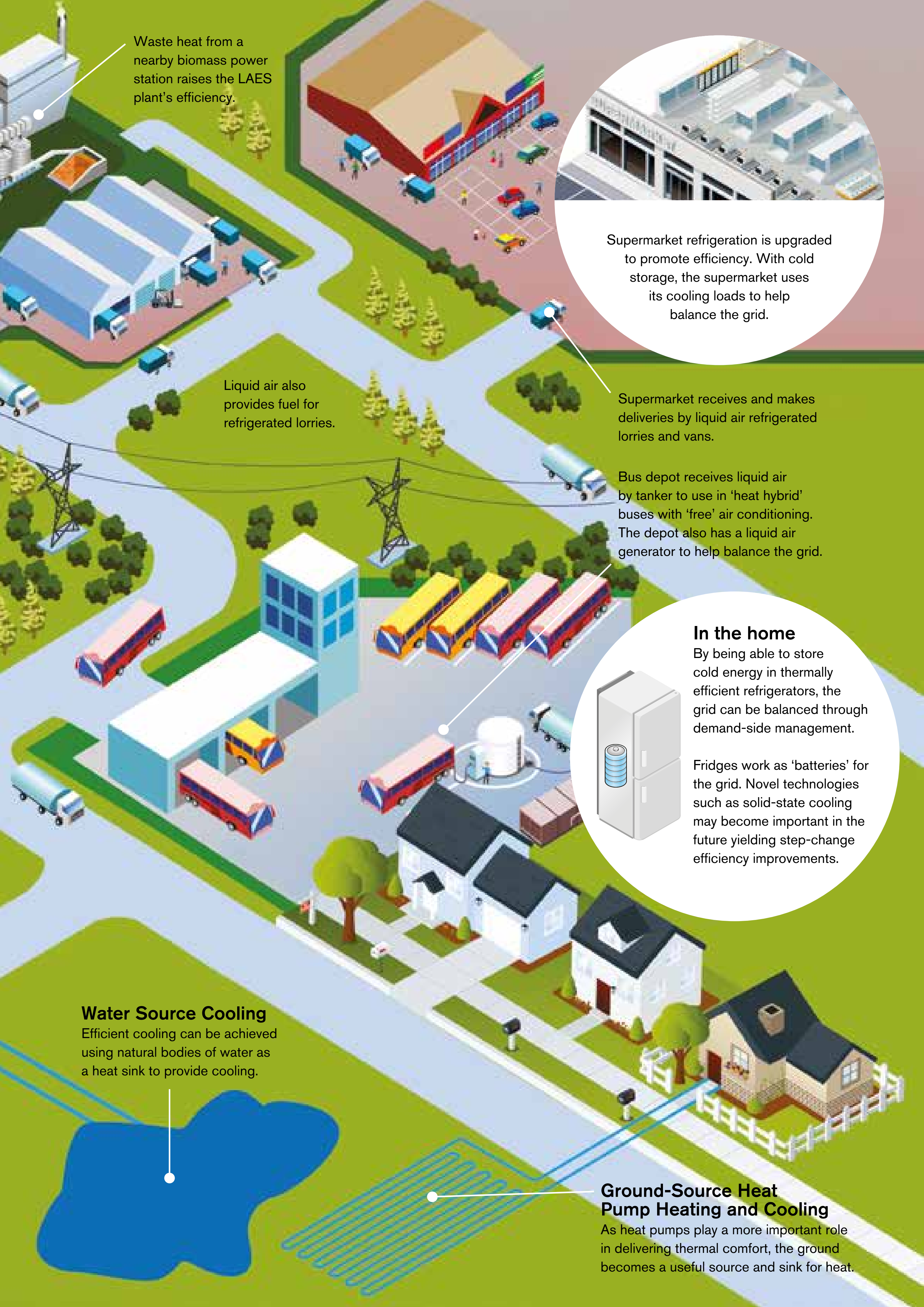
Data Networks

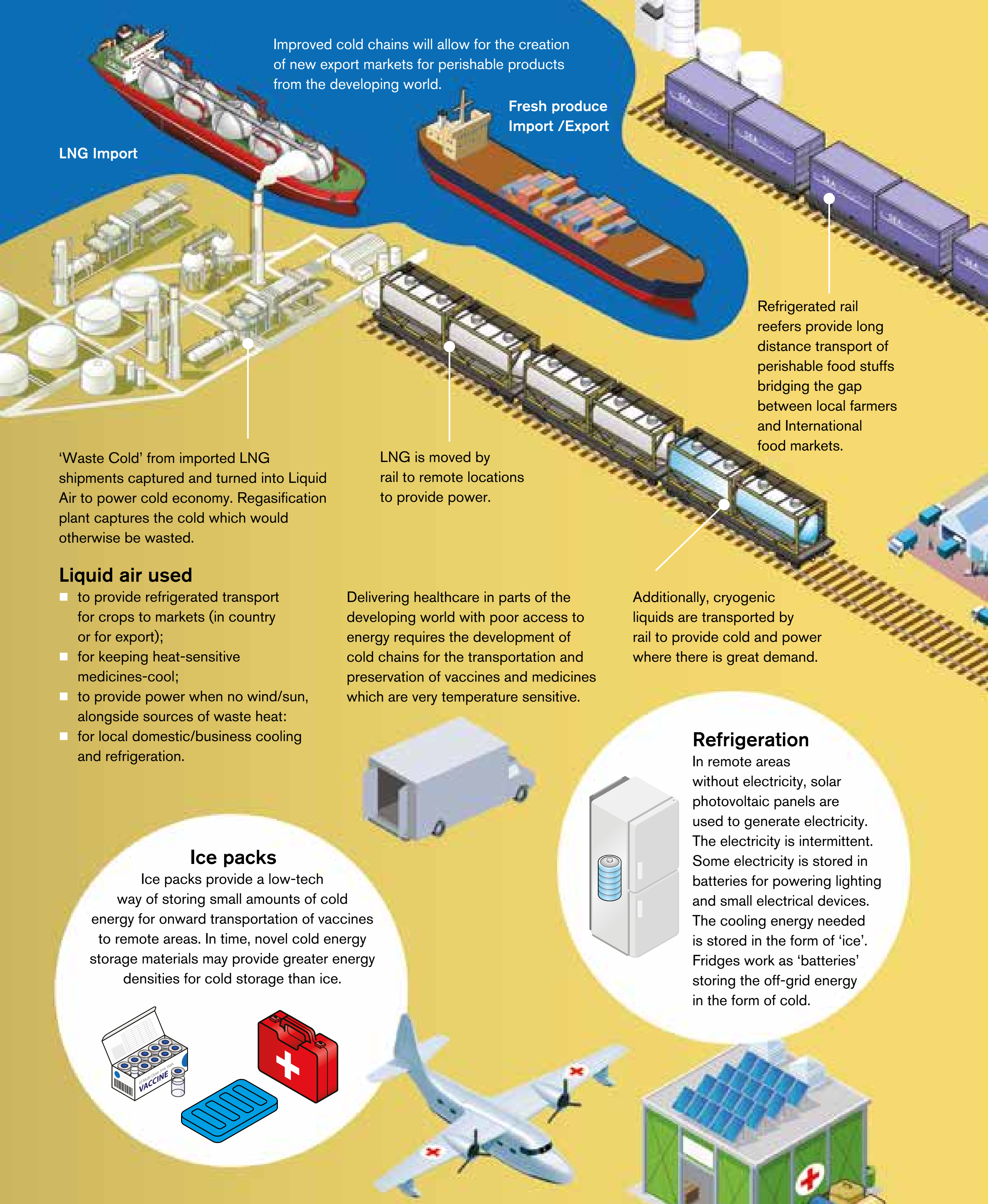
Data centres are both energy intensive users of cooling, and also require backup power. By using smarter thermal technologies, cooling requirements can be minimised. By further integrating cold and power, off-peak energy can be used to generate cold which can then be stored and used to provide cooling and power at peak times.

District Cooling

In areas of high urban density, district cooling systems may provide a more efficient method for delivering cooling services, centralising plant and sharing services leading to greater system efficiencies.

DOING COLD SMARTER: THE FUTURE COLD ECONOMY


Waste heat from a nearby biomass power station raises the LAES plant's efficiency.
Supermarket refrigeration is upgraded to promote efficiency. With cold storage, the supermarket uses its cooling loads to help balance the grid.
Liquid air also provides fuel for refrigerated lorries.
Supermarket receives and makes deliveries by liquid air refrigerated lorries and vans.
Bus depot receives liquid air by tanker to use in 'heat hybrid' buses with 'free' air conditioning. The depot also has a liquid air generator to help balance the grid.
In the home
By being able to store cold energy in thermally efficient refrigerators, the grid can be balanced through demand-side management.
Fridges work as 'batteries' for the grid. Novel technologies such as solid-state cooling may become important in the future yielding step-change efficiency improvements.
Water Source Cooling
Efficient cooling can be achieved using natural bodies of water as a heat sink to provide cooling.
Ground-Source Heat Pump Heating and Cooling
As heat pumps play a more important role in delivering thermal comfort, the ground becomes a useful source and sink for heat.



Improved cold chains will allow for the creation of new export markets for perishable products from the developing world.

LNG Import

Fresh produce Import /Export

'Waste Cold' from imported LNG shipments captured and turned into Liquid Air to power cold economy. Regasification plant captures the cold which would otherwise be wasted.

LNG is moved by rail to remote locations to provide power.

Refrigerated rail reefers provide long distance transport of perishable food stuffs bridging the gap between local farmers and International food markets.

Liquid air used

- to provide refrigerated transport for crops to markets (in country or for export);
- for keeping heat-sensitive medicines-cool;
- to provide power when no wind/sun, alongside sources of waste heat:
- for local domestic/business cooling and refrigeration.

Delivering healthcare in parts of the developing world with poor access to energy requires the development of cold chains for the transportation and preservation of vaccines and medicines which are very temperature sensitive.

Additionally, cryogenic liquids are transported by rail to provide cold and power where there is great demand.

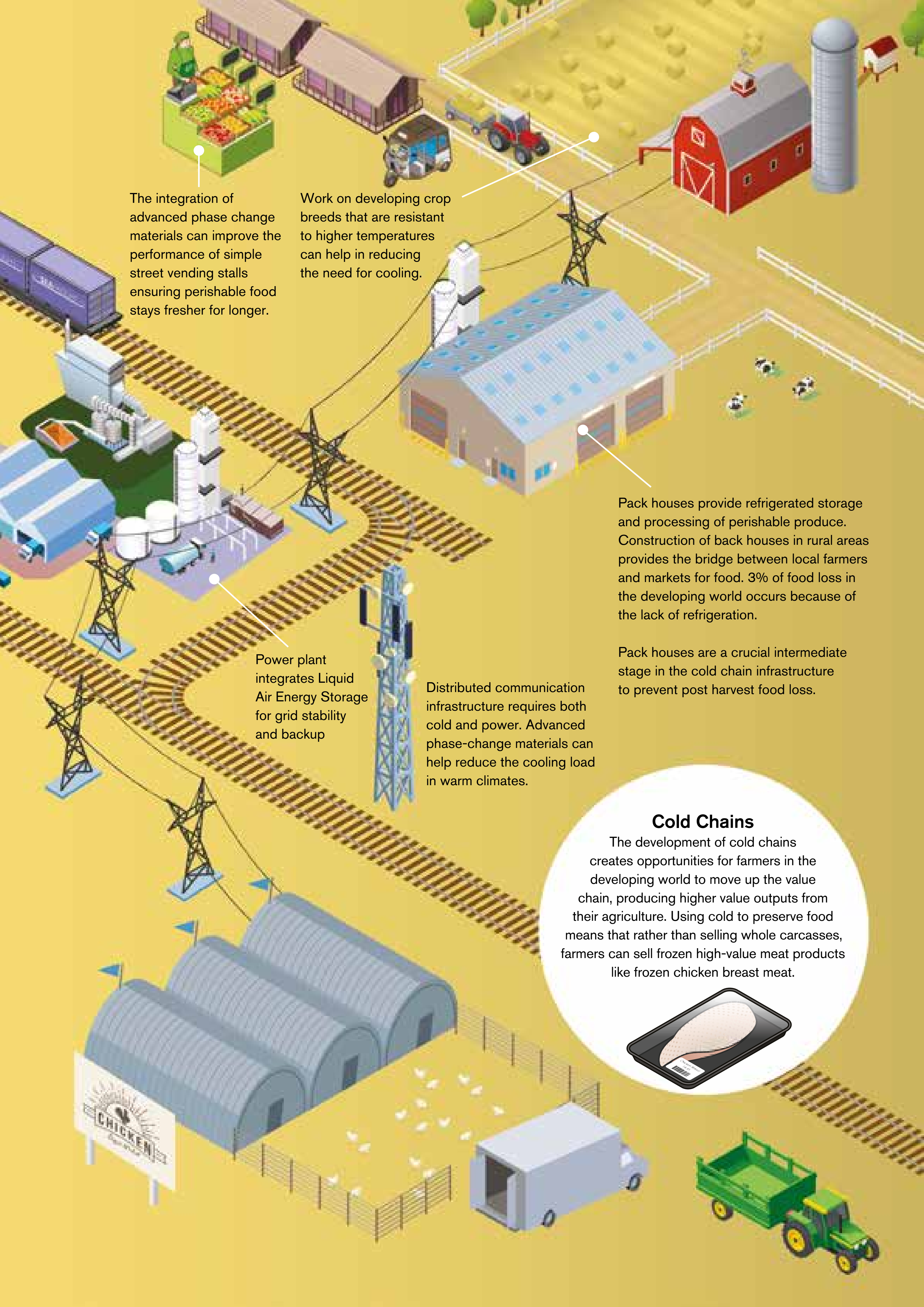
Ice packs

Ice packs provide a low-tech way of storing small amounts of cold energy for onward transportation of vaccines to remote areas. In time, novel cold energy storage materials may provide greater energy densities for cold storage than ice.

