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The emerging Cold Economy

Sustainable solutions for rapidly increasing cooling needs

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Introduction

The provision of cold is a vital foundation of modern society; without it, the supply of food, medicine and data as we know it would simply break down. Yet compared to electricity, transport and heat, cold has received little attention in the energy debate so far. This needs to change, because cooling is energy intensive and highly polluting, and demand is booming, so there is an urgent need to make cold more sustainable.

Cooling underpins many aspects of modern life: air conditioning; data centres; superconductors; medicine; industry; and perhaps most vital, the 'cold chain' of refrigerated warehouses and vehicles needed to preserve food from farm to consumer. Cooling consumes up to 14% of the UK's electricity, and the combined annual cost of electric and transport cooling in the UK is more than £5 billion.

Demand is increasing worldwide, nowhere more so than in emerging markets, where it is needed to reduce high levels of food wastage, and satisfy the changing diets and lifestyles of the fast emerging middle class. One estimate suggests that by 2030 global demand for cooling could grow by the equivalent of three times the current generating capacity of the UK.[1]

At the same time, however, vast amounts of cold are wasted, for example during the re-gasification of LNG at import terminals, which could potentially be recycled to reduce the cost and environmental impact of cooling in both buildings and vehicles. This insight has stimulated new thinking aimed at creating business and environmental value from the efficient integration of cold into the wider energy system. The concept which has since been coined the 'Cold Economy' has been advanced in various papers published by Liquid Air Energy Network, the Centre for Low Carbon Futures, the Institution of Mechanical Engineers, the University of Birmingham and others. The Cold Economy is based on a systems analysis and covers many aspects of efficiency, but crucially involves the recycling of waste cold and 'wrong time' energy – such as excess wind power generated at night when demand is low – to provide low-carbon, zero-emission cooling and power. This would lead in turn to wider environmental and health benefits, while also creating business opportunities, growth and jobs.

At first sight the potential of the Cold Economy appears large. Rapid growth in demand for cooling in the developing world, and the high environmental costs of meeting it with conventional refrigeration technologies, suggest a major global business opportunity for novel cooling solutions that are both cost effective and sustainable. And Britain appears well placed, since a suite of clean cold technologies is already in development, and the country has world-class capabilities in cryogenics, engineering, manufacturing and finance. Government and industry could make a strategic decision to take advantage of these favourable conditions and secure a global leadership role for the UK in this major potential growth market.

It is early days, however, and success is far from guaranteed. Realising the Cold Economy – and capturing the value it offers – will depend on joined-up thinking and co-operation among previously disparate organisations, and requires a concerted effort by industry, academia and government to develop, test and deploy novel clean cold solutions.

The purpose of this paper is to review briefly the idea of the Cold Economy and its potential, and to identify the challenges ahead and outline a series of recommendations. We begin with a brief overview based on information provided by the technology developers and a review of a range of industry papers mentioned above. We have not validated the numbers we report here, but have simply summarised from the existing literature to describe the Cold Economy concept and its potential. We then use this to develop a list of key questions that need to be answered, which will help stimulate the development of smarter clean cold solutions and perhaps a fully-fledged Cold Economy.

In from the cold

Cooling has been overlooked in the energy debate, which has until now focused largely on electricity, transport and heat. In temperate northern countries such as Britain this is perhaps understandable, since air conditioning is much less important and the need for cooling therefore less obvious. Yet cooling underpins many aspects of modern life: data centres; superconductors; medicine; industry; and the cold chain of refrigerated warehouses and vehicles needed to preserve food from producer to consumer. Cooling consumes up to 14% of the UK's electricity, and the combined annual cost of electric and transport cooling in the UK is more than £5 billion. The figures are likely to be as high or higher in other advanced economies.

Demand for cooling is growing strongly worldwide, but nowhere more so than in the rapidly industrialising economies of China and India, where sales of air conditioning units are booming[2], and investment in cold chains starting to take off. The level of cold chain provision is currently low, but massive expansion is needed to cope with rapidly changing demographics – urbanisation, the new middle classes and changing diets – and to reduce high levels of food wastage.

Demand for cooling is expected to increase significantly in developing economies as incomes rise. The global middle class is predicted to swell from about 2 billion people today to almost 5 billion in 2030[3], with virtually all the new members living in developing countries, accelerating the shift towards urban living and more western diets. India's government forecasts an investment need of $15 billion on its cold chain over the next five years[4], and China's refrigerated storage capacity is expected to increase 20-fold between 2007 and 2017 to 5 billion cubic feet. As a result, global demand for cooling until 2030 is projected to grow by the equivalent of three times the total power output of the UK.

