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ABOUT THE BIRMINGHAM ENERGY INSTITUTE

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

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

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

INFORMING AND SHAPING POLICY

The Birmingham Energy Institute leads the way in providing a sound evidence base to inform policy makers. The Institute draws on the broad capabilities and expertise at the University of Birmingham and its strong relationship with collaborators from academia, industry and the third sector, to generate new thinking on contemporary issues of global, national and civic concern.

The policy commissions investigating 'The Future of UK Nuclear Energy' (2012) and 'Future Urban Living' (2014) have helped shape the thinking of government and policy makers as the UK seeks to transform how it generates and consumes energy. These were led by Lord Hunt of Kings Heath and Lord Shipley of Gosforth.

Furthermore, by working with the 'Industry and Parliament Trust' academics from the Birmingham Centre for Environmental and Energy Economics and Management, Birmingham Energy Institute Centre, have worked to encourage dialogue between policymakers and academics on sustainability and energy issues. Recently they have contributed to the IPT 'Sustainability Commission Report' and the Energy report generated by the Resilient Futures programme.

Birmingham Energy Institute academics are also leading work on a White Paper analysing the contribution of fuel cells and hydrogen to UK national energy security and energy affordability that will inform Westminster politics in autumn 2015.
There are a number of future energy related policy commissions in the pipeline focussing on innovation, transport and energy markets.

CONTENTS

Co-ordinator: Gavin Harper
Editor: David Strahan

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>
> LORD ROBIN TEVERSON

LETTER FROM THE CHAIRMAN

Energy has been at the front of political and academic debate in recent years. We regularly rehearse the arguments over fossil fuels and climate change. In politics the rising cost of energy to power and heat our homes grabbed major attention leading up to the last election. Winter deaths from inadequate house insulation, the cost of nuclear generation, the benefits or otherwise of fracking, energy security, the state of competition between the Big Six – these are all topics that feature in the current discussion around energy. Many even reach the headlines of our daily papers and broadcast media.

But one aspect of this debate that seems never to appear on the energy horizon is cold. We are all experts on heat, but when it comes to the 16% or so of our generating capacity that is used to keep our offices, food, cars, medicines, homes and scientific instruments cool, there has been little to say.

Having spoken on energy issues in Parliament for seven years I cannot remember one debate, or one piece of legislation that has tackled this growing use of our energy.

Out there in the wider world, a lack of refrigeration in developing countries means that food produced by farmers cannot reach markets, and the amount lost to pestilence and high temperatures is far higher: almost 50% of fruit and vegetables are discarded before ever reaching a consumer.

But keeping ourselves, our food, and our medicines cool is going to be an increasing challenge. Keeping things cold currently uses some of the more polluting technologies in terms of carbon and other emissions. It is a challenge not just for the warmer parts of the world but us here in the UK too.

For all these reasons I jumped at the opportunity to chair the University of Birmingham's Commission on cold of which this report is the prime output. I hope that it will kick-off a wider policy debate, and our recommendations become the tip of the iceberg when it comes to policy formulation and future action.

As the report also shows, we have some real innovators in the UK in cold technologies. Some concentrated attention could mean that the UK plays a major role worldwide in this increasingly important area.

Robin Teverson

Lord Robin Teverson

FOREWORD

Cold has been much neglected in the energy debate. Governments are developing strategies and policies to green everything from electricity to transport to heat, but 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. The 'greening' of cold is clearly an urgent global problem – but it may also offer Britain a massive business opportunity.

Cold may have been ignored but is vitally important to many aspects of modern life. An effective cold chain, for example, is essential for tackling problems such as food waste, food security, water conservation and public health. Cooling is also critical for many less obvious but essential functions: data centres couldn't operate without it, nor for example MRI scanners in medicine or superconductors in power electronics. Cooling also provides modern levels of comfort in hot countries – and can make the difference between some regions being habitable or not.

At the same time, vast amounts of cold are wasted – for instance during the re-gasification of LNG – which could in principle be recycled to satisfy some of this demand and start to reduce the environmental damage caused by cooling. Such a system-level approach – which starts by asking what energy services we need, and what is the least damaging way to provide them, rather than accepting existing practices as a fait accompli – has recently been coined the 'Cold Economy'. It is clear the Cold Economy could unleash a wide range of innovative clean cold technologies and provide energy resilience, economic growth and environmental benefits, but there is an urgent need to develop a system-level analysis of this problem and the potential solutions to inform both industry and policymakers. The Birmingham Policy Commission: Doing Cold Smarter was convened to start this work.

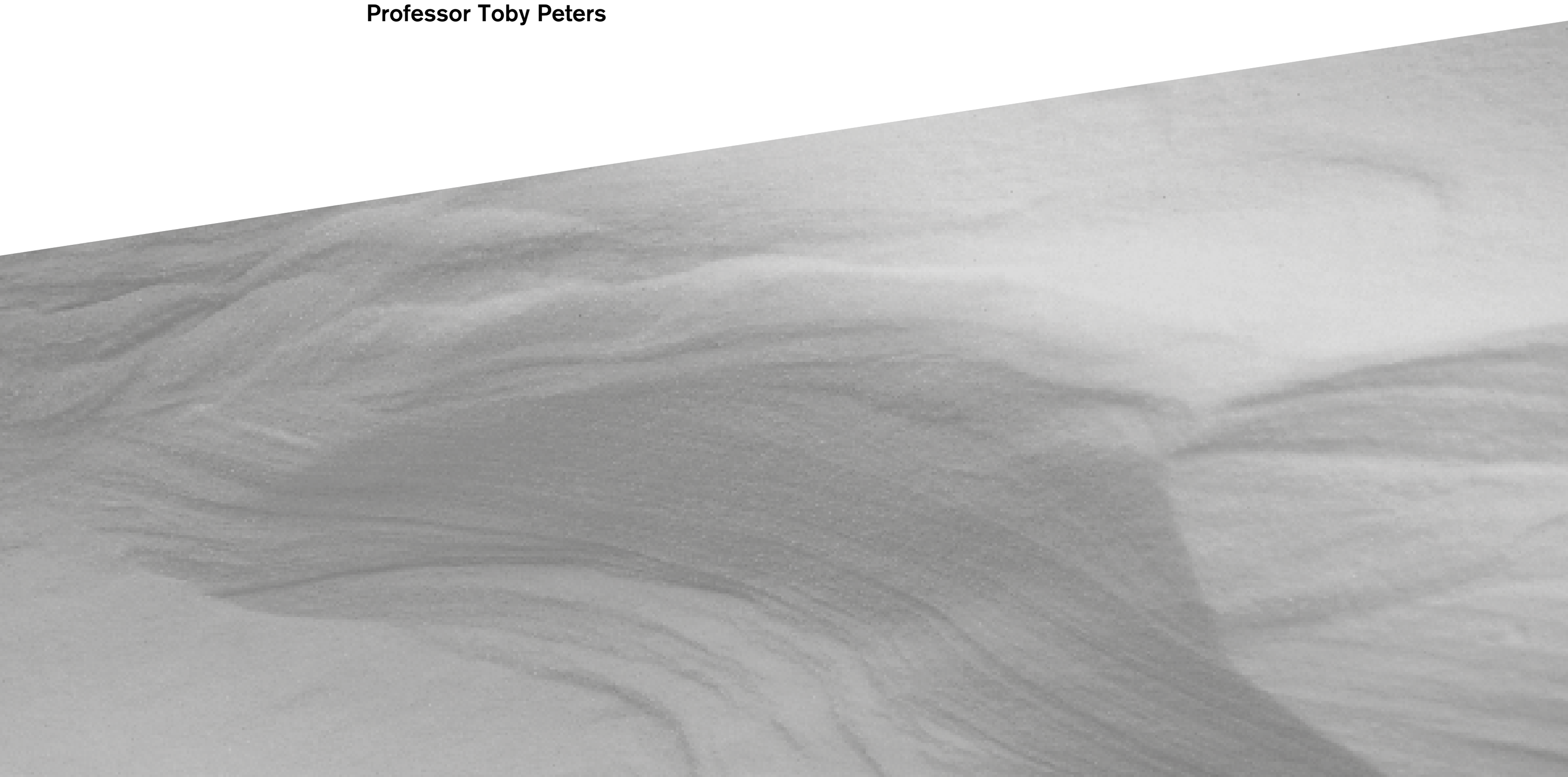
This inquiry is rather different from previous University of Birmingham policy commissions, such as those on nuclear power or the future of urban living, where the evidence and arguments were already well rehearsed. By contrast the debate around clean cold is at such an early stage – and good data on cooling hard still to come by – that the Commission restricted itself to tackling a short list of the most fundamental questions:

1. **Should UK plc invest to develop clean cold systems and technologies (rather than simply import them)?**
    a. What would be the impact on Britain’s domestic energy and environmental position?
    b. What is the scale of the global market opportunity?
    c. What are Britain’s strengths, weaknesses and competitive position relative to other countries, especially those in the Far East?
    d. What role could Britain adopt in the global value chain?
    e. What could be the value to UK plc?

2. **If the answer to 1 is ‘Yes’, what is required to enable it to happen from:**
    a. Industry
    b. Government
    c. Universities
    d. Innovation agencies such as Catapults?