Refrigeration

In remote areas without electricity, solar photovoltaic panels are used to generate electricity. The electricity is intermittent. Some electricity is stored in batteries for powering lighting and small electrical devices. The cooling energy needed is stored in the form of 'ice'. Fridges work as 'batteries' storing the off-grid energy in the form of cold.

DOING COLD SMARTER: IN THE DEVELOPING WORLD


The integration of advanced phase change materials can improve the performance of simple street vending stalls ensuring perishable food stays fresher for longer.
Work on developing crop breeds that are resistant to higher temperatures can help in reducing the need for cooling.
Pack houses provide refrigerated storage and processing of perishable produce. Construction of back houses in rural areas provides the bridge between local farmers and markets for food. 3% of food loss in the developing world occurs because of the lack of refrigeration.
Pack houses are a crucial intermediate stage in the cold chain infrastructure to prevent post harvest food loss.
Power plant integrates Liquid Air Energy Storage for grid stability and backup
Distributed communication infrastructure requires both cold and power. Advanced phase-change materials can help reduce the cooling load in warm climates.
Cold Chains
The development of cold chains creates opportunities for farmers in the developing world to move up the value chain, producing higher value outputs from their agriculture. Using cold to preserve food means that rather than selling whole carcasses, farmers can sell frozen high-value meat products like frozen chicken breast meat.
CHICKEN

GOAL 8: SUSTAINABLE ECONOMIC GROWTH AND DECENT WORK

Investment in new clean cold infrastructure in developing countries would generate local jobs in manufacturing and service roles, as well as conserving jobs in rural areas and calming food prices (see previous goals). It would increase agricultural productivity, which is critical for reducing poverty, hunger and food insecurity. Clean cold technologies and the 'cold economy' could also become a powerful engine of sustainable growth.

- Employment in farming is far higher in developing countries than developed[83], so investing in agricultural productivity is vital for reducing poverty and promoting wider growth. In low income countries agricultural growth is three times more effective in reducing poverty than growth in other sectors – and in Sub Saharan Africa it is 11 times more effective.[84]

- Over 90% of the world's 570 million farms are family owned, and they produce more than 80% of the world's food by value. So increasing the productivity of smallholders is vital for tackling hunger and food insecurity.[85]

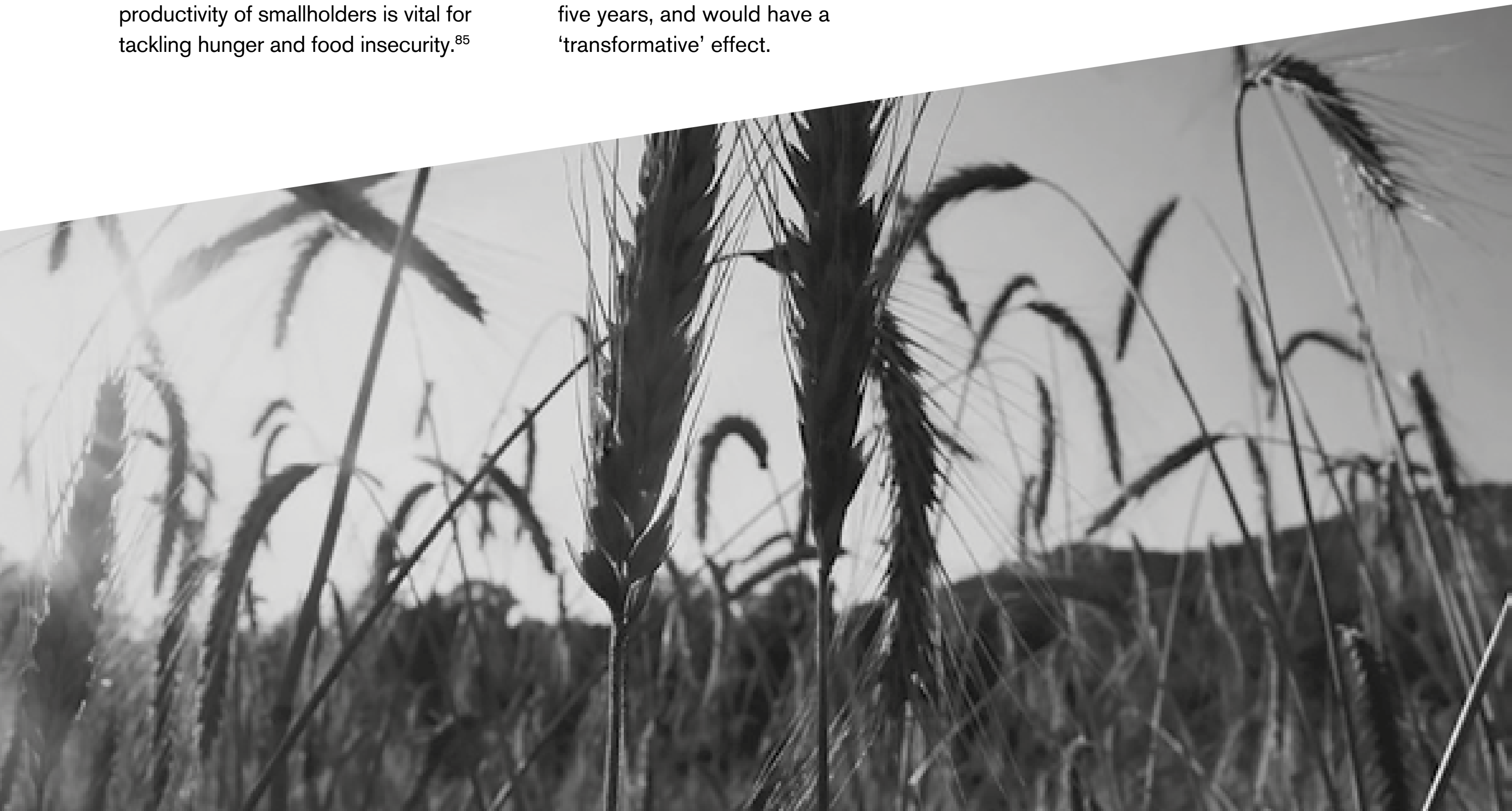
- Building out clean cold chains in developing countries would reduce food wastage along the supply chain and so raise the incomes of small farmers.

- Access to cooling at or near the farm gate would allow small farmers to move up the value chain, selling not just raw crops, but processed products. Access to cooling would allow fruit and vegetable farmers to produce value added frozen or chilled products, for example, and dairy farmers to become yoghurt or cheese makers. This in turn would strengthen rural communities and reduce the pressure to migrate to city slums.

- Clean cold chains could also allow small farmers to access higher value markets, increasing their incentive to raise productivity and output, leading to further growth. India's National Centre for Cold-chain Development says clean cold chains are vital to achieve the government's target of doubling farmers' incomes within five years, and would have a 'transformative' effect.

- Clean cold chains would also create non-farming jobs in transport, manufacturing and service. By creating decent jobs and raising farming incomes, clean cold chains would reduce the incentive to migrate to urban slums.

- Clean cold technologies and the 'cold economy' could also become a powerful engine of sustainable growth worldwide. The University of Birmingham's Commission on Cold found the cold economy could generate annual global savings of between £43 billion and £112 billion – a vast potential market and one which is set to grow for the rest of this century.



GOAL 9: INDUSTRY, INNOVATION AND INFRASTRUCTURE

Much of the infrastructure required by developing countries has yet to be built. This includes not only roads, railways, water and energy networks, and entire cities (see Goal 11), but also food and pharmaceutical 'cold chains' of refrigerated warehouses and vehicles, and district cooling systems for commercial buildings and high density housing. Innovative clean cold technologies and cold economy approaches could provide cooling at lower environmental and financial cost. The waste cold of LNG re-gasification could also be recycled to supply cooling services, with further major savings in energy, emissions and cost (see Goal 12). Given the scale of infrastructure development projected in developing countries, the benefits of this approach could be enormous.

- Huge amounts of infrastructure development is required in developing economies. '70% of India remains to be built', according to a report from the McKinsey Global Institute, and the same applies to other countries such as Bangladesh and Indonesia.[86]
- Cold chain infrastructure in developing countries is rudimentary to non-existent. China is thought to have 66,000 refrigerated vehicles serving a population of 1.3 billion, and India just 9,000 serving a population almost as large, whereas France has 140,000 for a population of just 66 million.
- India would need to build 70,000 pack-houses, an additional 53,000 refrigerated vehicles – five times its current fleet – and over 3 million tonnes of additional cold storage and distribution hubs simply to catch up with current levels of food production and demand – never mind satisfy future growth (Table 2).[87]
- Dearman forecasts the global fleet of transport refrigeration units could grow from around 4 million today to as many as 18 million by 2030, driven overwhelmingly by pent up demand in developing countries. If satisfied by conventional diesel powered TRUs, this would cause huge additional emissions of NOx and PM.
- Developing countries including Pakistan, Bangladesh, Vietnam and the Philippines are also building large amounts of LNG re-gasification capacity. The waste cold of LNG re-gasification could be re-cycled through liquid air or nitrogen to supply cooling in transport and other applications. India's LNG imports are forecast to grow fivefold to 2040 (Figure 6), when their waste cold could produce 52,000tpd of liquid air[88], enough to provide cooling for almost 211,000 chilled and frozen trucks.[89] LNG waste cold could also be recycled through innovative desalination technology to provide fresh water, energy storage and cooling simultaneously.
- In rural areas in developing countries, the liquid air 'tank of cold' approach explored in a recent report from the Institution of Mechanical Engineers could allow off-grid communities to access a wide range of cold and power services all powered by renewable energy (see Figure 5 and Appendix).[90] In cities a similar approach could be powered by grid electricity and LNG waste cold (Figure 4, and Appendix).

Type of Infrastructure	Infrastructure Requirement (A)	Infrastructure Created (B)	All India Gap (A–B)
Pack-house	70,080 nos.	249 nos.	69,831 nos.
Cold Storage (Bulk)	341,64,411 MT	318,23,700 MT	32,76,962 MT
Cold Storage (Ilub)	9,36,251 MT		
Reefer Vehicles	61,826 nos.	9,000 nos.	52,826 nos.
Ripening Chamber	9,131 nos.	812 nos.	8,319 nos.

