Clean cold sits at the nexus of sustainable social and economic progress

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***The UN's Sustainable Development Goals,** adopted last year, aim to finish the job set out by the Millennium Development Goals, and to massively widen their scope and ambition. By 2030, the new 'Global Goals' not only commit to abolish hunger and poverty worldwide, and ensure good healthcare, education, gender equality and access to clean water for all, but also set detailed targets around affordable clean energy, sustainable cities, infrastructure, climate action, decent work and economic growth, and responsible consumption. According to resolution A/RES/70/1, if the Global Goals are achieved, "the lives of all will be profoundly improved and our world will be transformed for the better".* [i]

The UN rightly argues its 17 goals and 169 associated targets are "integrated and indivisible", and that this interconnectedness will be vital to their success. Many of the linkages – between hunger, poverty and ill-health, for example, or water shortage and conflict, or economic growth and pollution - are already well understood. But it is surprising how many of the Global Goals share one common factor that is not yet widely recognised: ***cooling.***

Cooling was for many years the Cinderella of the energy debate, but a series of recent reports from the Institution of Mechanical Engineering, Dearman and the University of Birmingham Policy Commission on Cold has shown its importance to major environmental challenges including food, water, health, energy and climate change. What emerges from the new "indivisible" Global Goals is that cooling could also be critical for achieving economic and social progress.

Getting cooling right is central to tackling these problems because it is both vital to many aspects of modern life – food, medicine, data – but also energy intensive and highly polluting. The dilemma is becoming most acute in developing countries, where climates are typically hot, cooling infrastructure scant to non-existent, and cooling demand now booming - driven by rapid economic growth, rising incomes, urbanisation and climate change. Here cooling causes huge problems both by its absence, and by its provision through highly polluting conventional technologies. Either way, it causes or worsens many of the environmental, economic and social challenges identified by the UN.

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On the one hand, in most developing countries the lack of a continuous 'cold chain' of refrigerated warehouses and trucks contributes to high levels of post harvest food loss: the IIR estimates that if developing countries had the same level of cold chain as developed they would save 200 million tonnes of food.[ii] Food waste depresses farm incomes, raises food prices and worsens hunger. Such colossal food waste has equally large knock-on effects: the FAO estimates that food wastage occupies agricultural land twice the size of Australia[iii]; consumes 250 km^3 of water per year, three times the volume of Lake Geneva; and accounts for 3.3 billion tonnes of carbon dioxide (CO2) emissions, making it the third biggest emitter after the US and China.[iv]

In other words, the absence of cooling causes or exacerbates challenges in food, water, emissions, poverty and hunger. It also has a direct impact on health and mortality: a lack of adequate cold storage and refrigerated transport causes two million vaccine preventable deaths each year[v], and contributes to endemic low level food poisoning in much of the developing world.

On the other hand, 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[vi], whose spending power could rise to $33 trillion.[vii] Their lifestyles – changing diets, improved healthcare, online data and air conditioning - will be built on cold.

Air conditioning is a case in point. 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.[viii] And according to another forecast, by the end of the century global air conditioning will consume 10,000TWh[ix], about half the electricity consumed worldwide for all purposes in 2010. To put this in perspective, to generate 10,000TWh from wind would require 4.6TW of turbine capacity, more than ten times the world's total wind capacity today.[x]

In the near term, on current trends cooling will require an additional 139GW of generating capacity by 2030 - more than that of Canada – and raise greenhouse gas emissions by over 1.5 billion tonnes of carbon dioxide (GtCO2) per year, three times the current energy emissions of Britain or Brazil.[xi] The projected growth will dramatically worsen the environmental damage caused by cooling, which is already huge – though little recognised so far. The data is poor, but one estimate suggests that refrigeration and air conditioning cause 10% of global CO2 emissions[xii] – including both energy emissions and leaks of HFC refrigerants - three times more than is attributed to aviation and shipping combined.[xiii] 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.[xiv]

The global deal to phase out HFC refrigerants or 'F-gases' signed in Rwanda recently was described as 'single most important step we can take to limit the warming of the planet' by US Secretary of State John Kerry. But in fact HFCs cause only 20-25% of carbon dioxide equivalent emissions of cooling, and energy consumption the rest: at least 75%, or three times greater. Given the scale of projected cooling demand growth, the emissions savings from phasing out HFCs are likely to be overwhelmed by rising emissions from cooling energy consumption – unless we completely rethink how that energy is supplied.[xv]