The answers led the Commission to propose three urgent recommendations for the Government: establish an institutional champion to catalyse the development of clean cold; conduct a Technology Innovation Needs Assessment (TINA) for clean cold; and develop a rigorous system-level analysis of the environmental and financial benefits of the Cold Economy. We also developed a series of more detailed policy proposals, and a high-level technology roadmap to guide next steps and longer term progress – with the support of stakeholders from innovators to end-users. We hope the report and roadmap will prove useful not only to government but also universities, technology developers, industry and customers, and will contribute to the rapid development of clean cold technologies and the Cold Economy.

Professor Martin Freer
Professor Toby Peters



ACKNOWLEDGEMENTS

We wish to thank the many people have who have devoted considerable time and effort to the work of the Commission. These include the Commissioners, who contributed their tremendous knowledge of energy technology, economics, markets and policy; Lord Robin Teverson, who chaired the Commission with the insight and vision needed to keep the proceedings on track; and the witnesses and others who attended individual meetings and workshops.

The Commission greatly appreciates the depth and quality of the input from those who attended its evidence gathering sessions. At the heart of any successful process are organisation, planning and efficiency – capably provided by the Commission support team.

The views expressed in this report reflect the discussions of the Commission and the input received and do not necessarily reflect the personal views of those who contributed.

EXECUTIVE SUMMARY

AND RECOMMENDATIONS

DEMAND FOR COOLING IN ALL ITS FORMS IS ACCELERATING

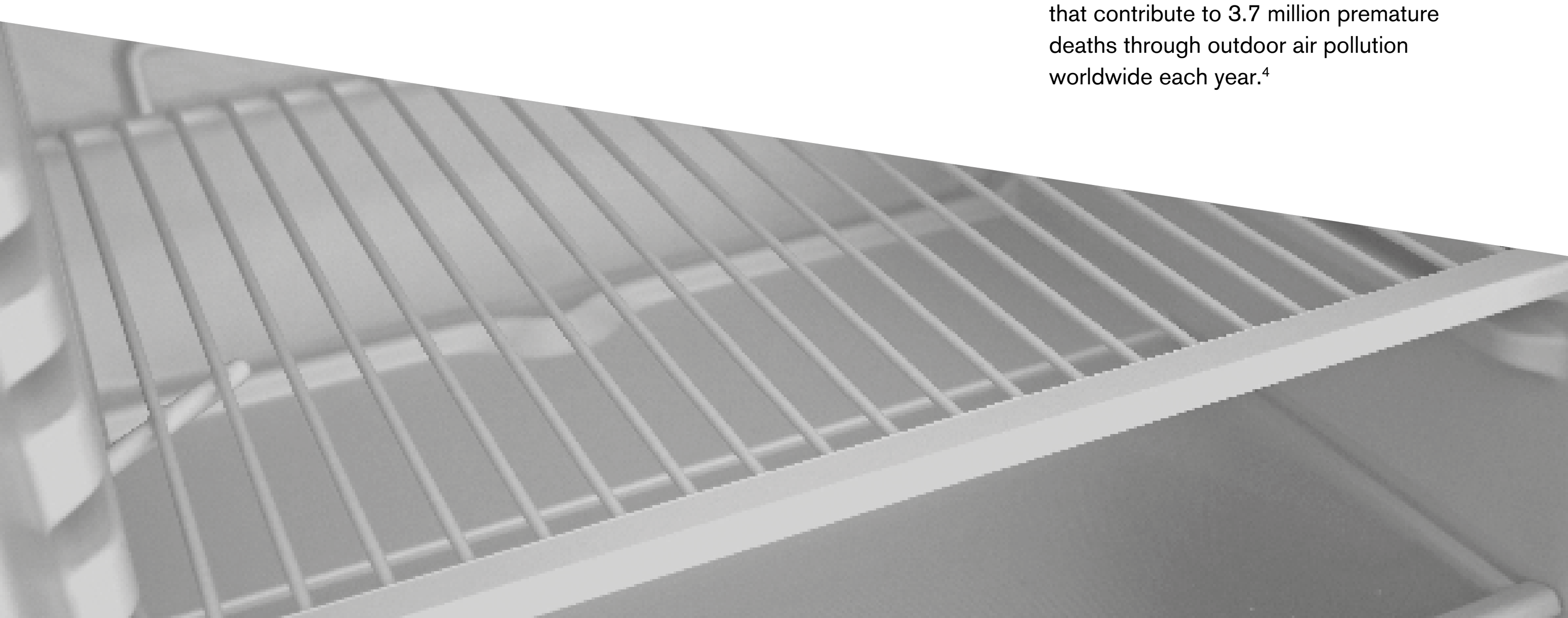
Cold is vital

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. 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. As the world's population heads towards 10 billion by 2050, and with more than 60% projected to be living in cities, there is no question that we will need far more cooling.

Cold is highly polluting

Yet existing cooling technologies consume large amounts of energy and can be highly polluting. The data is poor, but one estimate suggests that refrigeration and air conditioning cause 10% of global CO_2 emissions[1] – three times more than is attributed to aviation and shipping combined[2] – through energy consumption and leaks of HFC refrigerants that are themselves highly potent greenhouse gases. 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.[3] Diesel powered fridges on refrigerated vehicles also emit grossly disproportionate amounts of toxic NO_x and PM – many times more than a modern truck propulsion engine. These are two of the key pollutants that contribute to 3.7 million premature deaths through outdoor air pollution worldwide each year.[4]



Cooling demand is booming

For a technology that is so vital and yet so dirty, remarkably little is known for sure about the impacts of cooling; governments generally collect and publish little official data. But it is clear that cooling is already a significant energy consumer and polluter, and is likely to become massively more so given the projected demand growth – especially in developing countries undergoing rapid demographic change:

- The IPCC projects that global air conditioning energy demand will grow 33-fold from 300TWh in 2000 to more than 10,000 TWh in 2100, with most of the growth in developing economies.[5] 10,000TWh is roughly half the total electricity generated worldwide in 2010.[6]
- Worldwide energy demand for space cooling will overtake space heating by 2060, and outstrip it by 60% at the end of the century, as cooling demand in the developing countries of the global south grows faster than heating demand in the developed northern economies.[7]
- The European Commission expects cooling demand in EU buildings to rise 70% by 2030.[8]
- Chinese consumers bought 50 million air conditioning units – equivalent to half the entire US domestic air conditioner fleet – in 2010 alone.[9]
- The worldwide refrigerated vehicle fleet could grow from around 4 million[10] today to as much as 18 million by 2025 to satisfy currently unmet demand in developing countries.[11] In the EU, the pollution caused costs of transport refrigeration have been forecast to rise to €22 billion by 2025.[12]
- If nothing is done, within 15 years cooling will require an additional 139GW – more than the generating capacity of Canada – and raise greenhouse gas emissions by over 1.5 billion tonnes of CO_2 per year, three times the current energy emissions of Britain or Brazil.[13]

We need to 'do cold smarter'

The environmental impact of conventional cooling technologies can 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 capital rather than lifecycle costs, even when a more expensive product would save them money overall, and low levels of R&D, but also the sheer scale of projected demand growth. Evidence suggests the energy efficiency of cooling in some sectors could be raised by 30% on the basis of best-in-class products and practices alone, but 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. We clearly need to do cold smarter, and we believe the answer is to radically improve efficiency by developing a new 'Cold Economy'.

The Cold Economy: an environmental and business opportunity for UK plc

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. We estimate 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 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

Figure 1: The need to do cold smarter

produced at night when demand is low – to radically improve the efficiency of cooling, and reduce its environmental impact and cost. These waste or surplus resources can be used to provide cooling by converting them into a novel 'vector' – a means of storing and transporting cold – such as liquid air or nitrogen. A key insight of the Cold Economy is that energy can be stored and moved as cold rather than converted into electricity and then converted again to provide cooling. The Cold Economy is less about individual clean cold technologies – although these 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.

Evidence to the Commission suggested a four-stage approach to doing cold smarter, culminating in the Cold Economy:

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

2 **Reduce the energy required for cooling:** ie increase the efficiency cooling technologies – eg. cold stores could raise efficiency by an average of 30% using off the shelf solutions only[14] – 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 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?'. This can lead to far greater integration of cold demand with sources of waste cold and heat, and 'wrong-time' low carbon energy; the use of cryogens as vectors to store and transport cold and power; and the development of more efficient technologies, practices and materials.

We believe the benefits of this approach will be to reduce costs, CO_2 and local air pollution; improve energy and food security; and create business opportunities, growth and jobs. Making use of all the recoverable waste cold from projected UK LNG imports in 2030 could in principle increase the country's overall efficiency of cooling eight-fold and reduce costs by £1 billion or 20%.

The direct benefits of the Cold Economy to Britain appear significant, but are likely to be dwarfed by those to the developing world, because of the sheer scale of projected cooling demand growth, and the severity of the environmental impacts of a business as usual approach in those countries. The potential export market for clean cold technologies and know-how looks vast, and we suggest that building a Cold Economy at home is the best way to ensure Britain captures a significant slice. This requires both new policies from government, and a technology roadmap.