Table 2: *Gaps in India's cold chain capacity. Source: NCCD*[91]

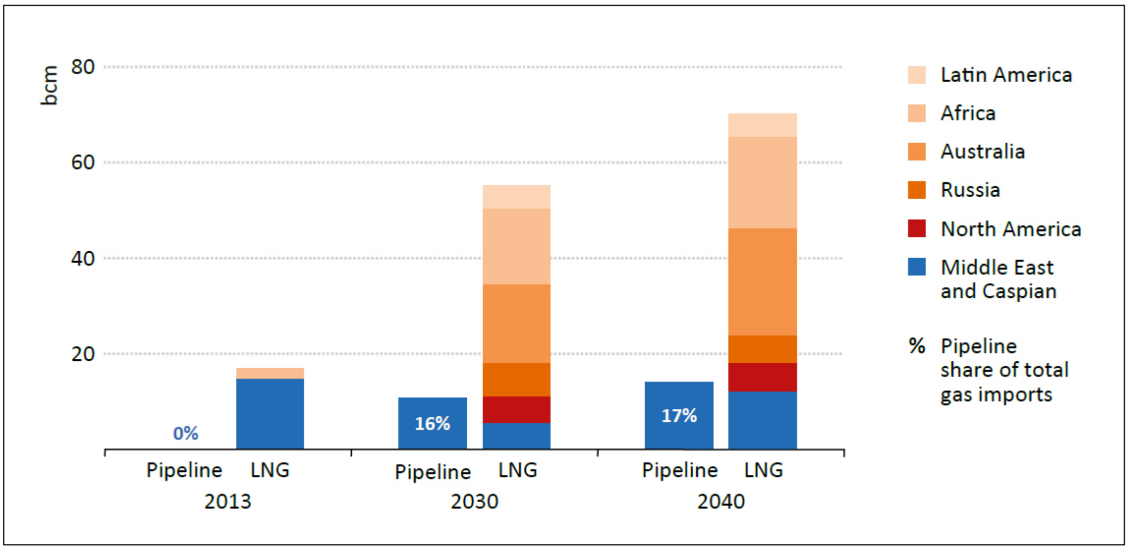


Figure 6: *India's gas imports to 2040. Source: IEA*[92]

GOAL 10: REDUCE INEQUALITIES

Clean cold technologies could help reduce inequality both within and between countries.

Inequality within developing countries:

- Income inequality: clean cold chains would reduce poverty by lowering food prices and raising farmers' income (Goals 1 and 2). Both effects would tend to raise the incomes of the poorest in society more than the richest, so reducing income inequality.

- The first target of Goal 10 is that the incomes of the poorest 40% of the population should grow faster than national average to 2030. Clean cold chains would help achieve this target by reducing food wastage, food prices and rural poverty, and raising agricultural productivity and earnings. India's National Centre for Cold-chain Development says clean cold chains are vital to achieve the government's target of doubling farmers' incomes within five years.

- Educational inequality: clean cold chains would reduce educational inequality by reducing hunger, poverty and conflict, improving the educational outcomes of the most disadvantaged in society. In particular it would reduce the pressure on farming families to make their children work (Goal 4). 98 million children work in agriculture worldwide[93] and 57 million children do not attend school.[94]

- Gender inequality: combined with policies to improve access of women farmers to agricultural resources, clean cold chains could help reduce the gender gap in Africa and elsewhere – particularly by enabling women farmers to access higher value export markets (Goal 5).

Inequality between countries:

- Cooling infrastructure is little recognised but key differentiator between developed and developing economies. France has 140,000 refrigerated trucks to serve a population of 66 million, for example, while India has just 9,000 for a population of 1.3 billion. The difference in cooling provision is not simply a symptom of different stages of development, but also a cause.

- Cooling is an enabling technology with widespread impacts across the economy and health. The 2 million vaccine preventable deaths that occur each year due to inadequate cold distribution happen overwhelmingly in developing countries. Developing medical cold chains could have a major impact on mortality, health and productivity – so narrowing the gap with developed countries.

- Developing clean cold chains would reduce wastage of food, water, fertilizer and other agricultural resources; reduce food prices; reduce poverty; improve educational outcomes; reduce gender inequality; and increase international trade through agricultural exports. All of these should raise productivity and growth in developing economies, so helping to narrow the gap with developed economies.

GOAL 11: SUSTAINABLE CITIES AND COMMUNITIES

Urbanisation in the developing world continues at a furious pace, and clean cooling is central if cities are to be made sustainable. Cooling is vital in cities for food, data, medicine and air conditioning comfort. Clean cold systems based on liquid air would reduce peak loads, and mitigate the 'heat island effect', meaning other cooling equipment could work less hard, reducing energy consumption and CO_2 emissions. Liquid air TRUs would eliminate NOx and PM emissions from transport refrigeration in cities, where they do most damage to human health. Producing liquid air with recycled LNG waste cold would further reduce the emissions and costs of cooling in cities.

- The global urban population is projected to grow from 3.6 billion today to 5 billion or 60% by 2030.[95] By then the biggest city will be Jakarta, with 37 million inhabitants, and all bar one of the ten largest cities will be in developing countries, many with hot climates.[96]

- The world's megacities such as Beijing, Delhi and Mumbai already have extremely high levels of local air pollution, with high concentrations of NOx and PM, the toxic pollutants that kill 3.7 million worldwide people each year.

- Existing cities will sprawl – each of the top ten cities will have more than 22 million inhabitants – and entirely new ones will be built – India plans 100 new 'Smart Cities'. According to the McKinsey Global Institute, '70% of India remains to be built', and the country needs up to 900 million square metres of commercial and residential space – or 'a new Chicago every year'.[97]

- Cooling demand in developing countries, driven largely by cities, continues to soar:
  - Fridge ownership in China rose from 7% of urban households in 1995 to 95% in 2007.[98]
  - Room air-conditioner ownership in India rose from 2 million in 2006 to 5 million by 2011, and is forecast to reach 200 million by 2030.[99]
  - Global air conditioning energy demand, driven overwhelmingly by cities in developing countries, is forecast to rise 33-fold by 2100 to more than 10,000 TWh, roughly half the total electricity generated worldwide in 2010 (see Figure 7).[100] To generate 10,000TWh from wind would, for example, require 4.6TW of wind turbine capacity, more than ten times the world's total wind capacity today.[101]

- Conventional cooling technologies in cities are often self-defeating because of the heat island effect: by expelling heat into their immediate surroundings, they force themselves and other cooling systems to work harder. In Phoenix, Arizona, for example, the heat island effect has already raised temperatures by over 4C, towards the upper end of the warming predicted for the entire planet through climate change, exacerbated by air conditioning units that prevent the city from cooling at night as much as it otherwise would.[102]

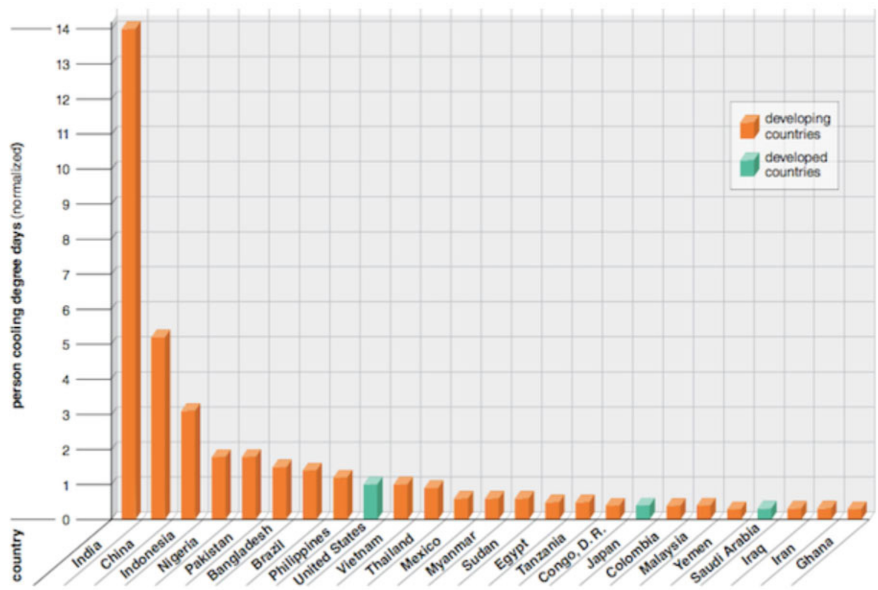
- Cleaner cold technologies such as district cooling systems would make cities more sustainable by providing efficient space cooling for commercial buildings and high density housing with far lower CO_2 emissions, particularly if integrated with sources of 'free' cooling such as river or sea water.[103]

- Electric-powered space cooling in cities at peak times of the day will also place significant stress on national electricity grids. This is both costly and contributes disproportionately to climate change as peak power generation is less efficient and more carbon intensive. A cold economy approach would relieve this stress by integrating waste, off-peak and under-utilised energy resources to meet cooling loads. As one example, liquid air technologies can act as energy storage devices that absorb electricity produced at night and then deliver zero emission cold and power at peak times in both buildings and vehicles. This both lowers CO_2 emissions and energy system costs.

- Many of the world's biggest cities are coastal, and close to LNG re-gasification terminals. LNG waste cold could be used to drive innovative desalination plants that work by freezing sea water.[104] Since ice or slush is also an effective means of storing off-peak electricity for daytime cooling[105], it is possible a single 'desalination' plant could simultaneously provide fresh water, energy storage and cooling, while reducing local air pollution and CO_2 emissions.

- Lawrence Berkeley estimates that shifting the 2030 world stock of room air conditioners from low efficiency technology using high-GWP refrigerants to higher efficiency technology and lower-GWP refrigerants in parallel would save over 25 billion tonnes of CO_2 equivalent emissions over the equipment's lifetime, and avoid the need for 680–1550 peak power plants of 500MW each.[106]

- Zero-emission transport cooling powered by liquid air would make cities more sustainable by reducing cost, emissions of CO_2, and emissions of NOx and PM where they do most harm to human health. Like district cooling, vehicles powered or cooled by liquid air, including auto-rickshaws, buses and refrigerated trucks, would also mitigate the heat island effect, reducing the cooling load on other cooling systems, further reducing energy demand, costs and emissions.



"Will AC Put a Chill on the Global Energy Supply?" by M. Sivak in American Scientist.

Figure 7: *If all countries had the same level of air conditioning comfort as the US, the world would consume around 10,000TWh per year, roughly half the electricity generated worldwide for all purposes in 2010.*[107] *Source: Scientific American*[108]

GOAL 12: RESPONSIBLE CONSUMPTION AND PRODUCTION

Goal 12 sets targets for the efficient use of natural resources, reducing waste through prevention and recycling, and encouraging sustainable practices among transnational companies. A core concept of the cold economy is to make efficient use of natural resources by matching energy carriers to the service required, and another is to recycle waste and under-utilised energy resources to meet cooling loads. A good example of both would be to integrate cold given off during LNG re-gasification into the production of liquid air or nitrogen to provide cooling services in vehicles and buildings (Figure 8). This would displace much of the electricity and diesel required, reduce the environmental and financial costs of cooling dramatically, and represent the extension of 'circular economy' principles to cooling for the first time.

- The global LNG trade is booming: the IEA forecasts the global LNG trade will jump 45% to 473bcm (350mtpa) by 2020[109], and more than 500bcm (370mtpa) in 2040.[110]
- During re-gasification each tonne of LNG releases up to 240kWh of 'coolth' or cold energy[111], which is quite separate from the chemical energy contained in its molecules and usually discarded. This represents a huge potential resource that could be recycled to reduce the environmental and financial costs of cooling: integrating LNG waste cold into air liquefaction reduces the electricity required by 70% and costs by about half.[112]