Another major driver in developing countries is the need to reduce high levels of food wastage – where it is estimated up to half of perishable food rots before ever reaching the market, largely due to the absence of cold chains. Globally it is estimated that 1.3 billion tonnes of food – or one third of food produced for human consumption – goes to waste each year while 800 million people go hungry.[5] Yet the International Institute for Refrigeration has estimated that if developing countries had the same level of refrigeration equipment as the developed, 200 million tonnes of perishable food would be saved each year, expanding the food supply by about 14%.[6] Reducing food wastage would also conserve huge quantities of farm inputs currently used to produce food that is never eaten: it is estimated that food wastage occupies a land area the size of Mexico; consumes 250 km^3 of water per year, three times the volume of Lake Geneva; and accounts for 3.3 billion tonnes of carbon emissions, the third biggest emitter after the USA and China.[7] The lack of a cold chain also hampers the effective distribution of vaccines – access to which could prevent more than two million deaths from diseases each year in developing countries.

If the stage seems set for a major expansion of cold chains in the developing world, providing these cooling services with conventional technologies would significantly impact demand for primary fuels, cost, global warming and human health. Cooling solutions currently used in developed countries particularly those for transport refrigeration have considerable negative impact on the environment and public health.

The energy consultancy E4tech has calculated that the transport refrigeration unit (TRU) of a refrigerated trailer emits 29 times as much particulate matter (PM) and six times as much nitrogen oxides (NOx) of the lorry's much larger (Euro VI) propulsion engine.[8] These are the toxic constituents of local air pollution that cause 29,000[9] premature deaths in Britain each year, over 400,000[10] in the EU and 600,000 in India. It has also been estimated that if broader emissions reduction targets are met, leakage of refrigerant gases could account for nearly 20% of global greenhouse gas emissions by 2050.

In short, while cooling is vital and demand seems set to rise strongly, there is an urgent need to replace conventional technologies with sustainable alternatives in developed economies and for developing economies to immediately adopt the more sustainable solutions of the Cold Economy.

Clean cold technologies

Even as cooling demand is soaring, large amounts of cold are lost to the environment as waste. The biggest source of waste cold is the cold required to turn natural gas into compact Liquefied Natural Gas (LNG) at -162°C for transport by ship, which is simply discarded when the LNG is re-gasified at the import terminal. Dearman has estimated that the projected global trade of LNG in 2030 would give off enough waste cold to provide cooling for over 4 million refrigerated lorries – more than the current global fleet.[11]

LNG is not the only source of waste energy that could be used to provide clean cold. As renewable generating capacity continues to rise, the incidence of 'wrong time' electricity – such as wind power generated at night when demand is low – will increase. The trick in both cases is to find suitable 'vectors' to capture, store and transport the waste energy so that it can be used to supply cold and power loads. One idea is liquid air or nitrogen.

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. Re-gasification also gives off usable and valuable cold, which gives liquid air a particular advantage wherever there is a need for *energy storage and cooling*. Storing liquid air requires only an insulated tank, which is cheap. Re-gasification then produces both power and cooling from a single tank of cryogen.

Liquid air is not yet produced commercially, but liquid nitrogen, which can be used in the same way, is widely available throughout the industrialised world. Both are produced by plants powered by electricity – and so could be used to absorb wrong time renewable energy – and the production process can also integrate the waste cold given off by LNG re-gasification to drastically reduce the amount of electricity required.

A suite of technologies powered by the phase change expansion of liquid air or nitrogen is now being developed in Britain. Several are based on a novel zero-emission piston engine, invented by Peter Dearman, which is more efficient than previous cryogenic engines because it incorporates a heat exchange fluid to achieve rapid rates of heat transfer inside the cylinder:

- A liquid air transport refrigeration unit (TRU), currently being tested on a vehicle, and due to start fleet trials in 2015. The liquid air TRU is being developed by a consortium comprising the Dearman Engine Company, MIRA, Loughborough University, with around £1.5 million support from Innovate UK. The liquid air TRU is efficient because it extracts both cooling (from evaporation) and power (from expansion) from the same tank of cryogen.

- A 'heat hybrid' combination of a liquid air engine with a diesel engine, in which waste heat and cold are exchanged to raise the efficiency of both, and reduce diesel consumption of lorries and buses by about 25%. A heat hybrid bus could cut carbon emissions by as much as an electric hybrid for a lower capital outlay. The heat hybrid is being developed by another consortium comprising Dearman, Air Products, MIRA, Cenex, TRL, The Manufacturing Technology Centre and Productiv, which has been awarded nearly £2 million by Innovate UK to build a prototype this year.