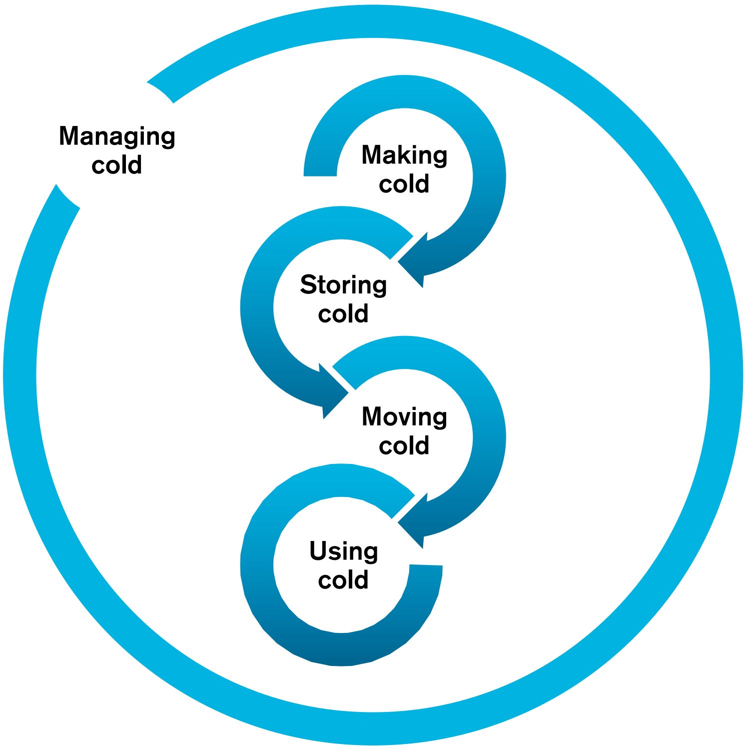


Figure 2: An integrated approach to cold

How to reach the Cold Economy: Roadmap

The roadmap for cold is intended to describe what is required to develop 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. It is a high-level industry roadmap, developed by the Commission and external experts. It is technology agnostic and resolutely practical: it does not fix its eyes solely on what might be achieved from blue-sky technologies in 15 years, but is equally occupied with the significant short-term gains from improved maintenance of existing equipment – and all the steps in between.

The aims of the roadmap are to reduce consumption of non-renewable natural resources, pollutant emissions, greenhouse gases (CO_2, refrigerants) and the total cost of ownership for equipment operators, but at the same time generate economic value to UK plc through improved productivity and exports, and social benefits for emerging economies through the creation of clean cold chains.

The roadmap focuses on driving new thinking in key areas

Making cold

- Harness waste/unused resources e.g.:
  - ‘wrong-time’ renewable energy (e.g. wind)
  - waste cold (e.g. LNG)
  - ambient heat and 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-level management

The roadmapping exercise revealed at least six groupings of industries and applications that for which the Cold Economy would generate value:

- **Built Environment:** Building energy, local-scale energy buffering and power generation, air conditioning, data centre cooling, warehouse refrigeration
- **Transport:** Propulsion, waste heat recovery, interaction with ICE and electrochemical systems, LiAir, LN_2, LH_2 LNG or NH_3 as a fuel, provision of a/c from cold
- Cold Chain: Transport refrigeration, depots, retail and medical
- **Industrial process:** Industrial Gases and Processes, LNG and LH_2 import and distribution, industrial-scale chilling and freezing processes
- **Advanced:** Superconductors, nanotechnology, other fundamental or advanced concepts

The results of the roadmapping exercise are summarised in Figures 3 and 4.

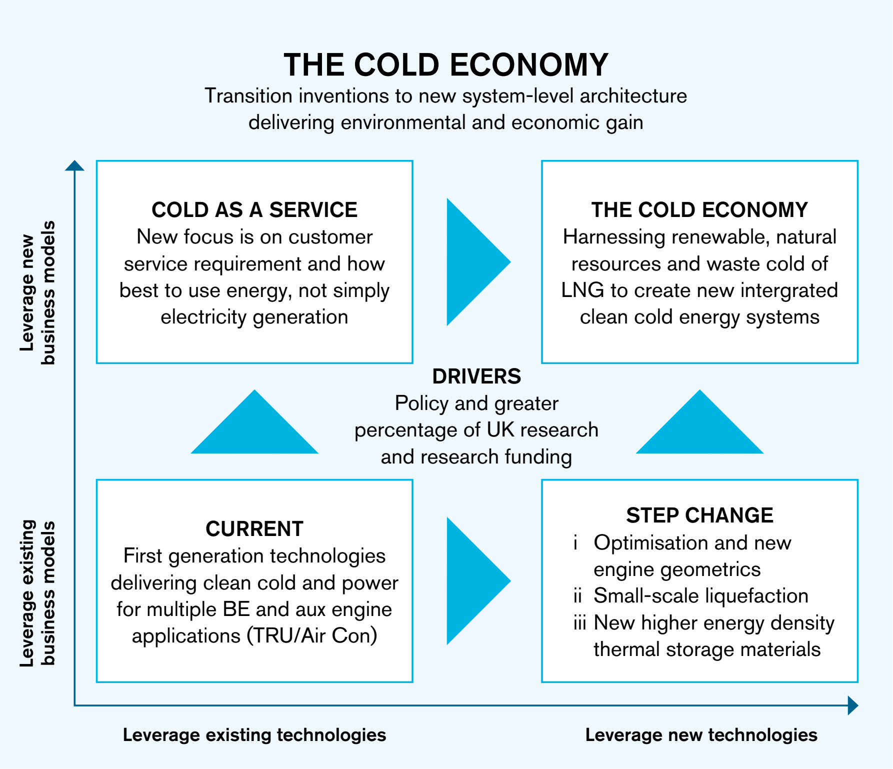
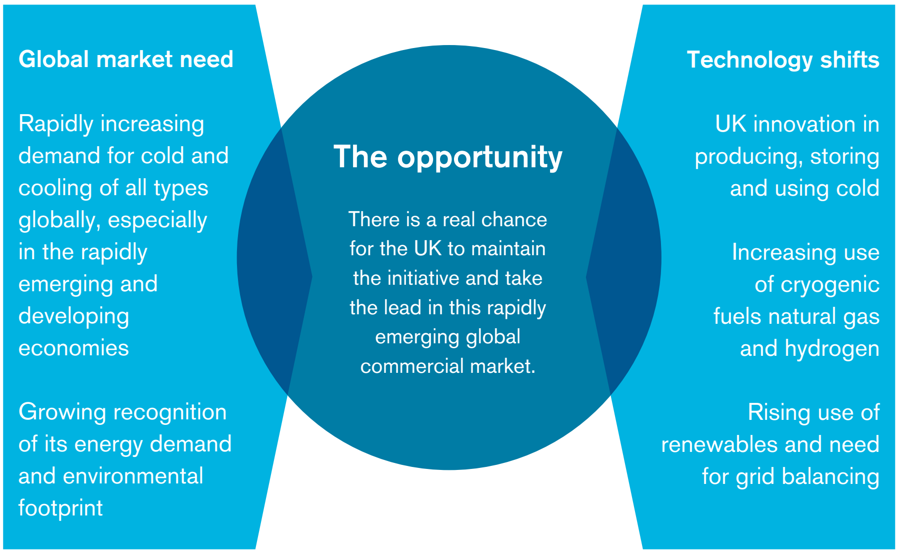


Figure 3: Transitional stages to the Cold Economy

Drivers for Change	Reduction in CO_2 footprint
	Increased pollution from NO_x and PM
	Transition to lower GWP 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 goods 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-gasification and liquid air liquefaction
	Grid balancing and district cooling and heating
	Vehicles: Liquid air – LN_2 – LH_2 systems
	Advanced superconductor technologies in power systems
	Food refrigeration and transport with liquid air generation and use
Interventions	Development of cold and cooling as a 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
	Develop@ UK skills base linked to state-of-the-art cold systems

Figure 4: Steps towards a cold economy

How to reach the Cold Economy: policy recommendations



Global market need

Rapidly increasing demand for cold and cooling of all types globally, especially in the rapidly emerging and developing economies

Growing recognition of its energy demand and environmental footprint

The opportunity

There is a real chance for the UK to maintain the initiative and take the lead in this rapidly emerging global commercial market.

Technology shifts

UK innovation in producing, storing and using cold

Increasing use of cryogenic fuels natural gas and hydrogen

Rising use of renewables and need for grid balancing

Figure 5: Why develop policy on cold?

There is a strong case for the British Government to take the lead and develop a comprehensive policy around clean cold, both to further its strategic aims for energy and the environment, and create a platform for innovation and exports that could help Britain secure a lead in what promises to be a major global market.

Developing policy on cold would deliver:

- **Reduced costs to industry and consumers:** E4tech estimates that doubling Britain's cooling efficiency through the Cold Economy could save the country around £1 billion;
- **Reduced CO$_2$ emissions:** key is deploying more efficient, low carbon technologies;
- **Energy security:** raising cooling efficiency reduces the electricity required, and would therefore improve capacity margins;
- **Grid balancing:** some clean cold technologies incorporate thermal energy storage, meaning they can help reduce peak electrical loads on hot days;
- **Food security:** improved cold chains would reduce food loss worldwide, so helping to constrain food price rises in both developing and developed countries;
- **Air quality and health:** existing transport refrigeration and diesel generators emit grossly disproportionate amounts of NO$_X$ and PM; the profile of toxic air pollution is rising rapidly following the Volkswagen emissions testing scandal, while recent court judgements that oblige Britain to submit a new air quality strategy to Brussels by the end of this year;
- **Exports, growth, jobs and skills:** if the immediate benefits from greening Britain's cooling are worth £1 billion as E4tech estimates, we would expect potential value of supplying clean cold to the global market to be many times higher. Based on the estimated value of clean cold to Britain, scaling by GDP produces a global value of £43 billion, and scaling by population gives a global value of £112 billion.[15] Even at the lower figure – which takes no account of projected cooling demand growth in developing countries – the opportunity is enormous.