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 (NOx) and almost 30 times more toxic particulate matter (PM) than the (Euro VI) propulsion engine pulling them around.[xvi] It also suggests the cost to EU countries of TRU emissions of CO2e, NOx and PM could total €22 billion over the next decade. NOx and PM cause over 400,000 premature deaths in the EU each year[xvii], and 3.7 million worldwide.[xviii]

Analysis by Dearman and E4tech also suggests the worldwide refrigerated vehicle fleet could grow from around 4 million[xix] today to as many as 18 million by 2025 to satisfy currently unmet demand in developing countries.[xx] This fleet would emit the same amount of particulate matter (PM) from refrigeration alone as around 1 billion diesel cars[xxi], roughly equal to the entire global car fleet today, representing an environmental and health catastrophe.

So there is an urgent need to resolve the cooling dilemma; it is crucial that the primary energy demand for providing cold does not grow at the same rate as cold demand itself. But if the environmental, economic and social challenges caused by cooling are horribly entangled, the good news is that, by the same token, *clean cold* technologies and approaches would have an equally leveraged effect, and could help to achieve many more of the UN targets than might be suspected at first glance.

Clean cold technologies and the 'cold economy'

A recently published report from the Birmingham Policy Commission, entitled *Doing Cold Smarter,* investigated the environmental and economic potential of developing a 'cold economy' based on novel clean cold technologies and a system-level approach to cooling.[xxii]

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 *(see Box 1 – What is Liquid Air?)*.

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 are vital – and more about the efficient integration of cooling with waste and renewable resources, and with the wider energy system *(see Box 2 overleaf - A tank of cold: synergies from aggregating applications).* 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

What is liquid air?

Air turns to liquid when refrigerated to -196°C, and can be conveniently stored in insulated but unpressurised vessels. Exposure to heat (including ambient) causes rapid re-gasification and a 700-fold expansion in volume, which can be used to drive a turbine or piston engine. This re-gasification gives off large amounts of cold, so liquid air (LAIR) can be regarded as an energy 'vector' to transport cold and power in time and place.

Since the boiling point of liquid air (-196°C) is far below ambient temperatures, the environment can provide all the heat needed to make liquid air boil. The low boiling point also means the expansion process can be boosted by the addition of low grade waste heat (up to +150°C), which other technologies would find difficult to exploit and which significantly improves the overall efficiency.

Liquid air is not yet produced commercially, but liquid nitrogen (LIN), which can be used in the same way, is produced throughout the industrialised world. The industrial gas companies have large amounts of spare nitrogen production capacity for the simple reason there is far more nitrogen than oxygen in the atmosphere but proportionately less commercial demand. This surplus could be used in place of liquid air to support early deployment. 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 (20%) less energy.

Both LAIR and LIN can be produced extremely cheaply by incorporating the waste cold from LNG re-gasification, which reduces the electricity required for air liquefaction by 70% and costs by about half.

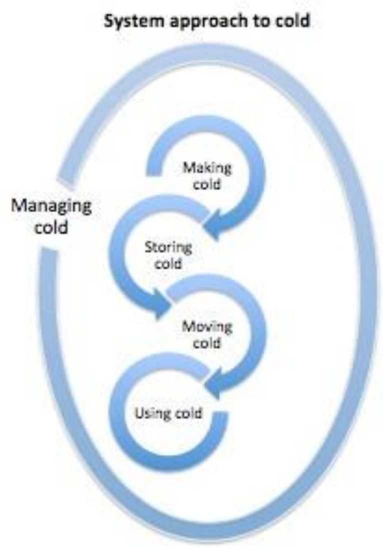
environment and so increase the cooling load, are self-evidently sub-optimal. It may also make sense to store wrong-time energy as cold rather than electricity. For example, if what we need is air conditioning at peak times, it could be far cheaper to use off-peak electricity to produce ice to displace conventional air conditioning the following day, rather than to charge an expensive lithium ion battery to power it.