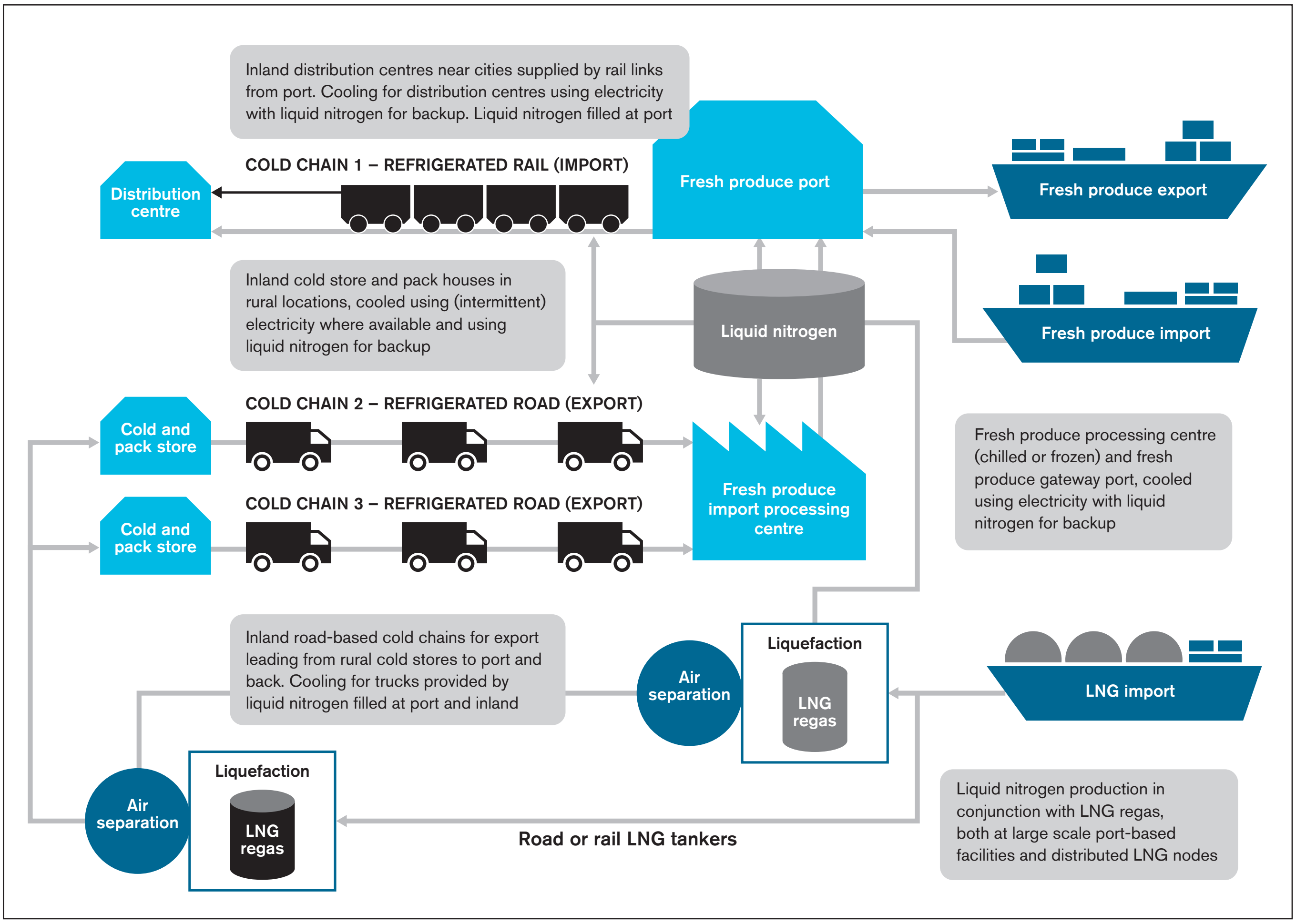


***Figure 8:** Recycling LNG waste cold to provide cold chain cooling in India.*
Source: Dearman/E4tech[116]

- New re-gasification plants being built in Pakistan, Bangladesh, Vietnam and the Philippines are due to start importing by 2020. India's largest LNG import terminal, at Dahej in Gujarat, imported 10.5mt of LNG last year, with enough waste cold to produce almost 10,700tpd of liquid air, which could provide cooling for over 43,000 refrigerated trucks. India's total projected LNG imports in 2040 could support five times as many (Figure 8).[113]
- Alternatively, LNG waste cold could be used to drive innovative desalination plants that work by freezing sea water.[114] Since ice or slush is also an effective means of storing off-peak electricity for daytime cooling[115], it is possible a single 'desalination' plant could simultaneously provide fresh water, energy storage and cooling, while reducing local air pollution and CO_2 emissions.

GOAL 13: CLIMATE ACTION

Cooling is a major and fast growing cause of global warming, and therefore clean cold must be an integral part of the solution. Cooling heats the planet both by its emissions of CO_2 and leaks of highly potent HFC refrigerant gases ('F-gases'), and in cities through the heat island effect. Rising temperatures will increase demand for cooling and so create a vicious circle – unless cooling is decarbonised. On the other hand, clean cold technologies will reduce not only the direct GHG emissions of cooling, but also those from food waste and its needless consequences – water pumping, deforestation and fertiliser production and use. The direct emissions reductions of clean cold technologies will increase as electricity grids decarbonise.

Cooling is a major part of the problem:

- Cooling is already a major and growing emitter: one estimate suggests refrigeration and air conditioning cause 10% of global CO_2 emissions[117] – three times more than is attributed to aviation and shipping combined.[118] Another suggests cooling emissions currently account for 7% of the total, but are growing three times faster, so cooling's share will almost double to 13% by 2030.[119]

- Around 20%-25% of CO_2 equivalent emissions from cooling are produced by leaks of hydrofluorocarbon (HFC) refrigerant gases ('F-gases'). These are highly potent greenhouse gases, some of which trap over 10,000 times more heat than carbon dioxide. Because the volumes leaked are relatively small, F-gases currently account for only 2% of global CO_2e emissions, but the rapid growth in cooling equipment in developing countries is projected to raise this to 20% of global emissions.[120] The global agreement to phase out HFC refrigerants signed in Rwanda recently, while important, does nothing to tackle the 75% of cooling emissions that come from energy consumption, the growth of which is likely to overwhelm any reduction in HFCs.[121]

- Air conditioner sales are growing at 10–15% per year in hot, populous developing countries such as Brazil, India and Indonesia. Lawrence Berkeley National Laboratory estimates the global stock of room air conditioners will rise by an additional 700 million by 2030, and 1.6 billion by 2059.[122] In 2010 alone, Chinese consumers bought 50 million air conditioning units – equivalent to half the entire US domestic air conditioner fleet.[123]

- The IPCC projects that global air conditioning energy demand will grow 33-fold from 300TWh in 2000 to more than 10,000 TWh in 2100, with most of the growth in developing economies.[124] 10,000TWh is roughly half the total electricity generated worldwide in 2010.[125] If this sounds far-fetched, something similar has already happened in the US, where in 2007 building air conditioning alone consumed almost as much as the country had consumed fifty years earlier for all purposes – 484TWh versus 497TWh.[126]

- Worldwide energy demand for space cooling will overtake space heating by 2060, and outstrip it by 60% at the end of the century, as cooling demand in the developing countries of the global south grows faster than heating demand in the developed northern economies (Figure 10).[127] But cooling demand will also grow in the global north: the European Commission expects cooling demand in EU buildings to rise 70% by 2030.[128]

- If nothing is done, within fifteen years cooling will require at least an additional 139GW – more than the generating capacity of Canada – and raise greenhouse gas emissions by over 1.5 billion tonnes of CO_2 per year[129], three times the current energy emissions of Britain or Brazil.[130]

- At a global level, cooling is self-defeating: the more fossil fuel we burn to keep ourselves and our food cool, the more carbon we will emit, the hotter the planet will become, and the more fossil fuel we will need to burn to keep cool. Saudi Arabia burned a record 1 million barrels of oil per day to generate electricity in July 2014[131], and more than 50% of Saudi summer peak power demand is driven by air conditioning.[132]

- In cities, conventional building and vehicle cooling technologies also contribute to the heat island effect, by rejecting heat into their immediate surroundings, raising temperatures and causing cooling equipment to work even harder. In Phoenix, Arizona, for example, the heat island effect has already raised temperatures by over 4C, towards the upper end of the warming predicted for the entire planet through climate change.[133] More generally, it has been estimated that this effect is responsible for 5–10% of urban peak electricity use for air conditioning in US cities.[134]

…but clean cooling is an integral part of the solution:

- The energy efficiency of many cooling applications could be raised by 30% simply on the basis of current best-in-class technologies and best practice, according to the University of Birmingham's Commission on Cold.[135]

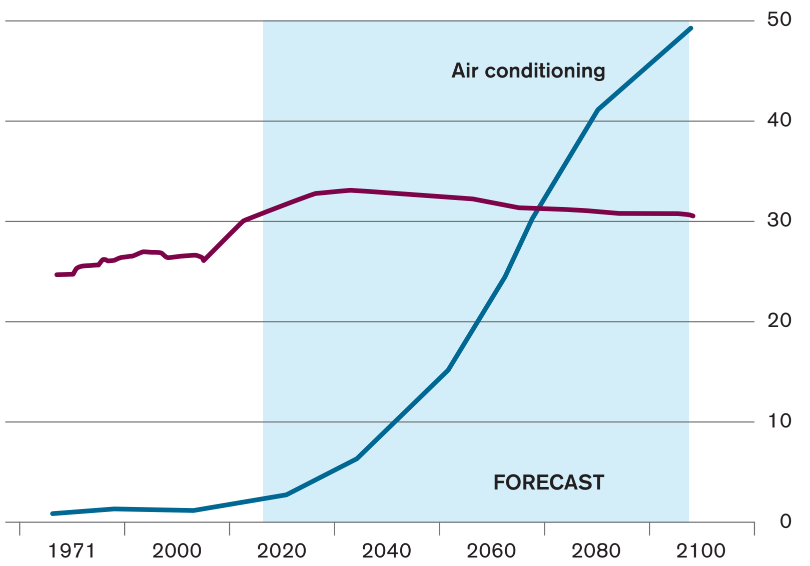
- Lawrence Berkeley estimates that shifting the 2030 world stock of room air conditioners from low efficiency technology using high-GWP refrigerants to higher efficiency technology and lower-GWP refrigerants in parallel would save over 25 billion tonnes of CO_2 equivalent emissions over the equipment's lifetime, and avoid the need for 680-1550 peak power plants of 500MW each.[136] Dearman engine transport refrigeration units could not only operate with climate-neutral F-gases such as CO_2, but would also eliminate the CO_2 emissions from diesel combustion.[137]

- Transport refrigeration units powered by liquid air would reduce CO_2 immediately compared to diesel powered TRUs on the basis of liquid nitrogen produced on grid electricity in European countries. If the EU were to convert to liquid air TRUs over the next decade, it would save 36 million tonnes of CO_2.[138]

- In developing countries with carbon-intensive electricity grids, liquid air TRUs would reduce carbon emissions immediately if the liquid nitrogen were produced with waste cold from LNG re-gasification. In India, for example, the savings would range from 18% to 51% today, and from 27% to 56% in 2030 (see Goal 12 and Table 3).[139]

- Since liquid nitrogen is invariably produced at night when power prices are lower, it can help absorb 'wrong time' energy such as excess off-peak wind or nuclear generation to be used on demand for cooling applications.

- Clean cold chains would also reduce carbon emissions caused by food waste, the third biggest emitter after the US and China, and those caused by unnecessary fertiliser use and deforestation.



Source: PBL Netherlands Environmental Assessment Agency. The opinions stated include some forecasted views. We believe that we are basing our expectations and beliefs on reasonable assumptions within the bounds of what we currently know. However, there is no guarantee that any forecasts or opinions will be realized.