Many areas of policy clearly need work, particularly in light of the barriers to clean cold, which could be cleared by government intervention. But although the case for developing detailed policies is compelling, we believe there are more fundamental issues to resolve first. Awareness of the need for clean cold is woeful, for example, and the data around cooling is poor. For this reason our five key recommendations are intended to raise awareness of the importance of clean cold and improve the data and analysis of the cooling system in Britain. If these are accepted, we propose a further series of more detailed proposals. For a full description of our key and additional proposals see Sections 5 and 6 of the main report.

Existing transport refrigeration and diesel generators emit grossly disproportionate amounts of NO$_X$

KEY RECOMMENDATIONS

1 Raising awareness and long term commitment

We believe government has a major role to play in raising awareness of the environmental and economic importance of cooling. If the Government makes clear its long term commitment to the adoption of clean cold technologies it will increase the confidence of investors. We urge the Government to:

- Establish a lead department with responsibility for clean cold. Since cold touches so many aspects of the energy system, the environment and the economy, the development of policy should involve several arms of government – DECC, Defra, BIS, DfT and the Treasury – but we recommend that a single department should take ownership of this issue and co-ordinate with the others.
- Appoint an institutional champion for clean cold: we recommend the Energy Systems Catapult should adopt clean cold as one of its themes, and act as a co-ordinating body for analysis and development of clean cold technologies in Britain.
- Develop a concordat for the UK cooling and refrigeration industry: that encourages the development of products with high-efficiency, low levels of pollution and carbon impact, establishing UK industry as best-in-class.

2 Technology Innovation Needs Assessment for cooling

Technology Innovation Needs Assessments (TINAs) are carried out by the Low Carbon Innovation Co-ordination Group (LCICG), whose core members include DECC, BIS, the Engineering and Physical Sciences Research Council (EPSRC), the Energy Technologies Institute (ETI), Innovate UK and the Carbon Trust. TINAs are intended to identify and value the main innovation needs of specific low-carbon technology families to inform the prioritisation of public sector investment in low-carbon innovation. Each TINA analyses, estimates or identifies:

- the potential role of the technology in the UK's energy system
- the value to the UK from cutting the costs of the technology through innovation
- the value to the UK of the green growth opportunity from exports
- the case for UK public sector intervention in innovation
- the potential innovation priorities to deliver the greatest benefit to the UK

These are precisely the questions that need to be answered around clean cold. TINAs have already been conducted for ten energy sectors including an analysis of heating, which concluded innovation could reduce UK energy system costs by £14–66 billion and raise GDP by £2–12 billion to UK GDP to 2050. As we argue above, the value of clean cold technology exports to developing countries – which almost all have hot climates – could be far higher.[16]

3 System-level model of UK cold

This Commission has produced a first-take analysis of cooling demand and resources in the UK. But a proper understanding of the potential of the Cold Economy requires a more detailed and definitive model to be developed. This model should use whole-system methodology to evaluate the reduction in system cost – financial and environmental – that could be achieved by deploying new cooling technologies.

The whole-system approach is required because the potential benefits stretch far wider than those enjoyed by the individual owner or user of clean cold technologies. These benefits span transport, food, buildings, industry and energy, and include: lower costs; reduced emissions of greenhouse gases, NO_x and PM; and improved grid resilience resulting from reduced cooling loads and increased use of wrong-time renewable energy and waste heat and cold.

We recommend that Research Councils, Innovate UK and the Government jointly fund a study to assess the social benefits of implementing the measures outlined in this report. We expect this work would take a two-step approach: first to understand the cold value chain in more depth, and second to integrate this into whole systems models. For more detail see section 5 of the full report.

A truly system-level model of cooling in Britain would inform decisions in policy and research funding and provide the evidence to ensure interventions are directed where beneficial impacts are most likely. Building and integrating such models would start with the UK, but could then be extended to other markets. It would therefore highlight the value of clean cold technology innovation in developing export opportunities for business.

KEY RECOMMENDATIONS

4 Support demonstration projects

The environmental benefits of clean cold technologies are likely to be significant in Britain, but those in the developing world will be enormous, and the economic value of satisfying those needs equally large. For this reason government should consider supporting clean cold demonstration projects, both in Britain and abroad, as a platform for future exports. In Britain, such projects could explore ways of measuring cooling demand and aggregating cooling loads – for instance between a hotel, data centre and logistics business – to build a viable business case. In Africa, they could simultaneously demonstrate effective ways to reduce postharvest food loss – and the consequent waste of land, water and energy, and needless emission of CO_2 – while laying the foundations for future economic growth and British jobs.

5 Measurement and management of clean cold

It is axiomatic that `you cannot manage what you cannot measure', and many users of cooling have very little idea about how much energy they are consuming, the efficiency or inefficiency of their equipment, and how much pollution they are causing. This is true for individual cooling applications but probably even more so at the level of an entire company. Some large consumers of cold may have a clear idea of their cooling energy consumption but perhaps much less of their cooling requirement (coolth). We believe this requires 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, which may also help them identify cooling loads that could be aggregated and therefore supplied more efficiently through district cooling schemes. The Coefficient of Performance (CoP) used for individual appliances is too narrow a measure, and we favour a broader indexed approach capturing energy consumption, emissions (CO_2, NO_x, PM) and whether the energy source worsens or mitigates peak load.

The Government should consider leading the development of a broad metric of the energy and environmental impact of cooling and promoting it among companies on a voluntary reporting basis.

SECTION 1

COLD IS VITAL BUT DIRTY

COLD IS VITAL BUT DIRTY

Cold is vital

Even in a temperate country such as Britain, cooling is everywhere, and vital to many aspects of modern life. Without it, the supply of food, medicine, power and data would simply break down. It is no exaggeration to say that if cooling were somehow suddenly withdrawn from advanced economies, life would quickly become extremely difficult. Here is what we would have to do without:

- **Food:** Much of our food depends on the 'cold chain', a seamless network of refrigerated warehousing, sea-containers and trucks that stretch from the farm gate – which could be in Asia, Africa or Latin America – to the supermarket display cabinet. 70% of foods are chilled or frozen when produced[17], and 50% are retailed using refrigerated display, and increasing amounts are delivered to your doorstep by refrigerated home delivery vans. The total value of refrigerated food sold in the UK is around £56 billion per year[18], and the value of food transported cold worldwide in 2002 was $744 billion.[19] Domestic refrigeration is the biggest consumer of cooling energy in the UK, at around 13TWh per year or 4% of UK electricity.

- **Fertilizer:** Cooling is a vital step in the Haber-Bosch process that converts atmospheric nitrogen into ammonia fertilizer, credited with producing the food to feed 3 billion people – almost half the world's population. Put another way, this process provides all the food eaten every second day.

- **Medicine:** Many vital medicines and treatments require refrigeration to produce or transport – including the world's biggest selling medicine, the anti-cholesterol drug Lipitor.[20] MRI scanners could not work without the extreme cold of liquid helium.

- **Data and telecoms:** Data centres consume 2–3% of Britain's electricity, and half of that is for cooling[21], without which the internet would quickly collapse. Global data centre power consumption almost quadrupled between 2007 and 2013 to 43GW[22], roughly the generating capacity of South Africa.[23] At this growth rate, by 2030 the additional cooling load would require another 35GW of generating capacity, or more than that of Poland.[24]

- **Air conditioning:** Vital for modern levels of comfort in many parts of the world including the United States, where over 80% of homes[25] and commercial buildings[26] are equipped, and the Middle East and Asia. Skyscrapers worldwide would be uninhabitable without it. Car air conditioning in the US consumes an estimated 7–10 billion gallons of petrol per year.

- **Energy security:** Production of Liquefied Natural Gas (LNG) and other cryogenic fuels depends on industrial scale cooling. The global trade in LNG is forecast to reach 500mtpa by 2025 – the equivalent of ten times total current UK gas consumption[27] – and is vital to the energy security of many countries.

- **Industry:** Cooling is essential to produce industrial gases such as oxygen for steelmaking, chemicals, plastics, industry and hospitals, and nitrogen for fire suppression.

- **Science:** The Large Hadron Collider at CERN in Switzerland depends on cryogenic cooling; as do Maglev trains and the fuel for space rockets. Cryogenic cooling touches around 17% of the British economy.

In short, in developed countries, life without cooling is almost unthinkable. But in many parts of the world, people understand only too well what the absence of cooling means because they live with it daily. In fact, a lack of cold can be seen as the hidden link between several apparently separate looming global crises – food, energy and water – as the population heads to perhaps 10 billion by 2050.

Demand for food is projected to grow by 40% by 2030 and 70% by 2050[28]; at the same time The Food and Agriculture Organization of the United Nations (FAO) estimates that about a third of all food is lost to wastage worldwide.[29] Most food is lost between farm and retailer, and the problem is greatest in the developing world.[30] The International Institute of Refrigeration has estimated that if developing countries had same level of cold chain as developed, they could save 200 million tonnes of perishable food or 14% of the food supply.[31] Another study found that halving food wastage could feed an extra 1 billion people[32], which is comfortably higher than the 800 million who were chronically undernourished in 2012–14. The lack of cooling not only worsens food security but also food safety: low level food poisoning is an endemic problem in much of the developing world.[33]

The consequences of such colossal wastage spread far beyond hunger and inflated food prices. The FAO estimates that total 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 dioxide emissions, making it the third biggest emitter after the US and China.[34] In other words, if cold chains in the developing world could be brought up to the levels of those in the developed world, the benefits would extend far beyond the immediate reduction in wastage, hunger and rising food prices. They would even extend beyond agriculture, resources and climate: 25% of all vaccines arrive damaged or degraded[35], and two million people die each year from vaccine preventable diseases simply because of inadequate refrigerated distribution.[36]

It is clear that cooling matters.

