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The Cold Economy – Why? What? How?
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For many years cold has been the Cinderella of the energy debate. While governments have developed policies to green everything from electricity to transport to heat, the energy and environmental impacts of cooling have so far been largely ignored. This is 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. 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 may in turn offer Britain a massive business opportunity to build new technologies, advanced manufacturing hubs and global exports.

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.[1]

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 the size of Mexico; consumes 250 km3 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.[2] So as the world's population heads towards 10 billion by mid-century, increasing food demand by 60%[3], 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 CO2 emissions[4] – three times more than is attributed to aviation and shipping combined.[5] 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.[6]

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.[7] 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[8], and 3.7 million worldwide.[9]

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[*] Commercial disclosure: Toby Peters is the Founder and CEO of Dearman Engine Company, and was co-Founder of Highview Power Storage and co-inventor of Liquid Air Energy Storage.

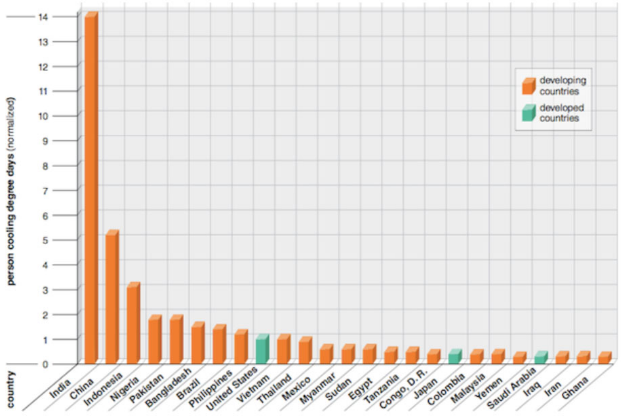
Cooling demand is booming

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. The OECD forecasts that the Asian Pacific middle class will multiply six-fold by 2030 to over 3 billion people, two thirds of the global total, whose spending power could rise to $33 trillion.[10] Their lifestyles – changing diets, improved healthcare, online data and air conditioning - will be built on cold.

The boom in cooling demand is already well established for some products in some countries: fridge ownership among Chinese urban households rose from 7% in 1995 to 95% in 2007, for example. But in others it is just getting started: 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.[11]

Air conditioning is a particular worry, because demand is driven by temperature and income, and the fast growing developing economies have hot climates. Air conditioning demand is already booming in China, where the proportion of urban households with air con soared from less than 1% in 1990 to 62% in 2003, and where in 2010 alone consumers bought 50 million units – equivalent to half the entire US domestic air conditioner fleet.[12] 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.[13]

Although air conditioning demand is already booming in Asia, it is still nowhere near its potential peak, according to one recent analysis.[14] Michael Sivak of the University of Michigan investigated how much energy would be required if all countries had the same level of air conditioning comfort as the US, where according to the Energy Information Administration 87% of households are equipped and residential cooling consumes 185TWh per year. The US currently consumes more energy for air conditioning than all other countries combined, but because many developing countries have large populations and hot climates, they would require far more cooling energy than the US for the same level of air conditioning comfort. The US would be knocked into 9th place, utterly dwarfed by India, China and Indonesia (see graph). The rest of the world would consume around 50 times more energy than the US, and altogether the world would consume around 9,500TWh per year, which is almost half the electricity consumed worldwide for all purposes in 2010.[15]



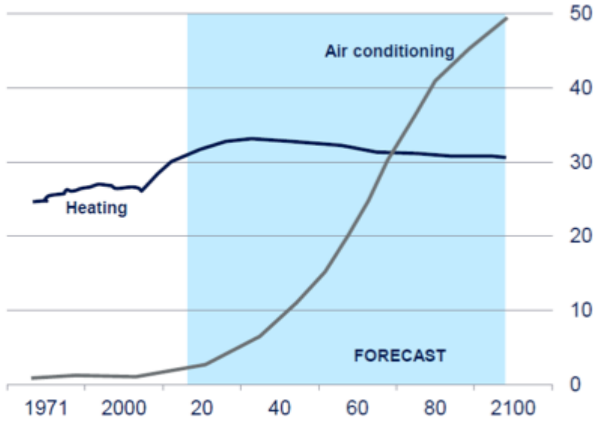
"Will AC Put a Chill on the Global Energy Supply?" by M. Sivak in American Scientist.