Figure 9: *Worldwide forecast energy demand for space heating and space cooling, exajoules. Source: PBL Netherlands Environmental Assessment Agency*[140]

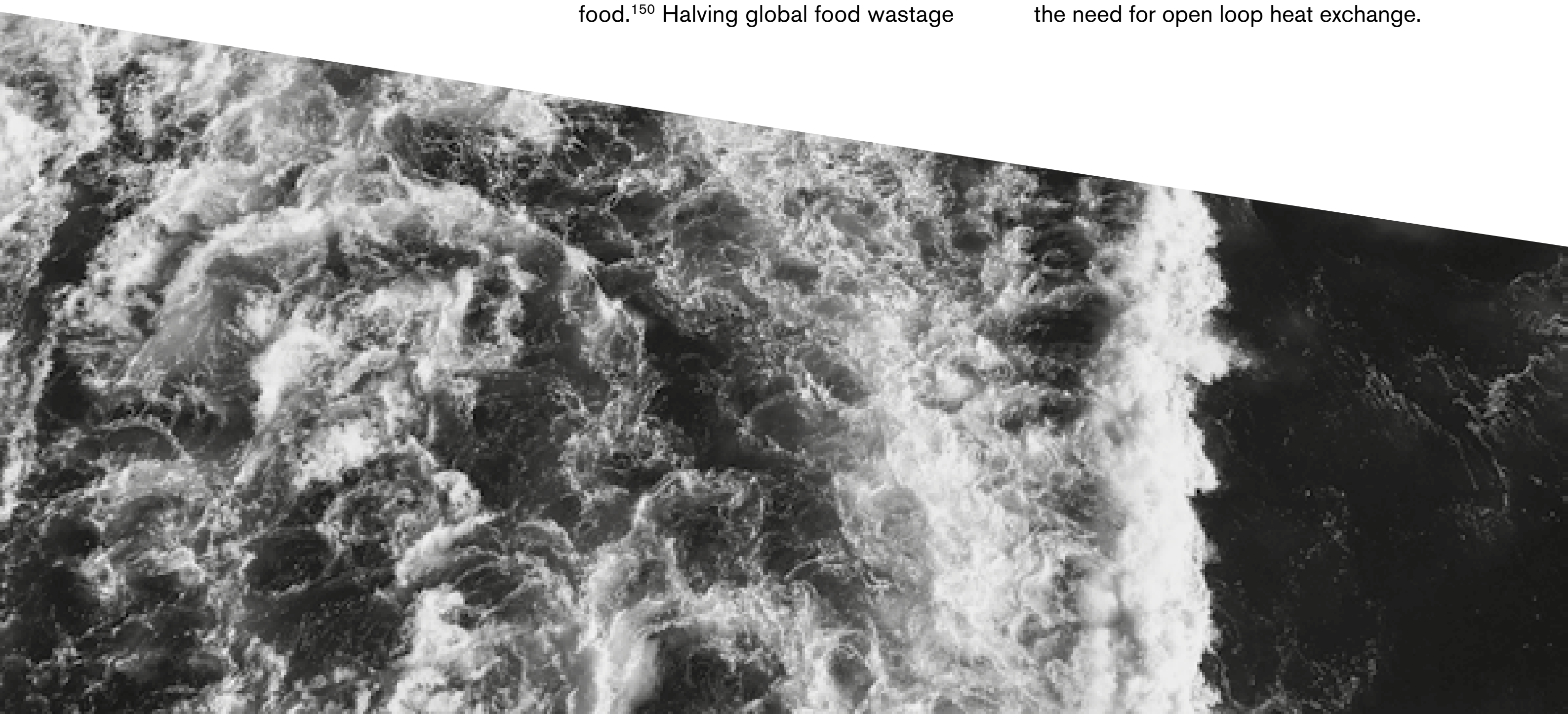
Application	Saving (2012 grid mix)	Saving (2030 grid mix)
Chilled	18%	27%
Frozen	51%	56%

Table 3: *CO_2 emissions savings in India from TRUs powered by liquid nitrogen made with LNG waste cold. Source Dearman/E4tech*[141]

GOAL 14: LIFE BELOW WATER

Clean cold technologies would improve the health of the world's rivers, lakes and seas by reducing food waste, CO_2 emissions and nitrogen pollution. Reducing food waste would relieve some of the pressure on global fish stocks. Reducing CO_2 emissions would mitigate the acidification of sea water, which causes particular damage to shellfish.[142] And reducing the use of nitrogen fertilizer would not only contribute to CO_2 reduction, but also reduce the eutrophication of inland and coastal waters, which kills fish and produces toxins harmful to humans. If the waste cold of LNG re-gasification were re-cycled as liquid air or nitrogen to provide distributed cooling services (see Goal 12), it would remove the need for 'open loop' re-gasification that causes great damage to local marine life.

- Global fish production is now approaching its sustainable limit, with 90% of the world's fish stocks fully or over-exploited[143], and wastage of fish and sea food in the supply chains of developing countries averages around 30%.[144] Halving global food wastage (see Goal 2) would reduce wastage of fish in the supply chain significantly.
- The world's oceans absorb about half of our CO_2 emissions, but this makes them more acidic. The pH of the world's oceans has already fallen by 30%, and on current trends will fall 150% by 2100.[145] Acidification particularly damages species that build their shells out of calcium, such as clams, mussels, sea urchins, barnacles, microscopic plankton and coral – a vital part of ecosystems worldwide.[146] Clean cold technologies would reduce CO_2 emissions from cooling, food waste, and fertilizer production and use (nitrous oxide soil emissions), and so mitigate ocean acidification.
- Eutrophication happens largely because nitrogen fertilizers are washed into rivers, lakes and coastal seas, where they cause algal blooms that deplete oxygen, kill fish and produce toxins harmful to humans.[147] In Lake Victoria, for example, eutrophication has caused extinction of many fish species and declining fish catches.[148]
- World fertilizer consumption was almost 187 million tonnes in 2014[149], and it is estimated that 23% of fertilizer is used to produce wasted food.[150] Halving global food wastage (see Goal 2) would therefore reduce fertilizer use by 11.5% or more than 21 million tonnes per year. This in turn would reduce the amount of nitrogen run-off and resulting eutrophication, therefore reducing harm to fish species and stocks, and toxic hazards to humans.
- LNG re-gasification terminals often employ an 'open loop' heat exchange system in which sea water is used to warm the cryogenic gas and then returns to the sea much colder and chlorinated. This reportedly destroys fish eggs and larvae and damages adult fish populations and catches. It has also been associated with some deaths of turtles and dolphins.[151] [152] If LNG were instead re-gasified using the heat from ambient air, which would itself become extremely cold, and could then be cheaply liquefied to provide distributed cooling services for vehicles and buildings, it would remove the need for open loop sea water heat exchange and the damage it does to marine life. LNG waste cold could also be used to drive innovative desalination plants to produce fresh water and space cooling, which would also avoid the need for open loop heat exchange.



GOAL 15: LIFE ON LAND

Clean cold technologies will help to protect life on land principally by reducing food wastage, and so easing the main driver of deforestation and land degradation. Protecting forests helps to defend biodiversity.

- Forests are vital for combating climate change and protecting biodiversity, but 13 million hectares are lost each year[153], largely to encroachment by agriculture.[154] At the same time arable land is being lost to desertification at a rate of 12 million hectares per year. Meanwhile the FAO predicts food demand will rise 60% by 2050, increasing the pressure on land resources. These pressures will only rise with climate change, since every 1C warming is forecast to reduce crop yields by 5%.[155]
- But nearly 30% of the world's agricultural land is used to produce food that never gets eaten – that's almost 1.4 billion hectares or twice the size of Australia.[156] So halving food wastage would free up 700 million hectares of agricultural land – more than twice the size of India[157] – and equate to 53 years of forest loss at the current rate.
- Clean cold chain technologies can help to relieve the pressure on forests and agricultural land as a vital component of a broader food waste reduction strategy. Protecting forests will help to protect biodiversity.

GOAL 16: PEACE AND JUSTICE

Clean cold technologies could indirectly help to maintain peace by helping to contain potential sources of conflict including rising food prices, water shortage and mass migration.

- Food riots broke out around the world in 2008 and 2011, in response to sharp spikes in the price of food, following droughts in Australia and Ukraine respectively. While social unrest can have many causes, research has shown that riots were more likely above a threshold of 210 on the FAO food price index (see Figure 11).

- Analysis suggests the food riots in 2011 were a contributory cause of the Arab Spring[158], and that a three-year long drought in Syria, which drove 1.5 million people off the land and into the country's cities, contributed to the outbreak of conflict there.[159] Both crises drove refugees and migrants to Europe.

- Competition for water from the world's major rivers has long been identified as a source of potential conflict between neighbouring states, such as Egypt, Sudan and Ethiopia; Afghanistan and Iran; India and Pakistan; and Turkey, Iraq and Syria. While countries have never yet gone to war over water, a recent report from the US State Department warned that in the next ten years water would increasingly be used as a weapon, and that water problems would increase the risk of instability, state failure and regional tensions (Figure 12).[160]

- Clean cold technologies will play a critical part if the world is to reduce food wastage by 50% (see Goal 2), reducing the food shortages and price spikes that contributed to recent outbreaks of violence. Halving food wastage could in turn save 125km³ of water per year (see Goal 6), reducing competition for an increasingly scarce resource. Both factors indirectly reduce the potential for conflict and mass migration.

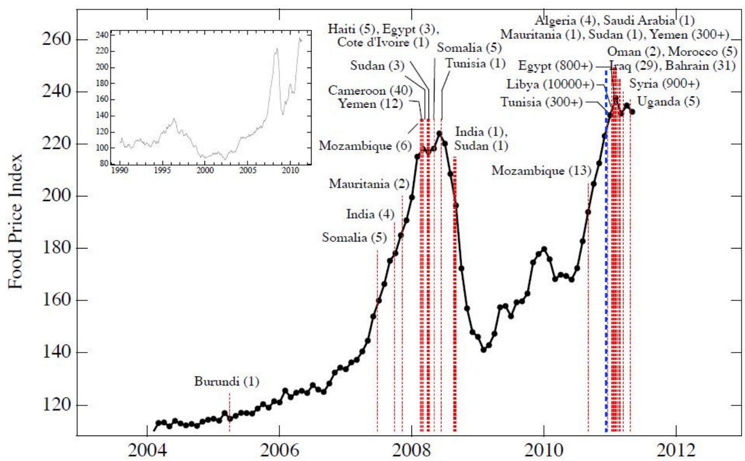


FIG. 1: Time dependence of FAO Food Price Index from January 2004 to May 2011. Red dashed vertical lines correspond to beginning dates of "food riots" and protests associated with the major recent unrest in North Africa and the Middle East. The overall death toll is reported in parentheses [26–55]. Blue vertical line indicates the date, December 13, 2010, on which we submitted a report to the U.S. government, warning of the link between food prices, social unrest and political instability [56]. Inset shows FAO Food Price Index from 1990 to 2011.

Global Water: Present to 2025

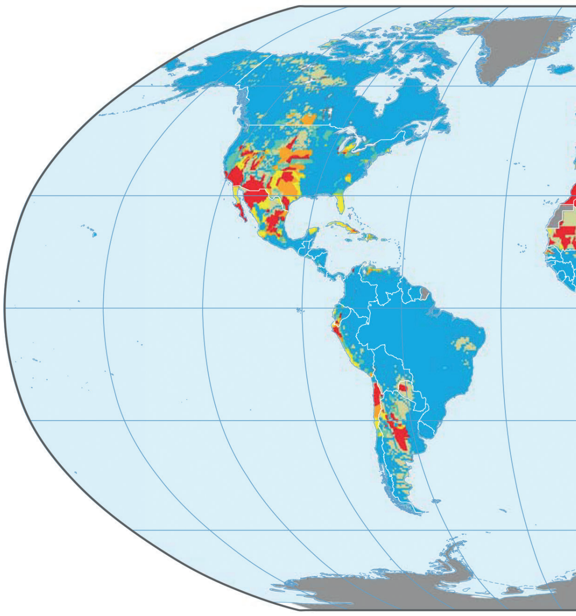
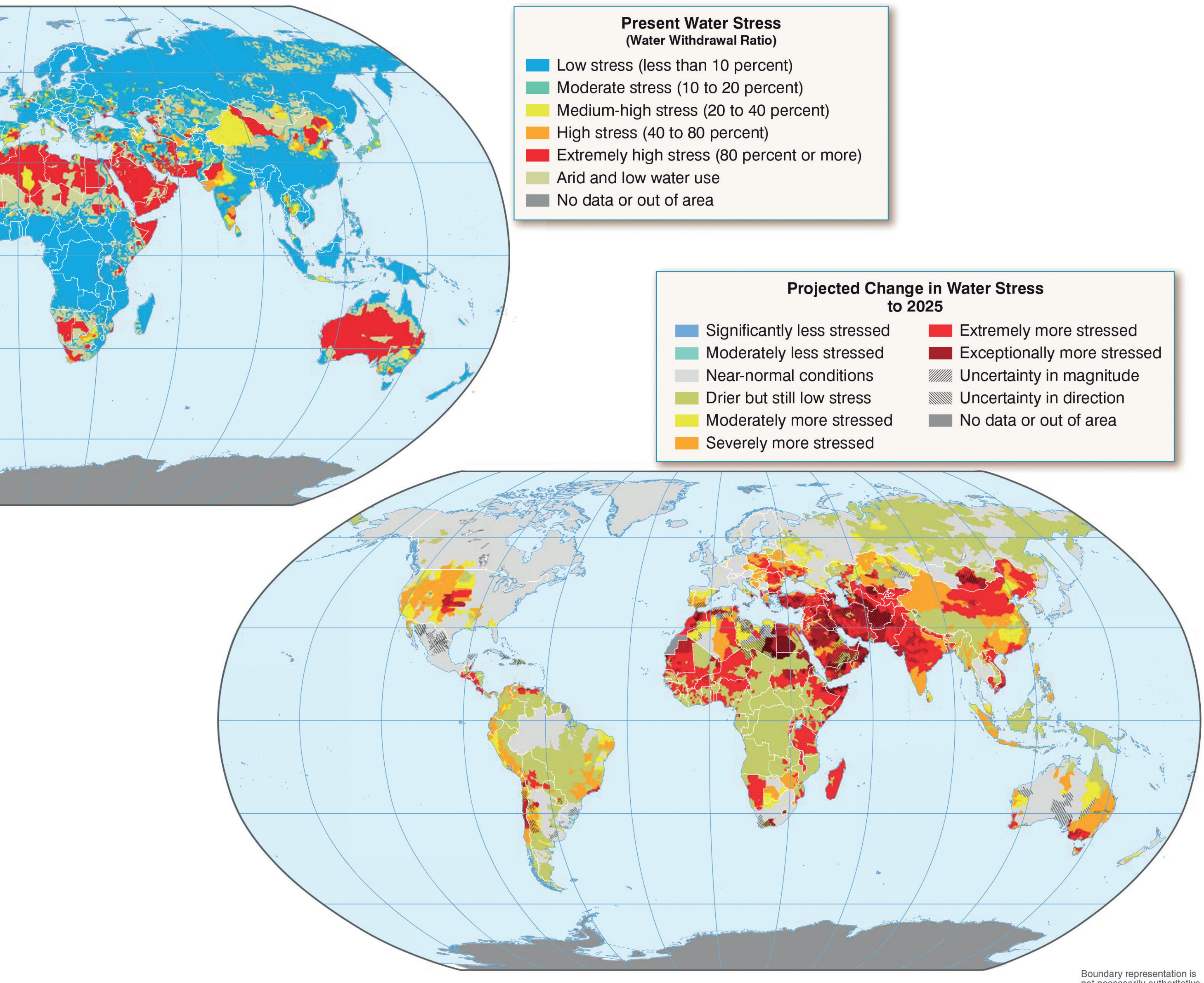