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

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

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

- **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;



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

A tank of cold: synergies from aggregating applications

The Dearman engine, which runs on LAIR or LIN, is being developed in a variety of applications that provide cold and power in vehicles and buildings. The first application is a zero-emission transport refrigeration unit (TRU), which is already in commercial demonstration, and once in production will be economic without subsidy against both the highly polluting diesel TRUs that currently dominate the logistics industry and evaporation-only nitrogen systems. Other applications in development include a back-up electricity generator, and a ‘heat hybrid’ engine for trucks and buses that reduces diesel consumption by over 25%. The technology could also provide a zero-emission propulsion engine for urban and last-mile delivery vehicles.

These applications – and others - are in development with substantial grant support from government agencies such as Innovate UK, and in collaboration with a wide range of industrial partners. They are economically competitive because they re-purpose existing technologies to solve obstinate energy problems at far lower cost than batteries or hydrogen.

Each application makes a compelling business case as a high performance, cost competitive, zero emission solution in its own right. In future, however, synergies could be achieved by integrating multiple Dearman and other liquid air applications around a single tank of cold, delivering major savings in energy, carbon, emissions and cost.

If a liquid nitrogen storage tank were installed at a logistics hub or food processing plant, for example, it could not only provide cryogenic ‘fuel’ for refrigerated vehicles, but also support a Liquid Air Energy Storage (LAES) plant. This could provide emergency back-up power for the hub - where a significant percentage of energy will be for cooling loads - or support services for the electricity grid, or both. Over time, as liquid air product portfolio expands, the same tank could fuel zero-emission forklift trucks and return-to- base delivery vehicles powered by diesel-liquid air heat hybrid engines.

Equally, a tank sited at an industrial park might supply several neighbouring businesses for different purposes but all with a common need for power and cold.
Continued overleaf

A tank of cold (continued)

For example, a data centre could make good use of the 'waste' cold from a liquid air backup electricity generator, since almost half its energy load would typically come from cooling, while next door, a transport operator could refuel buses fitted with Dearman heat-hybrid engines or auxiliary power and cooling systems. A biomass power station or gas fired CHP plant nearby could be integrated with Liquid Air Energy Storage to deliver grid-based electricity storage and convert waste heat converting into additional power.

In rural areas of developing countries, the tank of cold solution could support an integrated cold chain from farm to market, with strategically placed tanks of cold supplying cooling to pack-houses, to refrigerated vehicles, food processing hubs and retail outlets. It could also provide clean cold and power, energy storage, energy back-up for co-located rural medical centres.[xxiv]

Waste Cold

The Commission recognised that one of the key solutions was to recycle some of the vast amounts of waste cold given off during the re-gasification of Liquefied Natural Gas (LNG) at import terminals to reduce the primary energy demand, cost and environmental impact of providing cold.

The cold of LNG can be considered the packaging in which natural gas is transported. When natural gas is cooled to -162°C it liquefies and shrinks 600-fold in volume, making it economic to ship by super-tanker to a customer on the other side of the world. On arrival, the LNG must be warmed up to re-gasify before entering the natural gas pipeline. During re-gasification each tonne of LNG releases up to 240kWh of 'coolth' or cold energy[xxv], which is quite separate from the chemical energy contained in its molecules and is usually discarded.

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. Since only 23 of the world's 111 LNG import terminals do any form of cold recovery[xxvi], it seems reasonable to conclude that in many locations there is either insufficient local demand for waste cold, or that the business case is not compelling.

The key to recycling more LNG waste cold is to separate the generation and consumption of cold in both time and place. If the waste cold could be converted into a 'vector' or form that is storable and transportable, the energy could then be consumed in distant locations on demand, rather than tied to the location and re- gasification schedule of the LNG terminal. This should not only allow more of the waste cold to be recycled, but also put to the best use economically.

One recent suggestion is liquid air (LAIR) or liquid nitrogen (LIN) as just such a vector. These cryogens are produced by refrigerating air to -196°C, and pre-cooling the air with LNG waste cold would reduce the electricity required by 70% and production costs by half. The LNG waste cold resource could then be deployed to reduce the cost and environmental impact of booming demand for cooling throughout society - from data centres to air conditioning to food and pharmaceutical cold chains.