The study's author cautions that his results should be taken as a 'first approximation', but they match closely another analysis by the IPCC, which 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.[16] To put this in perspective, to generate 10,000TWh from wind would require 4.6TW of wind turbine capacity, more than ten times the world's total wind capacity today.[17]

Even this is not the end of the story, however. Air conditioning demand is also expected to keep growing in the developed economies: the European Commission expects cooling demand in EU buildings to rise 70% by 2030.[18] Demand is also likely to keep growing in the US, where penetration rose from 68% of all occupied housing units in 1993 to 87% in 2009.[19]

And of course if nothing is done, air conditioners and climate change will form a nasty feedback loop: the more fossil fuel we burn to keep ourselves 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. One study from the Netherlands Environmental Assessment Agency estimates that by 2100 worldwide energy demand for air-conditioning could increase by 72 percent as a result of climate change alone.[20] The same authors expect global 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.[21]

Figure 5: World forecast energy demand for space heating and space cooling
World energy demand, exajoules



Source: PBL Netherlands Environmental Assessment Agency[22]

Another fast growing source of cooling demand is data centres. Data centres consume 2-3% of Britain's electricity, and half of that is for cooling[23], without which the internet would quickly collapse. Global data centre power consumption almost quadrupled between 2007 and 2013 to 43GW[24], roughly the generating capacity of South Africa.[25] At this growth rate, by 2030 the additional cooling load would require another 35GW of generating capacity, or more than that of Poland.[26] At average global grid carbon intensity, that would raise data centre emissions from cooling alone by around 190mtCO2 per year to 300mtCO2 per year in 2030. [27] McKinsey estimated in 2008 that total data centre emissions would quadruple to 340mtCO2 by 2020 – overtaking the 2008 emissions from all energy consumption of Argentina and Malaysia combined.[28]

Nor is the rise in cooling demand simply a long term problem, according to the Birmingham Policy Commission on Cold, which reported last year. From a series of high level calculations around data centre cooling, refrigerated trucks, room air conditioning, car air conditioning and domestic refrigeration, the Commission concluded that if nothing is done, *within fifteen years* cooling will require an additional 139GW of power - more than the generating capacity of Canada – and raise greenhouse gas emissions by over 1.5 billion tonnes of CO2 per year, three times the current energy emissions of Britain or Brazil.[29]

An important but less widely recognised aspect of the problem is the 'cold chain' of refrigerated warehouses and vehicles needed to preserve food from farm to fork. Analysis by Dearman suggests the worldwide refrigerated vehicle fleet could grow from around 4 million[30] today to as large as 18 million by 2025 to satisfy potential growth demand in developing countries.[31] If this were met using traditional diesel-powered refrigeration technologies, it would cause huge additional emissions of carbon and toxic local air pollution. In the EU alone, the costs of pollution from transport refrigeration are forecast to rise to €22 billion by 2025.[32]

The challenge

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 in the EU. 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 presented to the Birmingham Policy Commission on Cold in 2015 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 even if business barriers could be overcome, this improvement would be utterly overwhelmed by the projected 33-fold growth in developing world air conditioning demand.[33] 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 Economy'.

The opportunity

Cooling poses a massive environmental challenge, but could also represent a major business opportunity for Britain if our companies and research institutions can establish a global lead in clean cold technologies – potentially creating thousands of new British manufacturing jobs. 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. We suggest the best way to capture some of this is for Britain to develop its own Cold Economy, which would not only produce environmental and economic benefits at home, but also serve as a platform for innovation and exports.

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 significantly 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 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.