Figure 10: *Correlation of food riots to food price spikes. Source: New England Complex Systems Institute[161]*

Figure 11: *Current areas of water stress and projected change in water stress. Source: US State Department[162]*



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Present water stress is defined as the ratio of total freshwater withdrawals (circa 2000) to annual renewable freshwater supply (1960–90 climatological norm), a quantity often referred to as the water withdrawal ratio (WWR). This provides an assessment of freshwater availability in a typical year relative to recent levels of socioeconomic demand for fresh water. High levels of water stress indicate that socioeconomic demand for freshwater approaches (or exceeds) the annual renewable supply.

The projected change in water stress is calculated as the ratio of projected water stress to present water stress during a 10-year time frame centered on the year 2025. The analysis looks at the A1B scenario of economic and environmental change used by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. The projected change in water stress indicator has categories which are analogous to a drought severity scale. For example, areas with a projected category of “extremely more stressed” are projected to experience the same level of water stress as areas experiencing “extreme drought” today.

Analysis is done at a level below the nation-state. For large countries (e.g. China, India, Russia, United States, etc.) aggregation of stress at the nation-state level would mask the risk of social disruption at local levels.

Source: ISciences, LLC

GOAL 17: PARTNERSHIPS FOR THE GOALS

Clean cold technologies are only now beginning to be commercialised in developed economies. In most developing countries, cooling infrastructure is currently rudimentary or non-existent, but many including China and India are rapidly catching up by installing conventional, highly polluting technologies. So we have a brief opportunity to steer development onto a greener path, in which developing countries leapfrog direct to clean cold and the 'cold economy' – making an important contribution to every one of the Global Goals.

The University of Birmingham Commission on Cold found the cold economy could not only massively improve the environmental impact of cooling, but also generate annual savings of between £43 billion and £112 billion worldwide – a vast potential market and one which is set to grow for the rest of this century. But all this will only be achieved through international partnerships between governments, companies and universities to support research, development, deployment, technology and knowledge transfer.

- Goal 17 calls for the mobilisation of additional financial resources from multiple sources for developing countries, and for the enhancement of north-south, south-south and triangular partnerships, and of international cooperation on science, technology and innovation, and enhanced knowledge sharing. This paper shows there is a strong argument for governments, international donors and multi-lateral organisations to include clean cold technologies in such agreements.

- Britain hosts an unrivalled collection of clean cold R&D programmes with international partners. These include the Birmingham Centre for Cryogenic Energy Storage (BCCES, £12 million), with close links to Chinese universities; the CryoHub, a pan-European consortium led by London South Bank University (€7 million); the National Centre for Sustainable Energy use in Food chains (CSEF, £12 million), with 33 partners led by Brunel University; and the UK Thermal Energy Research Accelerator (T-ERA, £60 million). It is vital that these kinds of partnerships should be extended to include academic and industrial partners in developing countries, both to promote clean cold in those countries, and to ensure the needs and challenges of developing countries are fully incorporated in the development of clean cold technologies.

- The University of Birmingham Commission on Cold developed an industry roadmap for the cold economy that focussed on largely on the UK. This should also be expanded in partnership with international partners in government, industry and universities to incorporate the needs and challenges of developing countries. Co-operation should also cover the development and promulgation of technology agnostic standards to cover clean cooling – including energy efficiency, F-gases and local air pollution.

Dearman zero-emission Transport Refrigeration in trial with Sainsbury's.

APPENDIX 1: THE COLD ECONOMY

Until recently cold was the Cinderella of the energy debate. While governments developed policies to green everything from electricity to transport to heat, the energy and environmental impacts of cooling were largely ignored. This was a serious oversight, since making things cold is energy intensive and can be highly polluting, and demand for cooling in all its forms is booming worldwide – especially in developing countries.

The global agreement to phase out HFC refrigerants or 'F-gases' signed in Rwanda recently is intended to eliminate emissions of these potent greenhouse gases, but it does nothing to tackle the 75% of cooling emissions that come from energy consumption, the growth of which is likely to overwhelm any reduction in HFCs.163 According to one projection, by the end of this century, global demand for air conditioning alone could consume the equivalent of half our worldwide electricity generation today – and most of the increase will come in developing markets. At the same time, huge amounts of cold are wasted, particularly during the re-gasification of LNG, which could be recycled as liquid air to provide clean cold services.

The 'greening' of cold is clearly an urgent global problem, but this cannot be achieved through the current piecemeal approach. We believe it requires the development of a fully integrated 'cold economy', which combines novel clean cold technologies, the integration of waste and under-exploited energy resources, and system-level analysis to dramatically improve the environmental footprint of cold and produce large financial savings.

Cooling is vital

Even in a temperate country such as Britain, cooling is everywhere, and vital to many aspects of civilisation: food, medicine, energy, data and industry. Without cooling, these services would be impossible to provide, and in many parts of the world, life would be scarcely tolerable without air conditioning. Even in Britain and Europe, cooling is estimated to consume 16% of our electricity.[164]

In developing countries, however, billions of people live without cooling and suffer the consequences daily through hunger and ill-health. The lack of adequate cold storage and refrigerated transport causes two million vaccine preventable deaths each year, and the loss of 200 million tonnes of food, with consequences far beyond inflated food prices. The FAO estimates that food wastage occupies a land area twice the size of Australia; consumes 250km^3 of water per year, three times the volume of Lake Geneva; and accounts for 3.3 billion tonnes of carbon dioxide emissions, making it the third biggest emitter after the US and China.[165] So as the world's population heads towards 10 billion by mid-century, increasing food demand by 60%[166], there is no question that we will need far more cooling to conserve food and other vital resources.

Cooling is dirty

Yet existing cooling technologies consume large amounts of energy and can be highly polluting. Cooling is powered by fossil generated electricity, and diesel in refrigerated transport, and relies on HFC refrigerants that are themselves highly potent greenhouse gases. The data is poor, but one estimate suggests that refrigeration and air conditioning cause 10% of global CO_2 emissions[167] – three times more than is attributed to aviation and shipping combined.[168] Another estimate from the German government suggests cooling emissions currently account for 7% of the total, but are growing three times faster, so cooling's share will almost double to 13% by 2030.[169] The recent global deal to phase out HFC refrigerants is welcome progress, but relates only to the 25% of cooling emissions that come from leakage of F-gases, and do nothing to reduce the 75% of cooling emissions that come from energy consumption.

Cooling is also responsible for large amounts of toxic air pollution from the secondary diesel engines ('transport refrigeration units', or TRUs) used to power refrigeration on lorries and trailers. Analysis by Dearman shows these diesel TRUs can emit six times more nitrogen oxides (NO_x) and almost 30 times more toxic particulate matter (PM) than the (Euro VI) propulsion engine pulling them around.[170] It also suggests the cost to EU countries of TRU emissions of CO_2e, NO_x and PM could total €22 billion over the next decade. NO_x and PM cause over 400,000 premature deaths in the EU each year[171], and 3.7 million worldwide.[172] In Africa, air pollution kills more people prematurely (712,000) than dirty water (542,000) or childhood malnutrition (275,000), according to a recent OECD study. Deaths due to outdoor particulate matter alone rose 36% between 1990 and 2013 to 250,000, at a cost of $215 billion.[173]

Cooling demand is booming

Equally worrying is the impact of booming demand for cooling in the developing countries of the southern hemisphere, driven by rapid economic growth, urbanisation and rising incomes. Their lifestyles – changing diets, improved healthcare, online data and air conditioning – will be built on cold. Cooling infrastructure in many developing countries is still rudimentary or even non-existent, but this is changing fast:

- **Domestic refrigeration:** Demand for domestic refrigeration in developing countries is growing strongly – rising from 7% to 95% of China's urban households between 1995 and 2007, for example.[174] The projected rise in fridge electricity consumption in developing countries from 2005 to 2030[175] equates to the entire generating capacity of Belgium and Bulgaria combined[176], and could almost double annual emissions from this source to 450mtCO_2 per year by 2030.[177]

- **Air conditioning in China and India:** In much of the developing world the take-up of air conditioning is still very low, but this cannot last as incomes start to rise. In China, for example, less than 1% of urban households owned an air conditioner in 1990, but by 2003 the number had soared to 62%.[178] The same process is now starting in India, where the number of room air conditioners rose from 2 million in 2006 to 5 million by 2011, and is forecast to reach 200 million by 2030.[179]

- **Air conditioning in the developing world:** In the developing economies as a whole, power for air conditioning is projected to increase seven-fold[180] from 2005 to 2030, requiring an extra 73GW of power stations[181], or the combined generating capacity of Norway, Portugal and Romania[182] , and could raise emissions from this source more than six-fold to 590mtCO_2 per year by 2030.[183]

- As a result, the IPCC projects that **global air conditioning energy demand will grow 33-fold** by 2100 to more than 10,000 TWh, which is roughly half the total electricity generated worldwide in 2010.[184] Energy demand for space cooling will overtake that for space heating by 2060, and outstrip it by 60% at the end of the century.[185]

- **Vehicle air conditioning:** In China the number of air-conditioned vehicles has doubled in five years, and is expected to reach 100 million in 2015.[186] If China were ever to reach the same levels of per capita vehicle and vehicle air conditioning penetration as the US, this alone would consume an extra 2.8 million barrels of oil per day – roughly two thirds of China's current oil production, or more than the entire output of Venezuela[187], and increase greenhouse gas emissions by roughly 440mtCO_2 per year.[188]

- **Datacentre cooling:** Global data centre energy consumption quadrupled between 2007 and 2013 to 43GW[189], and around half of data centre energy consumption goes on cooling. At the current growth rate, by 2030 the additional cooling load would require another 35GW in generating capacity – greater than that of Poland[190], and could triple emissions from this source to 300mtCO_2 per year in 2030.[191]

- **Cold chain:** Conventional 'bottom up' analysis of the world's refrigerated vehicle fleet suggests numbers may grow from around 4 million[192] today to around 9 million in 2025. Analysis by E4tech and Dearman found this could be a huge underestimate, however. Taking account of the demographic change in the developing countries, it found the fleet could grow to as much as 17.9 million vehicles to meet demand.[193] The upper end of this range could increase annual CO_2 emissions by around 180mtCO_2e to 230mtCO_2e in 2025.[194]

- **India cold chain:** As one example, India has scarcely 9,000 refrigerated trucks to serve a population of 1.3 billion, but if it had the same ratio as Britain, India's fleet would number 1.5 million. A recent report from India's National Centre for Cold-chain Development (NCCD) found the country needs an additional 53,000 refrigerated vehicles, 70,000 pack houses and 3 million tonnes of cold storage capacity simply to catch up with current levels of consumption – never mind cater for future growth.[195]

This list is far from exhaustive and the calculations are broad brush. But taken together they suggest that if nothing is done, within fifteen years cooling will require an additional 139GW – more than the generating capacity of Canada – and raise greenhouse gas emissions by over 1.5 billion tonnes of CO_2 per year, three times the current energy emissions of Britain or Brazil.[196]

The challenge and opportunity

The environmental impact of conventional cooling technologies will be partially mitigated through existing efforts to improve efficiency and regulatory changes such as the phasing out of HFC refrigerant gases. But these improvements are highly unlikely to deal with the looming environmental challenge, in part because of entrenched barriers including equipment buyers' focus on up-front capital costs rather than lifecycle costs, and low levels of R&D, but also the sheer scale of projected demand growth. Evidence suggests the energy efficiency of cooling in some sectors could be raised by 30% on the basis of best-in-class products and practices alone, but this improvement would be utterly overwhelmed by (say) the projected 33-fold growth in developing world air conditioning demand.[197] The challenge then is to develop technologies and approaches to cooling capable of serving huge future demand growth but avoiding the environmental consequences of current technologies. We clearly need to do cold smarter, and we believe the answer is to radically improve efficiency by developing a new 'cold cconomy' – which the Birmingham Policy Commission on Cold estimated the Cold Economy could generate annual global savings of between £43 billion and £112 billion – a vast potential market and one which is set to grow for the rest of this century.