…but cold is also highly polluting

The current environmental footprint of cold – greenhouse gases

Cooling is important not just because it supports civilised life, but also because it consumes large amounts of energy and takes a heavy toll on the environment through emissions of greenhouse gases and toxic air pollutants. **Academics at London South Bank University (LSBU) estimate refrigeration and air conditioning (RAC) consumes around 16% of UK electricity and is responsible for 10% of global CO_2 emissions[37] – which is three times more than is attributed to aviation and shipping combined.[38] 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.[39]**

The main culprit is the vapour compression refrigeration cycle – the overwhelmingly dominant means of cooling – which was invented in 1805, commercialised for industrial uses towards the end of the 19th century, and spawned the global boom in domestic fridges and air conditioning ever since. The lifecycle greenhouse gas emissions of refrigeration devices comprise the CO_2 emitted by power stations that generate the electricity they consume, and leaks of HFC refrigerants, or 'F-gases', which are highly potent greenhouse gases.

It is the high global warming potential (GWP) F-gases that have captured the attention of policymakers, and it is easy to see why: the most commonly used F-gas, R404A, is 3,922 times more powerful than carbon dioxide, meaning that a leak of one kilogramme of refrigerant has the same global warming impact as four tonnes of carbon dioxide. But although the emissions from F-gas are grossly disproportionate to the volumes of gas leaked, the bulk of cooling emissions still come from energy consumption. Academics at LSBU estimate that 25% of the global warming impact of refrigeration and air conditioning is due to F-gas leakage and 75% due to emissions from power generation and diesel.[40] The EU regulations introduced this year will reduce the volume of high GWP F-gases available to scarcely 20% of current levels by 2030, meaning that energy will soon represent more than 90% of the sector's GHG emissions.[41]

The amount of energy consumed by cooling in individual sectors is significant. We estimate Britain's supermarkets consume around 9TWh of electricity per year, of which around 3.6TWh – or 1% of the country's power – goes on cooling[42], and the internet is another huge consumer of cold. On the roads, refrigerated vehicles are also big polluters. Work by Professor Savvas Tassou at Brunel University suggests that transport refrigeration consumes up to 20% of a refrigerated vehicle's diesel, and is therefore responsible for a fifth of its well-to-wheels CO_2.[43] Professor Judith Evans at LSBU calculates that in Britain transport refrigeration causes emissions of around $2mtCO_2$ per year from diesel consumption alone.[44] In Europe, a report from Dearman, a clean cold technology developer, found that the EU's fleet of 1 million refrigerated vehicles will emit $13mtCO_2e$ in 2015 from diesel and F-gas leakage combined.[45]

This last report, *Liquid Air on the European Highway*, also found that refrigerant leakage accounts for 17% of the lifecycle emissions of a transport refrigeration unit (TRU), and diesel consumption for around 90% of the rest – i.e. 75% of the total. So although it is clearly important to minimise and eventually eliminate F-gas leakage or use, it is even more important to eliminate the CO_2 emissions from energy consumption of refrigeration, which suggests the need to develop entirely new refrigeration cycles and technologies.

In short, cooling is not only vital but also highly damaging to the environment and health, causing high emissions, greenhouse gases and toxic air pollutants. In contrast to the widespread perception, however, the greater part of that pollution from cooling devices comes from their energy consumption rather than leaks of refrigerant gases.

The current environmental footprint of cold – toxic air pollution

Some cooling applications are also responsible for large emissions of toxic air pollutants including nitrogen oxides (NO_X) and particulate matter (PM). These are the pollutants that cause up to 52,500 premature deaths in Britain each year according to recent government estimates[46]; over 400,000 in the EU[47]; 600,000 in India[48]; and 3.3 million worldwide[49] – more than die from malaria and HIV Aids combined[50]. Cooling contributes to these emissions through the use of electricity generated by coal fired and to a lesser extent gas-fired power stations, transport refrigeration units and diesel electricity generators known as 'gensets'.

Fridges on trucks, trailers and vans are powered by electricity generated by burning diesel. For vans and smaller trucks this may be via an alternator or compressor mounted directly on the propulsion engine, but for most trucks and virtually all trailers, the power is produced by an entirely separate diesel engine. In Europe these auxiliary engines are essentially unregulated and therefore inefficient and highly polluting.

Analysis conducted by E4tech, the clean energy consultancy, for Dearman, has found that auxiliary transport refrigeration units can emit up to six times as much NO_x and 29 times as much PM as a Euro VI truck propulsion engine.[51] As a result, a recent report from Dearman found that in 2015 the European TRU fleet would emit 40,000 tonnes NO_x, equivalent to over 26 million Euro 6 diesel cars, and 5,000 tonnes of PM, equivalent to 56 million Euro 6 diesel cars.[52] The analysis found that if nothing is done the cumulative social cost of those emissions – including health costs, the value of the years of lost life and output, and damage to crops and buildings – will rise to over €7 billion by 2025.[53]

In developing countries such as India, where electricity grids are weak and power cuts a daily occurrence, cooling loads are closely connected to the use of diesel gensets, which like TRUs are highly polluting. Blackouts happen because the country has too little primary generating capacity, and cannot cope with daily demand peaks that are largely driven by air conditioning demand – which Tata Power estimates accounts for 40% of total consumption.[54] As a result, many commercial customers have installed diesel gensets to protect themselves from the country's frail grid – and these units now account for more than 90GW, or 36% of India's total power generation capacity.[55] Gensets in India are typically used far more often – on average 500 hours per year – than those in developed economies such as the UK.[56] Since much of this capacity will be turned on as a consequence of cooling demand, there is a clear need to develop cooling technologies based on energy storage that separate the generation of cold in time from its consumption.

In short, we would need to develop clean cold technologies on the basis of its current impact on the environment and health, even if global demand were static. But it is not: cooling demand is set to grow dramatically.

And demand is booming

Cold matters not only because it is vital to modern life, and currently imposes heavy costs on health and the environment, but also because demand for cooling is set to soar. There are several causes, including rising temperatures due to climate change, feedback loops caused by current cooling technologies, and structural economic growth in developing countries causing the emergence of a huge new middle class.

Structural growth in the developing economies

By far the strongest driver of global demand for cooling in the short to medium term is the tectonic shift in the demographics of developing economies – which is already having a dramatic effect.

The emerging markets boom of the last three decades is a familiar story. Less well known is the surge in cooling that has been an integral part of that expansion. In China, for example, fridge ownership among urban households rose from 7% to 95% between 1995 and 2007[57]; and cold storage capacity soared nine-fold from just 250 million cubic feet to more than 2 billion in the three years to 2010[58], and is on track to more than double again by 2017.[59] Chinese consumers bought 50 million air conditioning units – equivalent to half the entire US domestic air conditioner fleet – in 2010 alone.[60]

China's cold chain business is reported to be growing at 25% per year and projected to be worth $75 billion by 2017.[61] Cold chain investment is also booming in India, where annual revenues from the sector are forecast to reach $13 billion by 2017.[62] This correlation should come as no surprise: as people's incomes rise, they naturally buy the appliances and services that improve the quality, safety and variety of the food they eat.

The sharp slowdown in the Chinese economy this year may of course slow the growth in demand for cooling for a time, but the demographic factors supporting future growth in the developing world look irresistible. The population growing fast; the middle class in Asia is expected to swell from around 500 million people today to 3 billion people by 2030, two thirds of the global total[63]; and in some countries the population is getting younger and therefore more productive. Urbanisation proceeds apace: Goldman Sachs expects India's cities to swell by 500 million people over the next 25 years, and the UN forecasts the global urban population will rise from 3.9 billion in 2014 to 6.4 billion by 2050 or 66% of the total.[64]

All this should tend to increase demand for western-style diets and levels of comfort, most of which depends on cooling.

The rapid growth in cooling demand in developing countries is driven not only by shifting demographics, but also by a yawning need: primarily the imperative to reduce food waste in order to feed a population of 9 or 10 billion by 2050 – it's estimated that halving food wastage could feed an extra 1 billion people.[65] And the International Institute of Refrigeration (IIR) estimates that if developing countries had the same level of refrigerated transport and warehousing as found in the developed world, 200 million tonnes of perishable food would be saved each year – or 14% of the food supply.[66]

Despite the strong growth in the developing giants, cold chains remain rudimentary or non-existent in most developing countries, meaning that in India just 4% of fresh produce is transported cold[67], compared to more than 90% in the UK. China meanwhile has an estimated 66,000 refrigerated trucks to serve a population of 1.3 billion, compared to France which has 140,000 to serve 66 million.[68] At the same time, new food safety regulations come into force in China this year that mean 20% of fresh fruits and vegetables, 50% of meat and 65% of seafood will now have to be transported by cold chain, compared to 5%, 15% and 23% today.[69] So there is clearly massive headroom for growth.