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:

1. **Reduce cold load/cooling work required**: e.g. better building design, vaccines that survive at higher temperatures;
2. **Reduce the energy required for cooling**: i.e. increase the efficiency cooling technologies – e.g. cold stores could raise efficiency by an average of 30% using off the shelf solutions only[34] - 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:

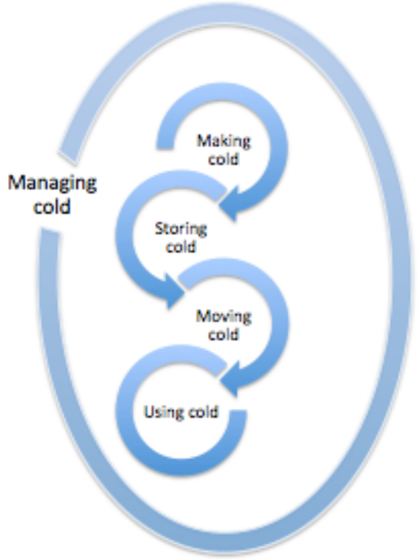
Making cold
Harness waste/ unused resources e.g.
- 'wrong time' renewable energy (e.g. wind)
- waste cold (e.g. LNG)
- ambient heat & cold (e.g. ground source)

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

System approach to cold



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.[35] 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.

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 which goes into commercial trials this year.

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. 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 below.

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 pursued at the Birmingham Centre for Cryogenic Energy Storage (BCCES) at the University of Birmingham, founded in 2013 with £12 million of government and industry funding. A major part of its work is to investigate new thermal storage materials.

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. Analysis for its recent report, *Liquid Air on the European Highway,* found that 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. Dearman TRUs would be zero emission, lower carbon and – because they require smaller volumes of conventional refrigerants - reduce F-gas leakage.

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. For example, one study found that if Beijing had switched from fossil fuel to electric vehicles – which produce 80% less heat – during the summer of 2012, temperatures in the city would have been reduced by 1°C. This in turn would have cut electricity consumption by 14.4GWh and CO2 emissions by 11,800 tonnes per day.[36] 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. Integrating the waste cold of LNG into air liquefaction would reduce the electricity required significantly 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. 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.[37]

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.[38] This does not include the value of the *social* benefits of liquid air transport refrigeration from reduced emissions of carbon dioxide (CO2), 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[39], on the basis of cost factors calculated by Ricardo-AEA for the European Commission.[40] 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.[41]

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[42]
- Even on the basis of the low levels of LNG re-gasification in 2014, the Isle of Grain terminal could produce enough LAIR to support a fleet of 2,600 truck TRUs or 1,875 trailer TRUs;
- 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 2022 could provide liquid air cooling for over half a million refrigerated lorries, or fuel 230,000 heat hybrid buses with air conditioning or 1 million zero-emission auto rickshaws;
- India's projected LNG imports in 2040 could produce enough liquid air[43] to provide cooling for almost 211,000 chilled and frozen trucks[44];

- If India were to fill the deficit in refrigerated vehicles identified by the NCCD with TRUs running on liquid air rather than diesel, the annual savings in 2020 would be $179 million;
- Singapore's projected LNG imports in 2020 could help produce 6,000tpd of liquid air, more than enough to provide cooling for the city state's fleet of refrigerated vehicles and air conditioning for its 4,700 buses, while reducing costs by US$20 million net.
- Crucially, the introduction of LAIR air-conditioning would also enable Singapore and other hot countries to switch from diesel to electric powered buses, whose range currently would be severely depleted if air conditioning were powered from the main traction battery.

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 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.[45] Across the EU as a whole, annual public RAC R&D funding has averaged £23.5 million per year or 0.22%.

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:

- T-ERA Last November saw the launch of the 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. The academic members comprise Aston University, The University of Birmingham, The University of Leicester, Loughborough University, The University of Nottingham, The University of Warwick and the British Geological Survey, and the corporate members include Cofely, Jaguar Land Rover, Highview and Dearman.

- 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. The Centre's themes include research into how to optimise the design, operation and integration of cryogenic energy storage systems into the grid, and fundamental research into new materials such as nano-particles that might raise the energy density of thermal energy storage.

- 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. It will use large scale liquid air energy storage to absorb local intermittent renewable generation and supply it back to the grid, while simultaneously providing cooling to the cold store and reducing its peak power requirements. Project partners include universities and companies from the UK, Belgium, France, Spain and Bulgaria.[46]

- 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. Its projects are creating innovation in many areas including: integrated thermal energy storage frozen food cabinets, innovative air distribution in chilled food factories and innovative isothermal refrigeration shelves.

- 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.