The Cold Economy

The cold economy is a radically new approach that applies a system-level analysis to recruit vast untapped resources of waste cold, 'free' cold, waste heat, renewable heat, and 'wrong time' energy – such as wind or nuclear power produced at night when demand is low – to radically improve the efficiency of cooling, and reduce its environmental impact and cost. These waste or surplus resources can be used to provide cooling by converting them into a novel 'vector' – a means of storing and transporting cold – such as liquid air or nitrogen. A key insight of the cold economy is that energy can be stored and moved as cold rather than converted into electricity and then converted again to provide cooling. The cold economy is less about individual clean cold technologies – although these

These ideas are now gaining broader acceptance; in 2015 the Birmingham Commission on Cold adopted a four-stage approach to doing cold smarter, culminating in the cold economy:

1. **Reduce cold load/cooling work required:** eg, better building design, vaccines that survive at higher temperatures;

2. **Reduce the energy required for cooling:** ie, increase the efficiency cooling technologies – eg, cold stores could raise efficiency by an average of 30% using off the shelf solutions only[198] – and reduce the global warming potential (GWP) of refrigerant gases;

3. **System level thinking/cold economy:**
   a. Harness waste resources: 'wrong time' renewables; waste cold (LNG); waste heat, or renewable heat from biomass or ground source heat pumps; system integration across buildings and transport;
   b. Cold energy storage to warehouse and shift wrong time energy to replace peak electricity demand and diesel consumption;

4. Having thus minimised energy demand, **convert remaining cooling loads to sustainable energy sources.**

The system level approach to cold that forms the basis of the cold economy can be represented as five interlocking functions:

Making cold
- Harness waste/unused resources eg,:
  - 'wrong time' renewable energy (eg, wind)
  - waste cold (eg, LNG)
  - ambient heat and cold (eg, ground source)

Storing cold
- Thermal energy storage to warehouse

Moving cold
- New energy vectors and material to shift cold

Using cold
- Reduce cold loads
- Increase efficiency and reduce GWP of conventional technologies
- New technologies to harness novel thermal stores and energy vectors

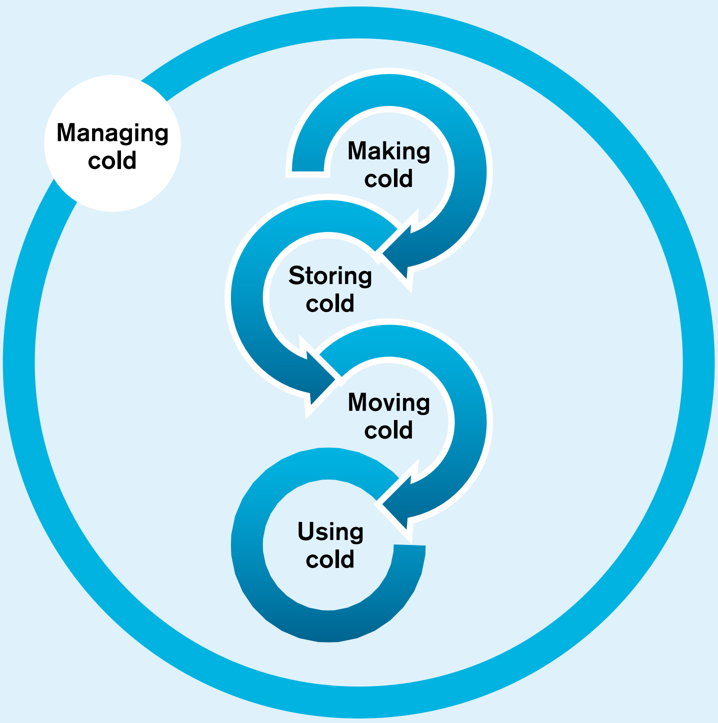
Managing cold
- Data monitoring
- Intelligent controls

are vital – and more about the efficient integration of cooling with waste and renewable resources, and with the wider energy system. It recognises the scale of cooling demand growth and the need to pre-empt its environmental impact, and the opportunities this will generate.

The cold economy approach is powerful in part because it recognises that there is no demand for cold per se, but for services that depend on it such as chilled food, comfortably cool rooms in hot climates and online data. This approach turns our thinking about cooling on its head. For the first time we are asking ourselves 'what is the energy service we require, and how can we provide it in the least damaging way', rather than 'how much electricity do I need to generate?'

If the service required is cooling, current approaches such as burning diesel, which produces power and heat rather than cold, or electric powered air conditioners that expel heat into their immediate environment and so increase the cooling load, are self-evidently sub-optimal. In Phoenix, Arizona, for example, the heat island effect has already raised temperatures by over 4C, towards the upper end of the warming predicted for the entire planet through climate change, exacerbated by air conditioning units that prevent the city from cooling at night as much as it otherwise would.[199] It may also affect our choice of energy storage medium: if what we need is air conditioning at peak times, it could be far cheaper to use off-peak electricity to produce ice to displace conventional air conditioning the following day rather than to charge an expensive lithium ion battery to power it.

System approach to cold



The role of liquid air

One newly proposed energy vector that could enable the cold economy is liquid air, which will power the zero-emission engine Transport Refrigeration Unit (TRU) being developed by Dearman and is now in commercial trials with Sainsbury's (see Appendix 2).

Air can be turned into a liquid by cooling it to around -196°C in an industrial Air Separation Unit powered by electricity. 700 litres of ambient air becomes about 1 litre of liquid air, which can then be stored in an unpressurised insulated vessel. When heat is reintroduced to liquid air it boils and turns back into a gas, expanding 700 times in volume. This expansion can be used to drive a piston engine or turbine to produce mechanical power or electricity, while simultaneously giving off lots of cold – making it ideal for applications where both are required.

Liquid air is not yet produced commercially, but liquid nitrogen, which can be used in the same way, is produced and transported by road tanker – and sometimes pipeline – throughout the industrialised world. The industrial gas companies have large amounts of spare nitrogen production capacity for the simple reason there is four times more nitrogen in the atmosphere than oxygen but proportionately less commercial demand. This surplus could be used in place of liquid air to support early deployment: the ten EU countries that operate 80% of the EU refrigerated vehicle fleet have estimated spare liquid nitrogen production capacity of around 9,000 tonnes per day, enough to cool some 70,000 refrigerated vehicles.[200] In future, liquid air would be cheaper to produce than liquid nitrogen, because there is no need to separate the nitrogen and oxygen, meaning liquefaction requires less equipment and around a fifth less energy. Both liquid air and liquid nitrogen can be produced extremely cheaply by incorporating the waste cold from LNG re-gasification – see page 41.

These cryogens are clearly not the only way to store and transport cold – although they do have many advantages: storable at little more than atmospheric pressure; transportable; liquid, so quick to refuel; and with sufficient energy density to make many applications economic against diesel. Nitrogen is already produced in bulk for industrial purposes, there is substantial spare production capacity in most industrialised countries, and it is distributed daily by road tanker – so no immediate investment in infrastructure is required.

There is far more to the cold economy than liquid air or nitrogen, but we believe that developing these kinds of novel energy vectors is a vital aspect of doing cold smarter and will help the cooling sector to become economically and environmentally sustainable. This work is now being pioneered by several British companies and universities – see Research and Development (R&D) Investment page 41.

Clean cold applications of liquid air

Clean cold technologies are already being developed to run on liquid air or nitrogen. Dearman, for example, is developing its cryogen-fuelled piston engine to provide simultaneous cold and power as a Transport Refrigeration Unit (TRU), and in a stationary engine to provide backup power and cooling for commercial buildings. Dearman TRUs would be zero emission, and unlike many other low carbon technologies would also be cost competitive.

The use of liquid air or nitrogen for cooling need not be restricted to cold chains, but could also extend to commercial vehicle air conditioning – on buses, for instance - and backup power and cooling for data centres and other commercial buildings, where this form of cooling would have several advantages in addition to being zero-emission at the point of use.

In hot countries, providing air conditioning in buses and trains is an important way of making public transport attractive and deterring car use, congestion and emissions. Yet the cooling load in a hot climate is so great that providing air conditioning on a diesel powered bus could raise its fuel consumption by half, and in an electric bus severely reduces the vehicle's range. A cooling system based on liquid air or nitrogen could solve both problems.

In countries with unreliable electricity grids, liquid air or nitrogen could also provide back-up power and cooling for data centres, hospitals and other buildings with an absolute requirement for uninterrupted power and cooling. A Dearman engine would displace highly polluting diesel gensets.

In both vehicles and buildings, liquid air or nitrogen cooling would have the added advantage of counter-acting the heat island effect. Conventional vapour-compression air conditioning systems work by expelling heat into their immediate surroundings, raising the ambient temperature and forcing cooling equipment to work harder still. But with cryogenic cooling systems the only exhaust is clean cold air, which would tend to mitigate the heat island effect rather than reinforce it, so reducing the load on nearby cooling systems and their resulting emissions.

These are just some of the early benefits that could be secured by starting to develop a cold economy based on liquid air or nitrogen. Many liquid air applications are competitive against diesel without subsidy, and would be even more competitive if the liquid air or nitrogen were produced by recycling the huge amounts of waste cold given off during re-gasification of LNG.

LNG waste cold

One of the key concepts of the cold economy is to recycle the waste cold of LNG re-gasification through novel energy vectors such as liquid air or nitrogen to provide. Integrating the waste cold of LNG into air liquefaction would reduce the electricity required by up to 70% and cut the costs by half. Cheap liquid air could then be used to provide low carbon, zero emission 'cold and power' to vehicles and buildings in Europe's cities through innovative enabling technologies such as the Dearman engine.

Analysis by Dearman suggests the energy and financial potential of this approach is enormous. Each tonne of LNG contains the cold energy equivalent of 240kWh – quite apart from the chemical energy contained in its methane molecules – most of which is thrown away. The global LNG trade is expected to double to around 500 million tonnes per year by 2030, representing cold energy of 120TWh, theoretically equal to the annual output of 14 1GW nuclear power stations.[201] In more practical terms, this much LNG waste cold could help produce 184 million tonnes of liquid air, enough to supply cooling for 4.2 million liquid air refrigerated delivery trucks, more than the current global fleet.[202]

The financial value of this recycling could also be huge. Dearman modelling suggests it could add £30 to the value of each tonne of LNG – an increase of about 10% at current prices. At a projected global LNG trade of 500 million tonnes per year, that represents a potential market of £15 billion.[203] This does not include the value of the social benefits of liquid air transport refrigeration from reduced emissions of carbon dioxide (CO_2), nitrogen oxides (NOx) and particulate matter (PM), however, such as lower costs for hospital treatment, lost life and productivity, and damage to buildings and crops. In the EU, these benefits are estimated to be worth €8.7 billion (£6.4

billion) over the next decade[204], on the basis of cost factors calculated by Ricardo-AEA for the European Commission.[205] If LNG cold waste were used to produce the LAIR, those social benefits could be achieved even more cheaply and would equate to £11 per tonne of LNG recycled.[206]

In the few instances of LNG waste cold recovery to date, the cold has typically been re-cycled by selling it to industrial gas or petrochemical companies 'over the fence'. But this limits use of the cold to the immediate vicinity of the LNG terminal, and to periods when the LNG is actually being re-gasified, which may be intermittent. All the constraints of the traditional approach would be removed if the waste cold were re-cycled as liquid air or liquid nitrogen, and used not as an industrial gas but as a zero-emission energy 'vector' – a means of storing and moving cold and power in time and place.