The Chief Executive of India's National Centre for Cold-chain Development, Pawanexh Kohli, who gave evidence before the Doing Cold Smarter Commission, estimates India has perhaps 9,000 refrigerated trucks, far too few to service its 31 million tonnes of cold store capacity. To make proper use of just 10% of the cold store capacity, he calculates the country needs to build 30,000 new pack-houses with pre-cooling facilities, and needs 60,000 refrigerated trucks on the road at any one time.[70] By extension, making proper use of all of India's cold storage capacity would require 600,000 refrigerated trucks. Taking a broader international perspective, if India had the same ratio of refrigerated vehicles to the value of its grocery market ($375 billion in 2012) as Britain ($243 billion), it would have 129,000 refrigerated vehicles, 18 times more than at present.[71] And if it had the same ratio of refrigerated trucks to population as Britain, its fleet would number more than 1.5 million.[72] Either way, the growth potential is huge.

This headroom for growth exists across many forms of cooling, and the projected growth rates are prodigious. If the current and future demand for cooling services in developing countries were satisfied using conventional technologies, however, the environmental and health impacts described in the sections above could be enormous.

Climate change

As global temperatures continue to rise the demand for cooling is bound to increase, even in developed countries where the cooling market might be considered mature such as the US – where home air conditioning already accounts for 8% of the electricity generated for all purposes, costing consumers $15 billion per year, and causes emissions of around 196 million tonnes, or 2 tonnes per household with air conditioning.[73] According to another estimate, US air conditioning accounts for 20% of home electricity consumption and 13% of commercial demand, which together represent more electricity than is generated in the entire continent of Africa for all purposes.[74] Energy consumption may rise proportionately more than cooling load, since cooling equipment is typically sized to meet peak load. Peak temperatures are likely to rise more than average temperatures, and appliances are typically less efficient when operating at part load – which is most of the time. Defra projects that the average British summer temperature is likely to rise 3C to 4C by the 2080s.[75]

In any event, the European Commission expects cooling demand in EU buildings to rise 70% by 2030.[76] And the IPCC, in its reference scenario, projects that global air conditioning energy demand will grow 33-fold from 300TWh in 2000 to more than 10,000 TWh in 2100. **The IPCC says most of the growth will occur in developing economies, and 25% will be due to climate change.**[77] **10,000TWh is roughly half the total electricity generated worldwide in 2010.**[78]

Energy demand for heating will also increase, of course, but less quickly, because the northern economies where heating is required are generally wealthy enough – bar the poorest households – to afford it already. As a result, the energy required for space cooling worldwide is set to overtake that for space heating by 2060, and by the end of the century cooling will consume 60% more energy than heating according to the Netherlands Environmental Assessment Agency.

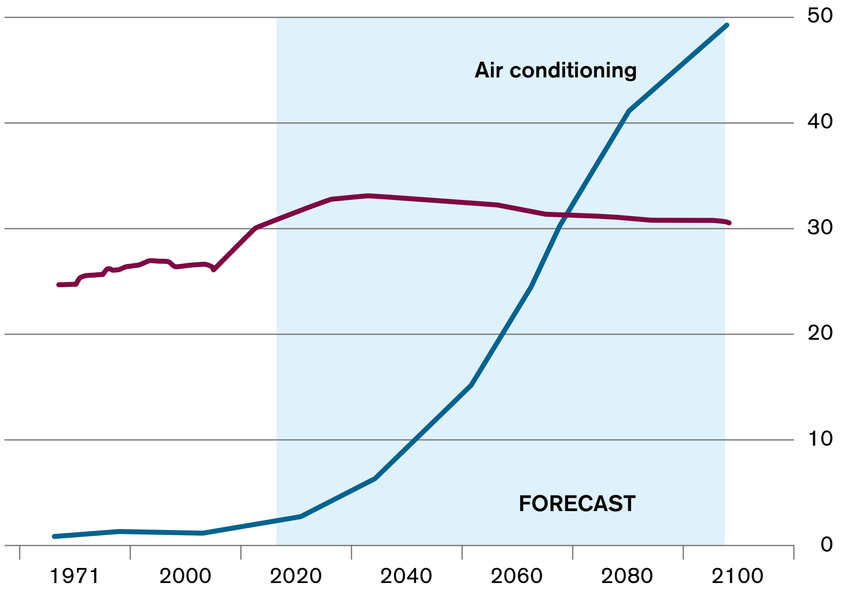


Figure 6: Worldwide forecast energy demand for space heating and space cooling, exajoules. Source: PBL Netherlands Environmental Assessment Agency[79]

Feedback loops

Cooling demand will also rise inexorably if we do not change course, as a result of two feedback loops. One is obvious and global: the more fossil fuel we burn to keep ourselves and our food cool, the more carbon we will emit, the hotter the planet will become, and the more fossil fuel we will need to burn to keep cool. For example, Saudi Arabia burned a record 1 million barrels of oil per day to generate electricity in July 2014[80], and more than 50% of Saudi summer peak power demand is driven by air conditioning.[81] This cycle clearly needs to be broken, both in the Kingdom and more generally.

The other feedback loop is less obvious and more localised, and relates to the way current cooling technologies contribute to the heat island effect. Cities create heat islands because heat from the sun is absorbed by tarmac and concrete, forcing cooling equipment to work harder. But air conditioners reject heat into their local environment, so raising temperatures and creating the need for yet more cooling. 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.[82] More generally, it has been estimated that this effect is responsible for 5–10% of urban peak electricity use for air conditioning in US cities.[83]

Vehicle exhausts also dump heat into the environment, forcing both vehicle and building air conditioners to work harder still. 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 CO_2 emissions by 11,800 tonnes per day.[84]

Rising demand for (diesel powered) Transport Refrigeration Units (TRUs) and bus air conditioning can only worsen the heat island effect: adding air conditioning to a double-decker bus in hot countries such as India could raise its fuel consumption by almost 50% according to one vehicle manufacturer. The answer here is not electric vehicles, however, since the cooling load in hot countries would severely deplete the vehicle's range. This suggests the need to develop cooling technologies that do not dump their rejected heat into their immediate environment, nor draw on the vehicle's propulsion energy.

The potential of untapped resources

While the environmental impacts of cooling are already heavy, and demand is projected to soar, there are also enormous waste resources that could be recycled to dramatically reduce the damage caused by our cooling needs.

Waste cold

Vast amounts of cold of are lost to the environment during the re-gasification of Liquefied Natural Gas (LNG) at import terminals, for example, and at gas 'let down' stations, where gas moves from high pressure to lower pressure pipelines. LNG produces so much waste cold because natural gas producers such as Qatar, Egypt and Australia liquefy natural gas by cooling it to −162C in massive industrial liquefiers (known as 'trains' because they stretch up to a mile long) in order to shrink the gas to a manageable volume for transport by supertanker. Once delivered to an import terminal in a consuming nation such as the UK, the LNG must be re-gasified before entering the pipeline network. Although the waste heat of power generation plants is sometimes used to warm the gas, import terminals generally burn some of the gas to warm the remainder or use sea water as a source of heat. Either way, vast amounts of cold are lost to the environment.

In Britain, if only half the cold thrown away in this fashion could be recycled, it would amount to almost 20TWh of 'coolth', or more than a fifth (22%) of our current cooling demand, and save around £1.3 billion in operating costs, according to evidence from E4tech, the sustainable energy consultancy. On the basis of projected LNG imports, the 'recoverable' waste cold in 2030 – half the actual resource – could be 80TWh, almost matching today's UK demand for cooling power.

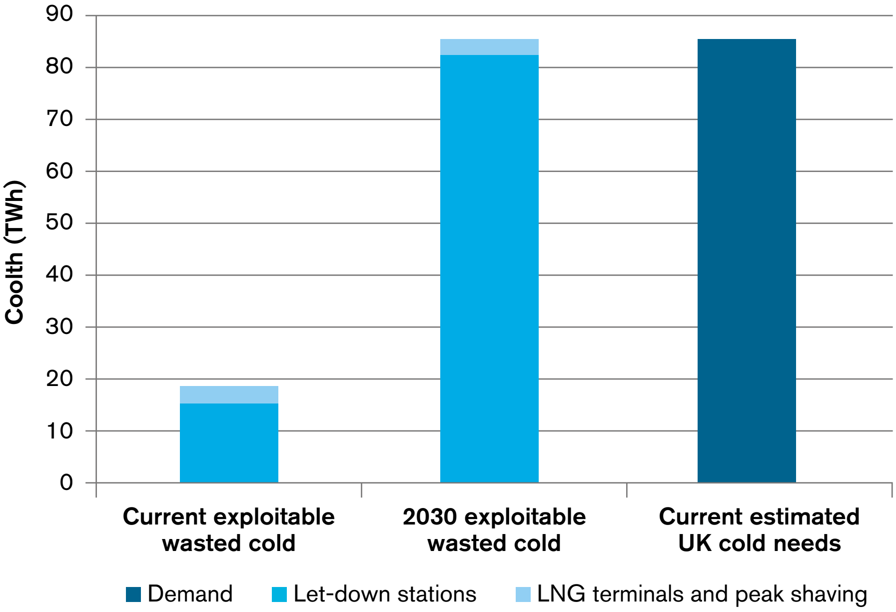


Figure 7: UK exploitable 'wasted' coolth and coolth demand. Source: E4tech/Dearman

The major developing economies have even greater waste cold resources in the form of rapidly expanding LNG re-gasification capacity. India has four LNG import terminals with capacity of 25 million tonnes per annum (25mtpa), expected to expand to 32mtpa, and a further 18 terminals have been proposed.[85] China meanwhile is expected to be importing more than 60mtpa by 2020.[86] The global LNG trade is expected to double to 500mtpa by 2025[87], which in theory has the potential to provide cooling 13 times greater than Britain's total current demand.[88]

Waste heat

It may seem counterintuitive, but waste heat can also be recycled to provide cooling, through something known as an absorption chiller. This cycle was first used commercially to import frozen beef from South America to Europe in the 1870s, and is now increasingly found in highly efficient 'tri-generation' schemes – where a gas or biomass fired generator provides a building or entire district with electricity, hot water and space cooling simultaneously. Sources of waste heat are myriad in buildings, industry and vehicles, and the potential to expand the use of absorption cooling is likely to be huge. The waste heat resource in Britain is estimated at 10-40TWh per year.[89]

The heat to drive absorption chillers can also be provided by solar thermal systems, which are increasingly being used to provide air conditioning for large buildings and being tested for small cold stores in remote rural locations. There are also many 'free' sources of cooling that could be exploited far more than at present. Ground-source and air-source heat pumps are becoming more common, but the name is somewhat deceptive; heat pumps can be used in reverse to provide cooling too. Rivers and sea water are another huge resource of 'free' cooling that could be exploited more.