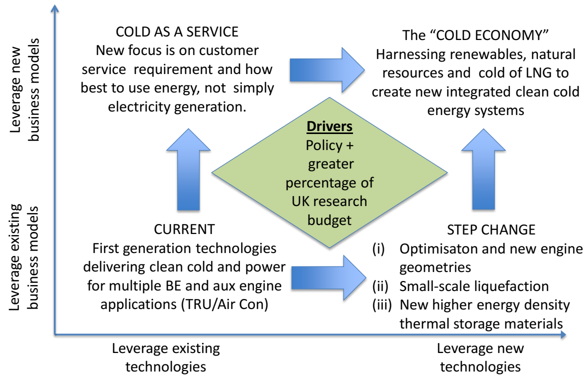
- Dearman, which is developing a suite of clean cold and power applications, has recently secured £17 million in private equity – on top of significant funding from government and industrial partners - to see it through to commercial production. The Dearman TRU, developed in collaboration with the University of Loughborough, Horiba MIRA, Hubbard Products, and Air Products, was part funded by a £900,000 grant from Innovate UK, and goes into commercial road trials in London in May. 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.

Altogether we 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.

Cold Economy – how to get there

Although considerable research and development is now going into the Cold Economy, it is unlikely to come about without a wider and coordinated effort. The Birmingham Policy Commission on Cold, which reported last year, developed a high level industry roadmap to guide the development of a vibrant British clean cold industry that will not only dramatically improve the environmental performance of cooling in this country, but also establish and maintain a lead in a new global market potentially worth £ hundreds of billions. The roadmap (see below) is technology agnostic and not only concerned with what might be achieved in from blue-sky technologies in 15 years, but equally preoccupied with the significant short term gains from improved maintenance of existing equipment – and all the steps in between.

THE COLD ECONOMY
Transition UK inventions to new system level architecture
delivering environmental and economic gain




Drivers for Change
Reduction in CO2 footprint
Increased pollution from Nox and PM
Transition to lower GMP refrigerants
Increased demand for cooling
Availability of cryogens and other novel vectors
Integration of cooling and cold as an energy vector
Expansion of UK manufacturing and jobs

Technology Innovations
Higher Efficiency Cooling Technologies (increased COP)
Development of new, low GWP, refrigerants and phase out of HFCs
Cold energy storage materials; high density, long term storage, rapid cycle
White good linked to district cooling schemes
Novel refrigeration and cooling technologies; magnetic, electro, sorbtion
Integration of thermal energy technologies delivering heating and cooling
Advanced cryogenic technologies; e.g. zero boil off systems
Enhanced heat pump technology

Cross over opportunities
Greater exploitation ground source heat and waste heat
LNG re-gassifiaction and liquid air liquifaction
Grid balancing and district cooling and heating
Vehicles: Liquid air - LN2 - LH2 systems
Advanced superconductor technologies in power systems
Food refrigeration and transport with liquid air generation and use

Interventions
Development of cold and cooling as product; move from technology focus
Create appropriate incentives and regulatory framework
Introduction of market mechanisms that allow new technologies to break through
Small and large scale demonstration facilities for proof of principle and validation
Manufacturing environment to accelerate price competitive technologies to market
Explotation of state-of-the-art manufacturing processes and data.
Develop a service culture and infrastructure related to cold technologies
Development of R&D capability on a scale which matches potential of cold
Devlop UK skills base linked to state-of-the-art cold systems

The Birmingham Policy Commission on Cold also made a series of policy recommendations to help achieve the Cold Economy. In summary, the Commission urged the government to:

1. Raise awareness of the environmental and economic importance of cooling to increase investor confidence.

2. Conduct a Technology Innovation Needs Assessment (TINA) for cooling, to evaluate the environmental, economic and export potential of clean cold technologies and the case for UK public sector intervention in innovation.

3. Develop a system-level model of UK cold, for a proper understanding of the potential of the Cold Economy.

4. Support demonstration projects in Britain and overseas to help develop a clean cold sector that could generate significant British jobs and exports.

5. Lead the development of a new broad measure of the energy efficiency and environmental impact of cooling, by which companies can judge their progress and performance relative to their peers.

These recommendations, if acted upon, could help achieve the Cold Economy, an elegant, innovative and circular approach to cold, the Cinderella of the energy debate, with the potential to create manufacturing jobs and exports in a new global market – clean cold.