While the global LNG trade is projected to grow strongly, only 23 of the world's 111 existing LNG import terminals yet do any form of cold recovery, so there is clearly huge potential not only in aggregate but also at many individual locations around the world - in both developed and developing countries. Dearman analysis shows:

- The exploitable waste cold from the UK's total projected LNG imports in 2030 could support 50,000 truck and trailer TRUs, almost a third more than the projected refrigerated truck and trailer fleet at that date;[207]
- The waste cold of LNG imports of seven western European countries in 2014 could have replaced diesel to provide cooling for 210,000 refrigerated vehicles, equivalent to more than a fifth of the entire EU fleet;
- India's projected LNG imports in 2040 could produce enough liquid air[208] to provide cooling for almost 211,000 chilled and frozen trucks[209].

A 'tank of cold'

At first glance it might seem that a cold economy based initially on liquid air and LNG waste cold would be restricted to more industrialised areas. But in fact the cold economy could extend to even the remotest parts of developing countries through an approach known as the 'tank of cold', by which rural communities are supplied with multiple cold and power services from a single tank of cryogen produced locally from renewable energy. A report from the Institution of Mechanical Engineers (IMechE) published in 2015 recognised the potential of this approach to transform rural economies and lives.[210]

Grid electricity in developing countries is often highly erratic, and in the countryside may be non-existent. In Tanzania, for example, only 2% of the rural population has access to electricity. This means any refrigeration in the countryside is powered by polluting and expensive imported diesel. A more sustainable cold chain would need to run on renewable energy, but the intermittency of wind and solar means this would also require some form of energy storage – for which liquid air is the ideal solution.

As the illustration on page 16-17 shows, an air liquefier located near a rural town is driven by a large solar array. During the day the plant cools air to around -196C, at which point it turns into a liquid and can be stored in an insulated tank until needed. In effect, the renewable energy is stored as one third power, two thirds cold. The liquid air could either be used at its production site – perhaps to generate electricity at peak times or at night for the local micro-grid – or delivered by road tanker to customers nearby.

The first and most energy intensive stage of the cold chain is to 'pre-cool' produce from ambient to the temperature that will best preserve it – e.g. 18C for tomatoes, 0C for apples and -18C for frozen foods including high value products such as fish. For some crops such as tomatoes it would be possible to pre-cool the crop on-board a liquid air refrigerated truck, meaning the load could be transported to nearby cold storage or direct to market with minimal deterioration due to heat. Other crops would be pre-cooled and stored at the local cold warehouse using liquid air, and then delivered by liquid air refrigerated truck to the city or port. (Standard diesel TRUs are not powerful enough to precool produce on-board, which would have to be done in a pre-cooling room powered by grid electricity – if available – or more likely by static diesel generator).

Liquid air transport refrigeration is particularly efficient because it extracts both cooling and power from the same unit of fuel. First the liquid air is passed through a heat exchanger in the cargo compartment, which cools the produce and warms the liquid air into a high pressure gas. This then drives a small piston engine to power a conventional refrigeration compressor – so the liquid air delivers two bangs for one buck. Modelling shows that in Tanzania, for example, transporting a variety of crops over long distances would be 40-50% cheaper using liquid air pre-cooling and refrigeration than diesel pre-cooling and refrigeration.[211]

With a liquid air production plant in place, farmers or rural businesses could set up new ventures to process their food – for

instance through blast freezing – and capture more of the value. The price of mangoes in Tanzania, for example, falls to $100 per tonne at harvest time, but rises to more than $3000 out of season, and a liquid air quick freezing system could freeze one tonne for just $137, creating a huge margin to cover the necessary investment. Other local businesses such as hotels could use liquid air for air conditioning and back-up power generation, while the local hospital could use the cold for medical purposes. If the liquid air plant invested in the equipment to separate air into liquid nitrogen and oxygen, there could be additional benefits such as nitrogen fertilizer production and oxygen for medical use.

The tank of cold concept could equally well apply to urban areas in both developing and developed economies, however, with cryogen storage tanks placed strategically placed in locations as diverse as industrial parks, bus depots and town centres. Again, these could provide a range of energy and cooling services to a variety of customers. As wind capacity continues to rise, liquid air would allow lower carbon overnight electricity to be deployed in peak power generation, transport, refrigeration and cooling – all from a single plant.

A new liquefier or Liquid Air Energy Storage (LAES) plant sited at an industrial park, for example, might supply a range of neighbouring businesses for different purposes. A datacentre might need liquid air for cooling and for its cryogenic backup electricity generator (genset), while a logistics company might want fuel for its ZEV forklift trucks and 'heat hybrid' lorries. A biomass power station or gas fired CHP plant could be integrated directly with the LAES unit, or if too distant, could install a cryogenic genset and tank, to be refilled periodically by deliveries from the central liquefier. With sufficient regional demand for liquid air, the liquefier could be sized to support a tanker distribution network.

A supermarket distribution hub, on the other hand, might install a large liquid air tank, to be regularly refilled from the nearest liquefier, which could support its Dearman engine truck refrigeration units, forklift trucks and a cryogenic genset for emergency power. A metropolitan bus depot could adopt a similar approach, with a large tank to support both its heat hybrid bus fleet, and a cryogenic genset for grid balancing. In the longer term, it might also support refuelling for private vehicles.

Research and Development (R&D) investment in the Cold Economy

Research into cooling has historically failed to match its economic importance and environmental impact. In Britain over the past decade, for example, research into Refrigeration and Air Conditioning (RAC) has attracted scarcely 0.2% of total UK and EU public funding for engineering research, despite the fact that cooling is by one estimate responsible for 10% of all CO_2 emissions.[212] More recently however this shortfall has begun to be rectified, through a series of major public and private investments into research into clean cold and the cold economy:

- Energy Research Accelerator (ERA), a major collaboration between six Midlands universities and over fifty companies to tackle some of the biggest energy challenges. ERA secured £180 million in funding from government and industry to cover three themes, one of which is thermal energy (T-ERA) – explicitly including the development of the global cold economy.

- A consortium led by Dearman has recently secured £15 million in funding from the Advanced Propulsion Centre and industrial partners for a project that will help develop its suite of clean cold and power applications. The Dearman transport refrigeration unit developed in collaboration with the University of Loughborough, Horiba MIRA, Hubbard Products, and Air Products, was part funded by a £900,000 grant from Innovate UK, and is now in commercial with Sainsbury's in London. The 4-cyclinder Dearman engine being developed as a back-up electricity generator, and as a diesel-liquid air 'heat hybrid' propulsion engine for buses and lorries, is supported by a £2 million grant from Innovate UK. Dearman is now building a prototype, which will be integrated into a bus at Horiba MIRA early next year. The project also involves Air Products, MTC, Productiv, Cenex and TRL.

- CryoHub: a €7 million European grant for pan-European consortium of researchers led by Professor Judith Evans, London South Bank University. The three year project will research the potential efficiency gains that might be achieved by integrating Liquid Air Energy Storage with existing cooling and heating equipment found in refrigerated warehouses and food processing plants – a good example of the cold economy approach.

- Birmingham Centre for Cryogenic Energy Storage (BCCES): a £12 million project led by Professor Yulong Ding of the University of Birmingham, including £7 million for bespoke cold/thermal and cryogenic energy storage and engine laboratories and equipment, and £4 million for a test-bed cryogenic energy storage pilot plant, as part of the energy storage strand of the last government's '8 Great Technologies' initiative.

- National Centre for Sustainable Energy use in Food chains (CSEF): research into energy, resource use and sustainability of the food chain, led by Professor Savvas Tassou from Brunel, and one of six centres funded by Research Councils UK (RCUK) to address 'End Use Energy Demand Reduction' in the UK. The Centre has 33 partners and £12.3m of funding from RCUK, industry partners and universities.

- i-STUTE: an interdisciplinary centre for Storage, Transformation and Upgrading of Thermal Energy. i-STUTE, funded through the RCUK energy programme, brings together the University of Warwick's School of Engineering and Warwick Business School together with London South Bank University, the University of Ulster and Loughborough University.

- Highview Power Storage built its Liquid Air Energy Storage pilot plant at Slough with the support of a £1 million grant from the Department of Energy and Climate Change (DECC). In 2014 the Slough plant was dismantled and moved to the Birmingham Centre for Cryogenic Storage for further research, and Highview went on to build a much larger 5MW pre-commercial demonstrator with the help of £8 million from DECC. It is now in the final stages commissioning and will provide balancing services to the grid for at least a year.

- Another consortium has secured a Newton Fund grant to support a green data centre project in Malaysia. The project The project combines innovative technologies from both Malaysia the UK, including a Dearman engine device to provide back-up power and cooling, that aims to reduce data centre energy consumption by 50%. The consortium made up of Dearman, Green Data Center LLP, Heriot-Watt University and Universiti Teknologi Malaysia.[213]

Altogether IT IS estimate that British public and private investment in research and development into the cold economy, liquid air energy storage and related clean cold technologies has now reached about £100 million, suggesting growing acceptance of a concept whose environmental and economic impact is likely to spread far beyond the business of cooling.

APPENDIX 2: THE DEARMAN ENGINE

Dearman zero-emission Transport Refrigeration in trial with Sainsbury's.

Sainsbury's has become the first company in the world to introduce a refrigerated delivery truck cooled by a liquid nitrogen powered Dearman engine. The zero-emission cooling unit replaces the traditional diesel engine used to chill the vehicle and will eliminate the exhaust emissions of refrigeration and significantly cut carbon dioxide emissions. During the three-month trial, the vehicle could save up to 1.6tCO_2, 37kg of nitrogen oxides and 2kg of particulate matter compared to a similar sized diesel system. The truck operates from Sainsbury's Waltham Point depot, delivering chilled goods to stores in the London area.

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

Because it produces both power and cooling from the same unit of 'fuel', the Dearman engine can serve as an efficient and zero emission transport refrigeration engine to replace the highly polluting secondary diesel units used on lorries today. But there are many other potential applications.

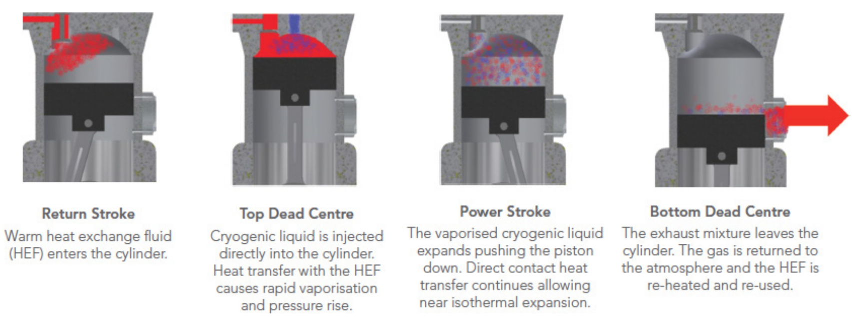
Because liquid air boils at -194°C (and liquid nitrogen at -196°C), its work output can be raised by the addition of waste heat from another source. This means the Dearman engine can be combined with a diesel engine or hydrogen fuel cell to form a 'heat hybrid', where waste heat and cold are exchanged between the engines to increase the efficiency of both and reduce fuel consumption. Modelling suggests this arrangement would turn waste heat into extra power at practical conversion efficiencies approaching 50%, and reduce bus and lorry diesel consumption by 25%. A consortium including DEC, Air Products, MIRA, Cenex, TRL, The Manufacturing Technology Centre and The Proving Factory has been awarded nearly £2 million by the Technology Strategy Board to build a heat hybrid prototype by 2016.

In future, the Dearman engine could also be used as a stand-alone propulsion engine for smaller, shorter distance vehicles such as auto-rickshaws ('tuk tuks') in developing countries, where the exhaust of clean cold air would provide 'free' air conditioning. It could also be used as a static back-up electricity generator to replace highly polluting diesel gen-sets. Dearman is part of a UK consortium which has won a Newton Fund grant for a clean data centre project that will incorporate a Dearman engine device to provide back-up power and cooling.

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

To find out more about the Dearman engine please visit: www.dearman.co.uk

An example power cycle is shown on the diagram below



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