Wrong-time energy

Cooling can also be provided by 'wrong-time' energy, such as nuclear or renewable electricity generated at night when demand is low, for example by generating cold at night and storing it for use during peak hours. At the moment, the energy storage debate focuses on electricity-to-electricity solutions such as pumped storage or batteries, but since so much energy demand – especially at peak times in hot climates – is for cooling, it makes sense to store surplus energy directly as cold.

This approach could reduce the cost and emissions of cooling – overnight electricity in Britain is cheaper and has lower carbon intensity than during the daytime – and help to relieve peak loads on stretched electrical grids. One example in California is the Ice Bear, which makes ice at night to deliver cooling to the building's air conditioners the following day, so reducing the demand for peak electricity. Eutectic beams and plates – which work rather like a picnic box cooler – can also provide cold for buildings and vehicles on the same principle. As renewable generating capacity continues to expand, so will the opportunities to absorb and store this energy efficiently until needed in the form of cold; the key is to think about the service required – cooling.

If ways can be found to integrate these resources into the delivery of cooling services, it could substantially increase the efficiency of cooling and reduce its environmental impact and cost. If not, and we continue to provide cooling through conventional technologies, the energy and environmental impacts of cooling are likely to multiply many times over.

The consequences of business as usual

If the world continues to satisfy demand for cooling using existing technologies, the already heavy impact on environment and health will be multiplied *many times* over as a result of future demand growth. We cannot predict quite how great the total impact will be, but it is possible to sketch some of the potential outcomes by extrapolating from a number of forecasts of various forms of cooling demand:

- **Domestic refrigeration:** Demand for domestic refrigeration in developing countries is growing strongly – rising from 7% to 95% of China's urban households between 1995 and 2007, for example.[90] The projected rise in fridge electricity consumption in developing countries from 2005 to 2030[91] equates to an extra 31GW of power generation[92], or the entire generating capacity of Belgium and Bulgaria combined.[93] Multiplying by the current average grid carbon intensity of non-OECD countries[94], emissions from the electricity demand of domestic refrigeration in developing countries will rise by 210mtCO_2 per year to a total of 450mtCO_2 per year by 2030.[95]

- **Air conditioning in China and India:** In much of the developing world the take-up of air conditioning is still very low, but this cannot last as incomes start to rise. In China, for example, less than 1% of urban households owned an air conditioner in 1990, but by 2003 that number had soared to 62%.[96] 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.[97]

- **Air conditioning in the developing world:** In developing economies as a whole, power for air conditioning is projected to increase seven-fold[98] from 2005 to 2030, requiring an extra 73GW of power stations[99], or the combined generating capacity of Norway, Portugal and Romania.[100] Multiplying by the current average grid carbon intensity of non-OECD countries[101], this would raise emissions associated with air conditioning in developing countries by almost 500mtCO_2 per year to 590mtCO_2 per year by 2030.[102]

The chart below shows what would happen if every country achieved the same level of air conditioning penetration as the US. Eight countries' energy demand for air conditioning would exceed that of the US, led by India, and in total air conditioning energy demand would be 45 times higher than current US consumption.

- **Vehicle air conditioning:** In China the number of air-conditioned vehicles has doubled in five years, and is expected to reach 100 million in 2015.[104] In the US, vehicle air conditioners are thought to consume 7–10 billion gallons of petrol per year, or 3.5% of US oil consumption in 2012.[105] If China were ever to reach the same levels of per capita vehicle and vehicle air conditioning penetration as the US, this alone would consume and extra 2.8 million barrels of oil per day – roughly two thirds of China's current oil production, or more than the entire output of Venezuela.[106] That would increase greenhouse gas emissions by roughly 440mtCO_2 per year.[107]

- **Cold chain:** Conventional 'bottom up' analysis of the world's refrigerated vehicle fleet suggests numbers may grow from around 4 million[108] today to around 9 million in 2025. Analysis by E4tech and Dearman found this could be a huge underestimate, however. Taking account of the demographic change in the developing countries discussed above, it found the fleet could grow to as much as 17.9 million vehicles to meet demand.[109] The upper end of this range could increase annual CO_2 emissions by around 180mtCO_2e to 230mtCO_2e in 2025.[110] In terms of toxic local air pollution, that would be the NO_x equivalent of almost 1.7 billion Euro 6 diesel cars, and the PM equivalent of more than 2.9 billion.[111]

- **Data centre cooling:** Global data centre energy consumption quadrupled between 2007 and 2013 to 43GW[112], and around half of data centre energy consumption goes on cooling. At the current growth rate, by 2030 the additional cooling load would require another 35GW in generating capacity – greater than that of Poland.[113]

At average global grid carbon intensity, that would raise data centre emissions from cooling only by around 190mtCO_2 per year to 300mtCO_2 per year in 2030.[114] McKinsey estimated in 2008 that total data centre emissions would quadruple to 340mtCO_2 by 2020 – overtaking the 2008 emissions from all energy consumption of Argentina and Malaysia combined.[115]

These examples are far from exhaustive and the calculations are broad brush. But taken together they suggest that if nothing is done, within fifteen years cooling will require an additional 139GW – more than the generating capacity of Canada – and raise greenhouse gas emissions by over 1.5 billion tonnes of CO_2 per year, three times the current energy emissions of Britain or Brazil.[116] If any of these examples sounds far-fetched, we should remember that something similar has already happened in the US, where in 2007 building air conditioning alone consumed almost as much electricity as the country had consumed fifty years earlier for all purposes – 484TWh versus 497TWh.[117]

Although growing demand for cooling in developing countries is likely to have the biggest impacts on the environment and health, the toll taken by existing demand in developed economies will also continue to grow, although at a slower pace. For example, the cumulative social cost of transport refrigeration in the EU – based on the damage costs of NO_x, PM and the abatement cost of CO_2 – will rise to €22 billion by 2025, according to a recent report from Dearman.[118]

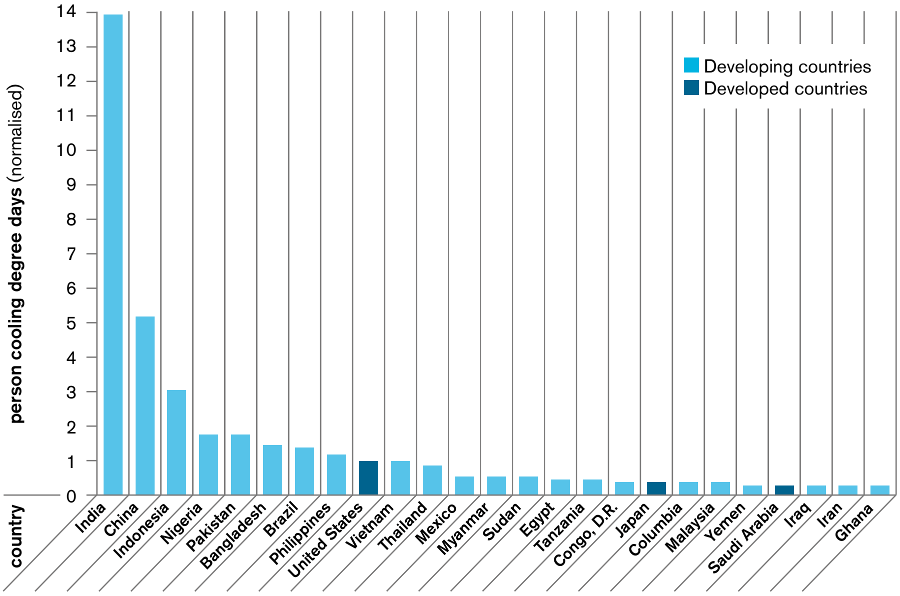


Figure 8: What if everyone consumed as much air conditioning as the US? Source: American Scientist[103]