- Grid scale 'Liquid Air Energy Storage' (LAES) is being developed by another British company, Highview Power Storage, which has demonstrated a plant that uses off-peak electricity to produce liquid air, stores it, and then re-gasifies it through a turbine to generate electricity at peak times. LAES was developed by Highview and Professor Yulong Ding, now at the University of Birmingham, from Peter Dearman's original idea. Highview is currently building a 5MW plant to demonstrate liquid air electricity generation and waste heat recovery with the waste management company Viridor. The project is funded by £8 million from DECC. Several industrial gas companies have now started to market LEAS technology including Air Products and Mitsubishi Hitachi.[12] LAES aims to be an attractive storage technology with the potential to capture a significant share of the demand for bulk energy storage which is forecast to be up to 15GW by 2030 and as much as 25GW by 2050. LAES plants could turn waste heat into additional power and provide cooling to neighbouring businesses.

Two other liquid engines are also in development. Ricardo's 'CryoPower' concept incorporates liquid nitrogen and diesel in a split cycle engine to achieve 'isothermal' compression and raise engine efficiency to 60%, compared to around 40% today. Ricardo has won financial support from Innovate UK to support testing of critical subsystems and if successful, the engine could transform the environmental performance of long-haul trucks.[13] Other innovative liquid air engines such as the EpiQair rotary engine are at an earlier stage of development.[14]

In short, liquid air or nitrogen appears to be a vector capable of joining up waste cold and wrong time energy with cooling loads, and the technologies needed to make use of liquid air are on the verge of commercialisation. This raises the possibility of an entirely new approach to cooling which would recycle these sources of cold and energy to reduce the carbon intensity, emissions and cost of cooling.

The Cold Economy

The emerging Cold Economy is about taking a new approach to the provision of cooling services. Two basic insights have driven its initial development. First, using current technologies to meet dramatically increased future demand for cooling will be economically wasteful and have significant environmental consequences. Second, a substantial global business opportunity exists for novel cooling solutions which are both cost effective and sustainable. Some of the most exciting innovations in both technology and systems-thinking around cold and power are happening in the UK. Only last year, the University of Birmingham secured £12 million in government and industry funding to found the Birmingham Centre for Cryogenic Energy Storage.

The Cold Economy is defined as the business and environmental value created by the efficient integration of cold into the wider energy system. The characteristics of a Cold Economy include:

> Greater recycling of waste energy, including waste cold, to supply cooling;

> Using liquid air and other cryogens as energy vectors, to store and deliver cold and power;

> Developing more efficient technologies, materials and practices;

> An energy system analysis that incorporates cold flows, including spatial & temporal balancing of dynamic needs.

The benefits of a Cold Economy could include:

> Reduced Greenhouse Gas (GHG) emissions and improved local air quality;

> Lower overall cost;

> New business opportunities and jobs for UK plc.

Preliminary analysis of the Cold Economy in a series of recent reports suggests the potential is enormous. Listing only the most obvious advantages:

Major reductions in carbon, emissions and cost

The suite of liquid air technologies being developed in Britain are zero-emission at the point of use, will deliver progressively larger CO_2 reductions as the carbon intensity of grid electricity falls, and have the potential to be cost competitive with diesel. A report from the Liquid Air Energy Network, published by the University of Birmingham with the help of grant funding from Innovate UK, estimates that a projected British fleet that grows to 36,000 liquid air equipped vehicles by 2025 could save over 1 billion litres of diesel, 1.4mtCO_2e (well-to-wheel) and £113 million net of investment costs. A fleet of just 13,000 liquid air refrigerated trailers would reduce PM emissions by 180 tonnes per year equal to taking 367,000 modern diesel lorries off the road.

Companies deploying such refrigerated transport vehicles would not only be able to capture the immediate economic value of efficient technologies, but also protect their reputation by reducing their environmental impact. Owners of urban refrigerated delivery fleets, for example, would reduce their exposure to stricter future emissions standards, and also support their continued licence to operate in increasingly congested urban areas.

Huge resource, carbon and cost-reduction potential of LNG waste cold and wrong time renewable energy

Liquid nitrogen can be supplied in the UK in the range of 5p to 8p per litre (at projected volumes) making it competitive with diesel in many applications. But integrating the waste cold of LNG re-gasification into the air liquefaction process reduces the electricity required by *two thirds*[15], leading to further substantial reductions in cost and carbon intensity. Nor is the scale of the LNG waste-cold resource widely recognised yet.