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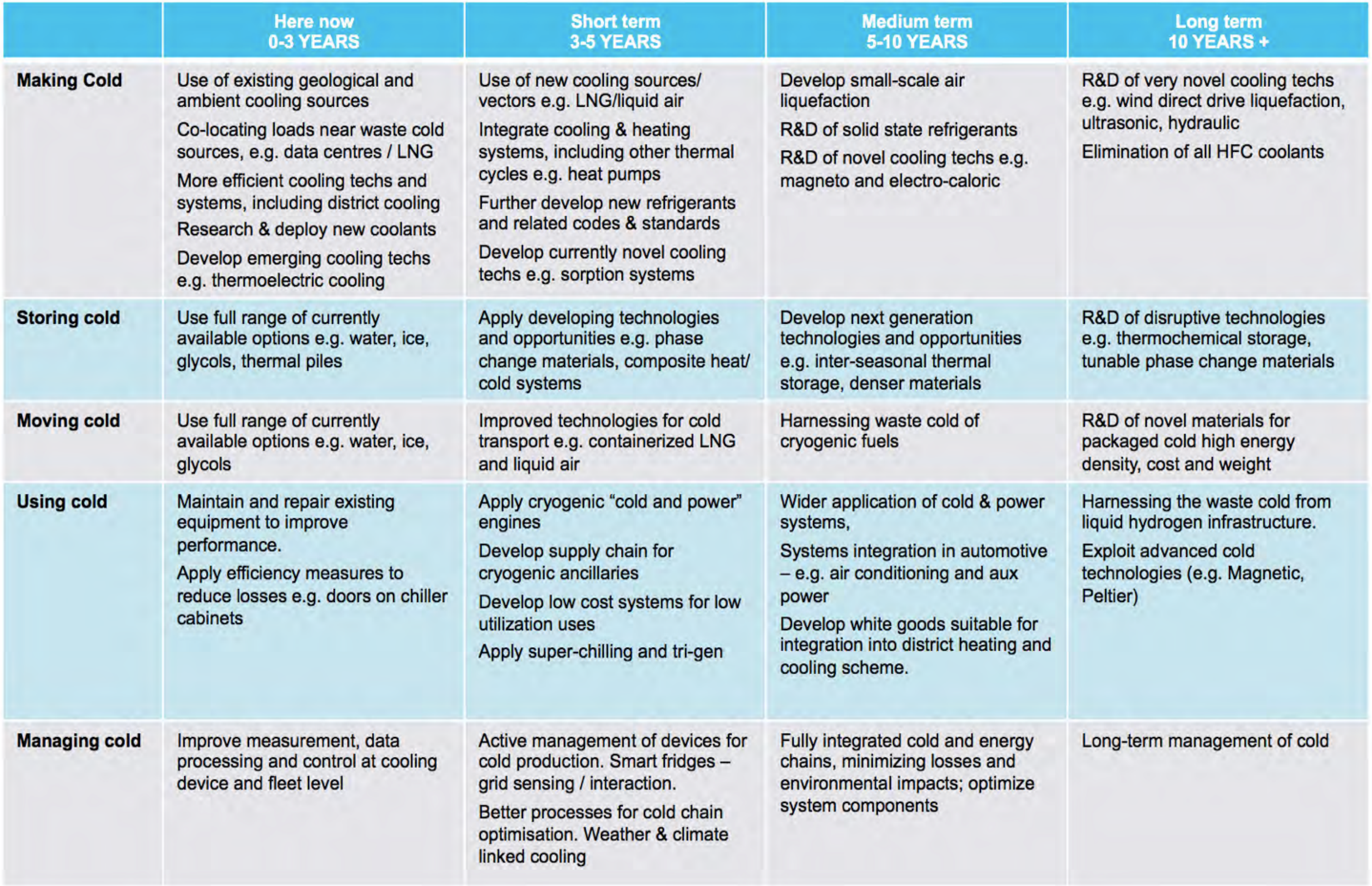
University of Birmingham 'Doing cold smarter' Policy Commission Report and Roadmap available to download at:

http://www.birmingham.ac.uk/research/activity/energy/policy/cold/policy-commission-launch.aspx