The LNG market is likely to remain oversupplied until at least 2020 according to the IEA, which forecasts export capacity will rise 45% over that period but global demand growth will average just 1.5% per year.[xxvii] Some other forecasters, such as the business consultancy Accenture, predict the glut will last for a decade, and recommend suppliers respond by developing small scale LNG and new applications to expand the pool of potential customers.[xxviii]

Another logical response would be to squeeze more value from each tonne of LNG sold by exploiting the waste cold of re-gasification, both at existing import terminals and in smaller scale re-gasification plants and applications developed in future. This approach could be particularly valuable in huge developing countries such as China and India, where LNG demand is still growing strongly (the IEA predicts 9% and 6% per year respectively), and which have yet to build almost all their essential cold chain infrastructure.

Clean cold and the Global Goals

The cold economy, and particularly the recycling of LNG waste cold, could have a significant part to play in achieving the Global Goals. It could help solve both the problems caused by the absence of adequate cooling infrastructure in developing countries, and those caused by booming demand and highly polluting conventional cooling technologies. A zero-emission Transport Refrigeration Unit (TRU), for example, by conserving food at far less environmental cost, could make a major contribution towards achieving many of the Global Goals. Because it would help reduce post-harvest food losses and emissions of CO2, NOx and PM, its impact would extend far beyond the environment and into the economic and social dimensions of sustainable development. Altogether "clean cold" could help achieve 14 of the 17 Global Goals:

Goal 1, end poverty in all its forms everywhere: since most of the world's poor work on the land[xxix], the issue of post-harvest food loss is critical. The development of clean cold chains would reduce post-harvest losses and increase the volume and quality of product reaching market; allow farmers to produce higher value crops and products; and improve access to national and even international markets. This would raise farmers' incomes, boost local economies and reduce the incentive to migrate to city slums. India's National Centre for Cold-chain Development (NCCD) has concluded that developing temperature controlled logistics in rural areas is the critical factor in achieving the government's target of doubling farmers' income over the next five years.

Goal 2, eliminate hunger and achieve food security and improved nutrition: clean cold chains would help achieve all three by reducing post harvest food loss, which would increase the volume, quality and nutritional value of food reaching the market, and reduce food price inflation – widely recognised as the critical cause of hunger. One study found that halving food wastage could feed an extra 1 billion people[xxx], comfortably higher than the 800 million who were chronically undernourished in 2012-14. Since global food demand is forecast to rise 60% by 2050[xxxi] technologies like cooling that reduce waste will become ever more vital.

Goal 3, ensure healthy lives at all ages: a lack of adequate cold chain causes 2 million vaccine preventable deaths each year[xxxii], and endemic low level food poisoning in the developing world, while diesel transport refrigeration units (TRUs) and gensets cause grossly disproportionate emissions of toxic NOx and PM. All three causes of death and illness would be ameliorated by clean cold chains and back-up cold and power generators.

Goal 6, sustainable clean water and sanitation for all: reducing food waste through clean cold chains would also reduce the associated waste of water – estimated at 250km^3 per year. According to the World Bank, at least 663 million people lack access to safe drinking water, and by 2025, 1.8 billion people will live in areas with absolute water scarcity.[xxxiii] Cooling could also increase the fresh water supply through innovative desalination techniques that work by freezing sea water.[xxxiv] Since ice is also an effective means of storing off-peak electricity for daytime cooling[xxxv], it is possible a single 'desalination' plant could simultaneously provide fresh water, energy storage and cooling, while reducing local air pollution and CO2 emissions.

Goal 7, access to affordable clean energy for all: TRUs running on liquid air or nitrogen would be cheaper than conventional, highly polluting diesel TRUs. They would be cheaper still if the liquid air were produce with waste cold from re-gasification of liquefied natural gas at LNG import terminals, which are proliferating in developing countries. Under Goal 7, specific targets include doubling the rate of efficiency improvement and substantially increasing the share of renewable energy, both of which would be supported by liquid air technologies. Since the largest and fastest growing developing economies typically have hot climates, global energy demand for space cooling will overtake that for space heating by 2060[xxxvi], requiring a fundamental rethink of the way cooling is provided. If nothing is done, by the end of the century space cooling energy demand will outstrip space heating by 60%.

Goal 8, sustainable economic growth and decent work for all: investment in new clean cold infrastructure in developing countries would generate local jobs in both manufacturing and service roles, as well as conserving jobs in rural areas and calming food prices (see above). Cold is essential for food processing, and provision of cooling would enable farmers to claim more of the value chain. 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. Processing crops or carcasses at the farm gate rather than further afield would limit the amount of waste product transported long distances.