According to a report published by the Centre for Low Carbon Futures and the University of Birmingham, the cold given off by the Isle of Grain LNG terminal over the course of a year would be enough to fuel London's entire 7,600 strong bus fleet as liquid air 'heat hybrids' – in which the liquid air engine increases the efficiency of the diesel through cooling/heat recovery - more than six times over. And the projected trade of 500 million tonnes of LNG in 2030 would provide enough waste cold for the production of 184 million tonnes of low cost, low carbon liquid air. That would be enough, for example, to supply cooling for 4.2 million refrigerated delivery trucks, more than the current global fleet. This illustrates the magnitude of the global market potential for liquid air.

At the same time, wrong time renewable energy is a second source of low cost, sustainable power that could be used to drive air liquefaction and produce liquid air. Overnight electricity is already cheaper and less carbon intensive than peak periods, and as the share of renewables continues to grow, so will the periods of excess wind production at night – which can even result in negative power prices. Without some means of absorbing such energy, the cost of 'constraint' payments to windfarm operators will increase. Using surplus electricity production to produce liquid air offers an attractive option within the portfolio of energy storage technologies, particularly for applications where electricity would otherwise be stored and subsequently used for providing cooling services.

Particular relevance to the developing world

Liquid air cold chains could be particularly effective in emerging markets such as India and China, which suffer high levels of local air pollution, and post-harvest food losses of up to 50%. Both India and China are investing to expand their rudimentary cold chains – India projects investment of $15 billion over the next five years. Local air pollution caused 1.8 million premature deaths in China and India in 2010, so both countries need a zero-emission alternative to diesel. Both are also rapidly expanding their LNG import capacity, raising the possibility of producing cheap, lower carbon liquid air or nitrogen to fuel a more sustainable cold chain. India's projected LNG imports of 60 million tonnes in 2022 could in principle produce enough liquid air to fuel over half a million zero-emission liquid air TRUs. India has set up a National Center for Cold Chain Development to develop LNG-assisted liquid air cold chains and the wider Cold Economy. Petronet LNG has recently advertised to invite companies to collaborate on its plan to develop a cold storage warehouse integrated with its LNG import terminal at Dahej in Gujarat.

Liquid air cold chains would allow developing countries to reduce food wastage more cheaply than traditional diesel solutions and without increasing local air pollution. This would then reduce the consequential waste of agricultural inputs such as land, water, fertiliser and labour currently used to produce food that is never eaten – and the carbon emissions they cause. It would expand the food supply, help reduce hunger, and improve small farmers' incomes. It would also allow farmers to integrate along the value chain, by producing, processing, storing, and selling high value perishable goods. Cold chains would also improve public health by making the general distribution of vaccines possible, and improve energy security by reducing the need for imports of oil or diesel.

In other words, it is in the common interest of developed and developing countries that regions of the world without integrated cold chains should leap-frog today's proven but out-dated cooling technologies, and instead adopt the more sustainable solutions of the Cold Economy especially where this would also be more cost-effective.

An opportunity for British business

The full potential of the Cold Economy is only just beginning to emerge, and could develop into a global market in clean cold technologies potentially worth many billions of pounds. And it is a market in which Britain has a natural lead, with its strong position in engine manufacturing and exports, and a growing but currently informal hub of clean cold research and expertise centred in the Midlands. The hub comprises a wide group of companies and research organisations working to develop the liquid air transport refrigeration as the first stage in a new Cold Economy, including Dearman, Hubbard Products Ltd, MIRA, MTC, Loughborough University, and the University of Birmingham Centre for Cryogenic Energy Research, set up with £12 million in government and industry funding. It has also recently appointed a Professor of Power and Cold Economy to further lead the thinking and development.

Government and industry could make a strategic decision to take advantage of these favourable conditions to attain a global leadership role for the UK as a solution provider in this major global growth market.

In order for the UK to develop a leadership position in the emerging global Cold Economy, it is important to create a domestic lead market – and the conditions appear favourable. Britain has a well-established industrial gas industry, with enough spare nitrogen production capacity to fuel 6,600 heat hybrid buses per day, and a country-wide road tanker distribution network. The spare nitrogen capacity could fuel the entire projected liquid air vehicle fleet until at least 2019. This could then help launch a liquid air supply industry projected to be worth more than £195 million per year by 2025.

Liquid air transport refrigeration offers a promising first application of clean cold technology. Early projects should aim to minimise complexity and avoid barriers to entry where possible. Early projects could therefore aim to connect a single source of waste cold with a single, large end user such as a supermarket. Another possible opportunity could be to equip or retrofit some London buses with liquid air heat hybrid technology. Liquid nitrogen would probably be sourced from existing producers to start with, but could eventually be produced far more cheaply by integrating air liquefaction with waste cold from the National Grid's Isle of Grain LNG terminal. In principle the terminal's annual waste cold would be sufficient to fuel London's entire 7,600-strong bus fleet as diesel-liquid air hybrids six times over.