Appendix 1: Summary features of Commission roadmap – full details in ‘Doing Cold Smarter’ report



	Here now 0-3 YEARS	Short term 3-5 YEARS	Medium term 5-10 YEARS	Long term 10 YEARS +
Making Cold	Use of existing geological and ambient cooling sources Co-locating loads near waste cold sources, e.g. data centres / LNG More efficient cooling techs and systems, including district cooling Research & deploy new coolants Develop emerging cooling techs e.g. thermoelectric cooling	Use of new cooling sources/ vectors e.g. LNG/liquid air Integrate cooling & heating systems, including other thermal cycles e.g. heat pumps Further develop new refrigerants and related codes & standards Develop currently novel cooling techs e.g. sorption systems	Develop small-scale air liquefaction R&D of solid state refrigerants R&D of novel cooling techs e.g. magneto and electro-caloric	R&D of very novel cooling techs e.g. wind direct drive liquefaction, ultrasonic, hydraulic Elimination of all HFC coolants
Storing cold	Use full range of currently available options e.g. water, ice, glycols, thermal piles	Apply developing technologies and opportunities e.g. phase change materials, composite heat/ cold systems	Develop next generation technologies and opportunities e.g. inter-seasonal thermal storage, denser materials	R&D of disruptive technologies e.g. thermochemical storage, tunable phase change materials
Moving cold	Use full range of currently available options e.g. water, ice, glycols	Improved technologies for cold transport e.g. containerized LNG and liquid air	Harnessing waste cold of cryogenic fuels	R&D of novel materials for packaged cold high energy density, cost and weight
Using cold	Maintain and repair existing equipment to improve performance. Apply efficiency measures to reduce losses e.g. doors on chiller cabinets	Apply cryogenic “cold and power” engines Develop supply chain for cryogenic ancillaries Develop low cost systems for low utilization uses Apply super-chilling and tri-gen	Wider application of cold & power systems, Systems integration in automotive – e.g. air conditioning and aux power Develop white goods suitable for integration into district heating and cooling scheme.	Harnessing the waste cold from liquid hydrogen infrastructure. Exploit advanced cold technologies (e.g. Magnetic, Peltier)
Managing cold	Improve measurement, data processing and control at cooling device and fleet level	Active management of devices for cold production. Smart fridges – grid sensing / interaction. Better processes for cold chain optimisation. Weather & climate linked cooling	Fully integrated cold and energy chains, minimizing losses and environmental impacts; optimize system components	Long-term management of cold

Appendix 2: What is liquid air?

Air turns to liquid when refrigerated to -196C, 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. The main potential applications are in electricity storage and transport, and in both, liquid air can provide the additional benefit of waste heat recovery and/or cooling.

Since the boiling point of liquid air (-196C) 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 +150C), 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, which makes up four fifths of the atmosphere and can be used in the same way as liquid air, 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 less energy.

As with batteries or hydrogen, the purpose of liquid air is to store 'wrong time' low or zero carbon electricity, which can then be used to displace high carbon coal or gas in electricity generation and petrol or diesel in vehicles. The carbon intensity of liquid air depends on the source of electricity used to make it, and most industrial liquefiers operate at night when greenhouse gas emissions of grid electricity are lower than average.

Appendix 3: Liquid Air Energy Storage

LAES is a novel, large-scale, long duration energy storage system based on standard components from the industrial gases and power generation industries. Electricity is used to drive an air liquefaction plant to produce liquid air, which is then stored in an insulated tank. When power is required, the liquid is pumped to high pressure, and then through a heat exchanger where it converts into a high pressure gas that drives a turbine to generate electricity. Cold from the evaporation is recycled to reduce the energy required by the liquefier, and waste heat from the liquefier or an external source increases the energy recovered from the expansion of liquid air. At commercial scale (10-250MW), LAES is expected to have a 'round trip' efficiency (electricity in/electricity out) of 60%. Integrating waste heat from (say) a power station nearby would raise efficiency to 70%.