Goal 9, industry, innovation and infrastructure: much of the infrastructure - including cooling - required by developing countries such as India has yet to be built, meaning they could leapfrog to more sustainable approaches. Liquid Air Energy Storage would help balance electricity grids, and make best use of renewable energy generation, while liquid air gensets would protect local communities from erratic grids and allow them to make best use of local renewable generation. The 'tank of cold' approach explored by the Institution of Mechanical Engineers in a recent report, could allow off-grid rural communities in developing countries to access a wide range of cold and power services all powered by renewable energy (see Box 2).[xxxvii]

Goal 11, sustainable cities and communities: cooling is vital in cities for food, data, medicine and air conditioning comfort. Clean cold systems based on liquid air would reduce 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.

Goal 12, responsible consumption and production: clean cold technologies can be fuelled by liquid air produced using recycled waste cold from the re-gasification of liquefied natural gas (LNG) at import terminals, which reduces the electricity required for air liquefaction by 70%. This would represent the first application of circular economy principles to the provision of cooling services, also known as the cold economy. India's projected LNG imports in 2040[xxxviii] could produce enough liquid air[xxxix] to provide cooling for almost 211,000 chilled and frozen trucks.[xl] If India were to follow a business-as-usual path, the huge projected increase in demand for both transport refrigeration and for cooling buildings at peak times would be powered by highly polluting diesel.

Goal 13, climate action: clean cold technologies would produce progressively larger CO_2 reductions as grids decarbonise. Liquid Air Energy Storage and liquid air gensets would reduce grid carbon intensity by time- shifting lower carbon renewable electricity to displace high carbon peak generation. This would enable higher renewable penetration of electricity grids than otherwise. Clean cold chains would 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.

Goal 14, life below water: by reducing food waste, clean cooling could ease the pressure on depleting fish stocks, while also reducing CO_2 emissions that cause ocean acidification. Integrating LNG waste cold into production of liquid air or nitrogen would eliminate the need to regasify LNG by warming it with seawater, which has potentially disastrous impacts on marine life.[xli]

Goal 15, life on land: by reducing waste of food and water, clean cold chains could reduce pressure on land and so help contain deforestation and desertification.

Goal 16, peace and justice: by reducing waste of food, land and water, clean cold technologies could help reduce conflict and mass migration.

Goal 17: partnerships for the goals: Britain is leading the development of clean cold technologies such as liquid air, but the greatest long term demand will be in developing countries, and deployment will require international partnerships and knowledge transfer.

Clean cold and the research agenda

The existence of an agreed set of global challenges is increasingly reflected in the way research funding is organised worldwide. Today government R&D spending is less likely to be allocated to individual academic disciplines, but rather to an overarching challenge, often requiring extensive inter-disciplinary collaboration. The British government adopted this approach in 2015, when it announced its overseas aid budget would be restructured to fund research tackling the challenges of the developing world, such as eliminating targeted diseases, crop protection, and mitigating climate change. The Research Councils will disburse a new Global Challenges Research Fund of

£1.5 billion over five years, and expect most of the funding to be inter-disciplinary.

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 an average of just £2.2 million in public funding each year, scarcely 0.2% of total UK funding for engineering research, despite the fact that cooling is by one estimate responsible for 10% of all CO2 emissions.[xlii]

Across the EU as a whole, annual public RAC R&D funding has averaged £23.5 million per year or 0.22%. More recently this shortfall has begun to be rectified, through public and private investments into clean cold–related research projects such as T-ERA, BCCES, CSEF and CryoHub, but these are largely focussed on the priorities of developed rather than developing economies.

Since research funding is now increasingly organised around the world's major challenges, and since the importance of cooling as a critical link between those challenges is becoming clearer, there is now a strong argument for establishing clean cold as an inter-disciplinary research theme within sustainability. The results of such research are likely to have environmental, economic and social impacts in developing countries far beyond the immediate business of cooling.

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University of Birmingham 'Doing cold smarter' Policy Commission Report and Roadmap available to download at:
http://www.birmingham.ac.uk/research/activity/energy/policy/cold/policy-commission-launch.aspx

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