The creation of domestic and export markets for liquid air technologies has the potential to generate large numbers of British jobs. Aggregating numbers from reports published and new market projections from E4tech suggests the cold economy could create or maintain more than 10,000 jobs by 2025 and in excess of 25,000 jobs by 2050 across development, manufacturing and after-sales support.

The reports from IMechE and others highlight, however, that if liquid air transport technologies take off, the major markets of the developing world would manufacture engines in-country, generating growth and skilled jobs for those economies too. After-sales service and maintenance work, and liquid air production and supply, would naturally be done locally. So although the environmental and economic benefits of a Cold Economy may well be felt first in Britain, they could have an even greater impact in developing economies over the medium term.

Realising the potential of the Cold Economy

Over the next ten years Britain will need to accelerate its adoption of novel energy technologies to have any chance of achieving its economic, climate and energy security goals. It will also need to improve the efficiency of the energy system as a whole, not simply by investing in individual technologies, but by integrating across conventional barriers. Considerable progress has been made in joining up transport, electricity and heat but – so far at least – very little attention has been paid to cold. It is time to fully assess the demand for cooling, the potential of the Cold Economy as an environmentally and economically sustainable approach, and to realise identified opportunities.

A viable cold energy system would need to deliver:

- Reduced GHG emissions and improved local air quality;
- Increased overall system efficiency;
- Lower overall cost;
- New business opportunities and jobs for the UK and further countries committed to developing a Cold Economy.

Realising identified opportunities is likely to require:

- Greater recycling of waste energy, including waste cold, to supply cooling;
- Using liquid air and other cryogens as energy vectors, to store and deliver cold and power;
- Developing more efficient technologies, materials and practices;
- An energy system analysis that incorporates cold flows, including spatial and temporal balancing of dynamic needs.

This new Cold Economy is an intriguing and potentially powerful idea. But turning it from idea into reality will depend on joined-up thinking and collaboration by industry, academia and government to develop, test and deploy novel solutions. So far there is no institution, group of institutions or programme in Britain or abroad that unifies the full innovation pipeline from R&D through to manufacturing process, skills development and product deployment. But with the development of new cold technologies in Britain in ferment, there is a real opportunity for Britain to strengthen its global leadership position and provide this conveyer belt from invention to market.

Planning and investment must focus in a joined-up approach on all three key areas: research and development; manufacturing; and skills. We recommend:

- **Research** to support the accelerated delivery of novel technologies that underpin the development, deployment, integration and optimisation of cold technologies across industry, buildings and transport.
- **Advanced cold manufacturing** to deliver cost-effective new cold products in volume to market both at home and abroad – creating UK manufacturing leadership.
- **Apprenticeship and training** that complements the innovation pipeline, meeting the manufacturing assembly, integration and after sales needs in a timely fashion.
- Developing **integrated commercial solutions** addressing identified market needs – for instance testing the viability of providing cooling services including financing to farmers in India.

The international dimension is essential. Britain should aim to deliver solutions in the fast-growing international markets in Asia, South America and Africa, so we need a high quality research and training environment that attracts the best worldwide.

The benefits and opportunities of the Cold Economy look promising, and much work has been done to highlight the urgent need to integrate cold into the energy system and policy landscape. This work has so far been led by a small group, however, and there remain significant areas of uncertainty. The full impact of the business as normal approach has not yet been fully calculated, nor the scale of the opportunity definitively established, nor the detailed means of securing it mapped out.

Below we pose five questions for industry, government and the research community, which we hope they will come together to answer. In analysing the scale of the opportunity, and the health, environmental and economic costs of failing to seize it, we will then understand the urgency of developing clean cold technologies and the policy frameworks needed to support them.

- What is the scale of the demand for cooling services up to 2030 and beyond in the UK and abroad?
- What would be the environmental, economic and health impacts of a business as usual approach?
- What would be the full economic value to the UK of developing a Cold Economy and clean cold technologies, including GDP, jobs, exports, and environmental and health impacts?
- What are the industrial, R&D and skill requirements that the UK requires to become a global leader in the development of new products and services for the Cold Economy worldwide?
- Is cold sufficiently recognised and integrated into policy on energy, air quality, transport, exports and overseas aid, and if not, what changes should be introduced?

Acknowledgements

We are grateful to Dearman for supporting this work.

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Published in the UK: February, 2015