Balancing the electricity grid will become increasingly challenging as the proportion of intermittent renewable generation continues to rise. This is not simply a question of holding power stations in reserve for when the wind drops, but also being able to absorb excess wind power when there is too little demand – often at night – a role for which storage is ideally suited. If such 'wrong time energy' is stored and used to displace fossil generators at peak times, CO2 emissions are reduced and 'constraint' (compensation) payments to wind farm operators avoided.

Appendix 4: The Dearman engine

The Dearman engine is a novel piston engine powered by the phase-change expansion of liquid air or liquid nitrogen. In principle it works just like a steam engine only 300°C colder. It was invented by Peter Dearman, a classic British 'garden shed' inventor, and is being developed by the Dearman Engine Company ('Dearman') 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 unit (TRU) to replace the highly polluting secondary diesel engines used on trucks today, which can emit up to 6 times as much NOx and 29 times as much PM as a modern lorry propulsion engine. The Dearman refrigeration engine is zero-emission, low carbon and now in on-vehicle trials with Horiba MIRA, and will go into commercial field trials in London in May.. Dearman's report *Liquid Air on the European Highway*, published in 2015, showed the cost of buying and running a zero-emission Dearman TRU for five years would be just 9% higher than a conventional TRU running on subsidised red diesel, which is still permitted in Britain, but 32% *lower* than one running on fuel priced fuel.[47] Across the EU, if the diesel TRU fleet were replaced with Dearman TRUs over the next decade, the diesel savings would be worth £30 billion at average EU prices in 2014.[48]

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, which Dearman claims could reduce bus and truck diesel consumption by over 25%. A consortium including DEC, Air Products, Horiba MIRA, Cenex, TRL, The Manufacturing Technology Centre and The Proving Factory has been awarded nearly £2 million by Innovate UK to build a heat hybrid prototype in 2016 while further developing and testing is being undertaken at the Birmingham Centre for Cryogenic Energy Storage.

Cryogenic expansion engines have existed for over a century, but the Dearman engine is novel because it uses a heat exchange fluid (HEF, made of water and glycol, just like conventional radiator fluid) to promote rapid and efficient re-gasification inside the engine cylinder, allowing it to dispense with the bulky and inefficient external heat exchanger that handicapped earlier cryogenic engine designs. First, warm HEF is injected into the cylinder, followed by liquid air or nitrogen. Then, as the fluids mix, direct heat transfer causes the cryogen to boil and expand, so pushing the piston down. The HEF continues to provide heat throughout the power stroke, leading to efficient 'isothermal' expansion. Afterwards the cool gaseous air exhausts harmlessly to the atmosphere while the HEF is re-heated and re-used.

Appendix 5: The value of LNG 'waste' cold

Natural gas is refrigerated to -162C to become Liquefied Natural Gas (LNG) for transport by supertanker from producing to consuming nations. At the import terminal the LNG is warmed to re-gasify before entering the pipeline network, and most of the cold that kept it in compact liquid form during the sea voyage is usually discarded.

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 500 million tonnes per year by 2030, representing cold energy of 120TWh, theoretically equal to the annual output of 14 1GW nuclear power stations. One way to recycle this waste cold could be through liquid air.

When LNG is re-gasified from its liquid state at -162C to enter the gas grid, the cold it gives off can be recycled through a co-located air liquefaction plant to help produce liquid air or nitrogen at around -196C. This reduces the electricity required to produce the cryogen and its carbon intensity by up to 70%, and the cost by about half. This approach has been demonstrated for some years at an LNG terminal at Osaka in Japan. Dearman says that if it were adopted more widely the impact could be huge, and the company's modelling suggests:

- the cold given off by the Isle of Grain LNG terminal each year could fuel London's entire bus fleet as liquid air 'heat hybrids' more than six times over, reducing diesel consumption by 25%;
- the waste cold from India's projected LNG imports in 2022 could provide liquid air cooling for over half a million refrigerated lorries, or fuel 230,000 heat hybrid buses or 1 million zero-emission autorickshaws;
- the projected global LNG trade in 2030 could provide liquid air cooling for 4.2 million refrigerated delivery lorries - more than the entire global fleet.

Recycling LNG waste cold in this way would reduce diesel consumption, greenhouse gas emissions and local air pollution, and would reduce costs even more than those operating on conventionally produced liquid nitrogen. In this way LNG waste cold could provide the 'fuel' for the Cold Economy.

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