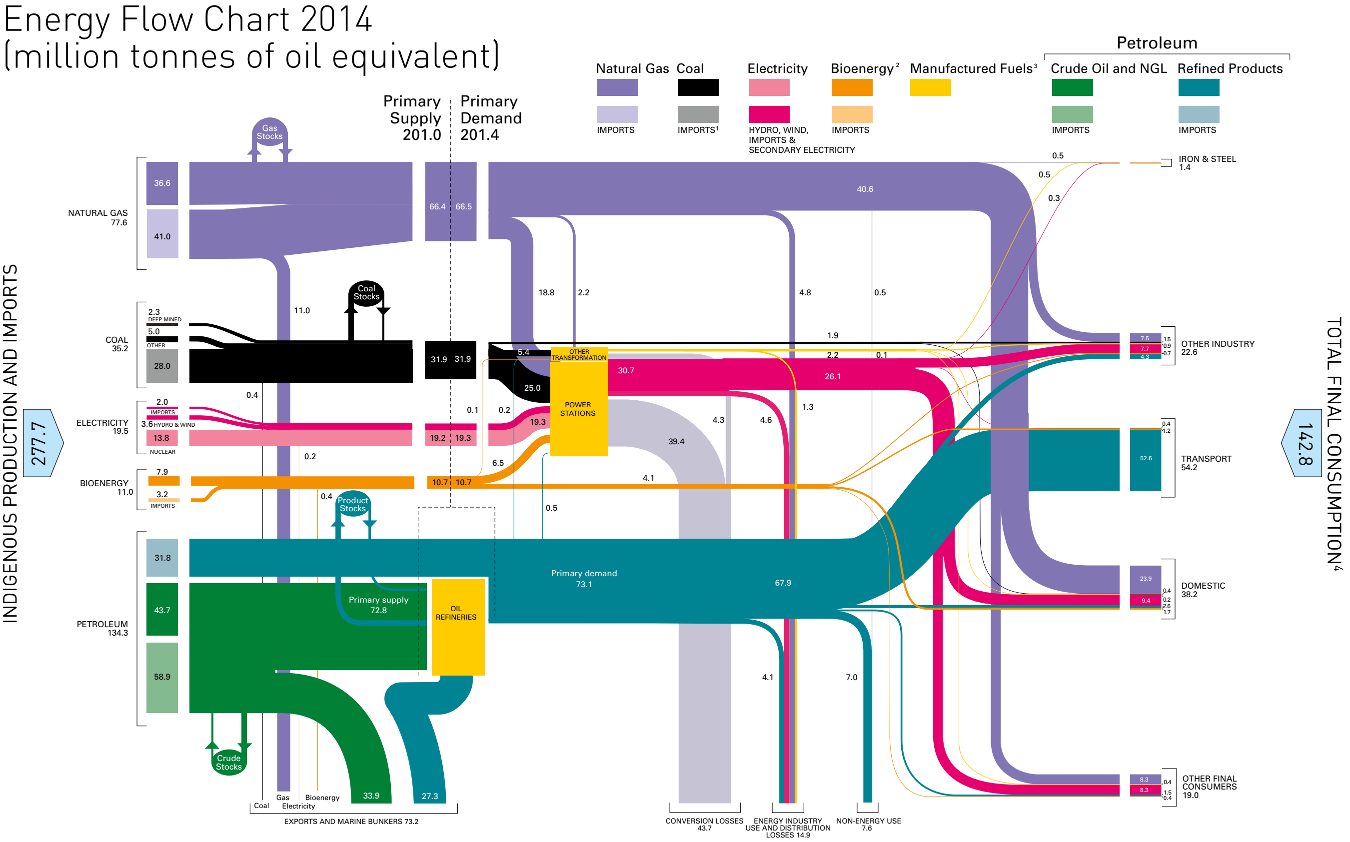
SECTION 2

WHY DOES THE PROBLEM PERSIST?

WHY DOES THE PROBLEM PERSIST?

Cooling may be vital, but it is also apparently invisible. Despite the damage it already causes to environment and human health, and the enormous threat posed by projected demand growth, it seems cooling has yet to appear on the radar. The public takes it for granted, the industry is conservative and the dominant technologies have scarcely changed in decades, and for most governments cold is still a largely strategy or policy-free zone.

Unlike electricity, transport and heat, cold has received very little attention from policymakers to date. Hard data on cooling energy demand is not collected, and cooling appears nowhere on the official Sankey diagram of the UK energy system (see below). Britain has a Renewable Heat Incentive but no Renewable Cold Incentive, and the European Commission is only now beginning to develop a Heating and Cooling Strategy. But perhaps the most troubling aspect is the low level of public funding for research and development into cold.


Energy Flow Chart 2014
(million tonnes of oil equivalent)

FOOTNOTES:
1. Coal imports and exports include manufactured fuels.
2. Bioenergy is renewable energy made from material of recent biological origin derived from plant or animal matter, known as biomass.
3. Includes heat sold.
4. Includes non-energy use.

This flowchart has been produced using the style of balance and figures in the 2015 Digest of UK Energy Statistics, Table 1.1.

Department
of Energy &
Climate Change

Figure 9: Sankey diagram of UK energy system. Cold is not represented. Source: DECC[119]

Research and development funding

A recent white paper entitled *A global Apollo programme to combat climate change* complained that renewable energy receives less than 2% of global public R&D funding, which it found 'totally astonishing' in view of the gravity of climate change. But the situation in cold is arguably even worse. In Britain over the past decade, 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, an order of magnitude lower, despite the fact that cooling is by one estimate responsible for 10% of all CO_2 emissions.[120] Across the EU as a whole, annual public RAC R&D funding has averaged £23.5 million per year or 0.22%. These levels of funding clearly fall far short of matching the environmental and economic importance of cooling.

In Britain, 70% of public R&D funding for cooling comes through the Engineering and Physical Sciences Research Council (EPSRC), and amounts to £1.58 million, just 0.19% of its total £815 million annual funding. Total EPSRC funding for its energy theme amounts to £677.3 million and there are 424 grants associated with the theme.[121]

Energy research funding is divided into several subthemes including conventional generation; energy efficiency; fusion; nuclear power; power networks; renewable energy; socio economic and policy; underpinning energy research and sustainable energy vectors. But cooling is nowhere to be seen. So not only is funding for cooling research vanishingly small, but the subject is omitted altogether in the EPSRC's energy mapping. There is no recognition here that thermal energy, both hot and cold, is one of the major energy challenges.

Funding body	**Total funding available (p.a.)**	**Average RAC funding (p.a.)**	**% of total funding**
EPSRC	£815m	£1.58m	0.19%
Carbon Trust	£50m	£0.39m	0.78%
Defra	£250m	£0.16m	0.06%
KTP	£60m	£0.06m	0.1%
Other UK	Unknown	£0.04m	-
Total UK	**£1.175 billion**	**£2.23m**	**0.19%**
EU	£10.7 billion	£23.5 m	0.22%

Table 1: Public research funds for Refrigeration and Air Conditioning. Source: LSBU.

At higher Technology Readiness Levels (TRLs), the key publicly funded sponsor of technology development is InnovateUK. Here too cooling scarcely features. An analysis of projects funded between 2004 and 2015[122] suggests just 1% of projects were principally about cold, cooling or refrigeration – even when generously defined – and only 0.12% of projects listed refrigeration as part of its objectives. It is clear that across the TRLs there is a serious under investment in low temperature technology and products.

The British Government has to its credit begun to recognise the importance of research and development in this field, committing material public funds to 1) the Thermal Energy Research Accelerator (T-ERA), with its focus on hot and cold thermal energy technologies, manufacturing and skills, and fundamental research, as part of the broader Energy Research Accelerator (ERA) programme, 2) the new Birmingham Centre for Cryogenic Energy Storage, founded as part of the government's 'Eight Great Technologies' initiative, and 3) a number of important commercial R&D projects. Yet total R&D investment, both here and abroad, falls far short of the economic and environmental weight of cooling.

RACHP sector	UK	Europe	Source
Air Conditioning	£0.7 billion	£8 billion	[BSRIA, 2008; ACHR News, 2008]
Commercial	£0.7 billion	£5.2 billion	[Bio-Intelligence, 2011]
Industrial	£0.35 billion	£2.3 billion	Own estimate
Transport	£0.2 billion	£2 billion	Own estimate
Domestic	Unknown	£0.04m	-
Heat pumps	£0.9 billion	£2.23m	0.19%
£59 million	£9 billion	£23.5 m	0.22%
€6.1 billion	[Euromonitor, 2013]		
[REHVA, 2012; BSRIA, 2010]			

Table 2: Market values per annum for the main sectors of the RACHP industry. Source: IOR[124]

Industry and innovation

Innovation is held back not only by the low level of public funding for R&D, but also by the structure of the cooling manufacturing and service sector. In Britain this is substantial, with 100,000 employees and estimated turnover of £3 billion per year[123] (see Table 2 above), but it is also fairly atomised. There are 13,000 firms of which 90% employ fewer than ten people. The market is competitive and margins are low, which limits the appetite and capacity for innovation, according to Professor Judith Evans of LSBU.

Not that Britain is short of good ideas for clean cold innovation – far from it. The Commission took evidence from a variety of companies developing technologies that could radically improve the efficiency of many forms of cooling.

- Camfridge, for example, is a spin-out from the University of Cambridge developing a novel magnetic cooling cycle that dispenses with refrigerant gases, which the company claims will raise the energy efficiency of domestic fridges by 40%.[125]
- Simply Air has developed a system to refrigerate supermarket display cabinets that makes use of cool air from outside, which it says reduces energy consumption by 25% in the British climate, and far more in colder ones.[126]
- Iceotope is working on a data centre cooling system that replaces air cooling with a system in which servers are immersed in a non-conducting polymer liquid, increasing performance by 40% and reducing energy and infrastructure costs.[127]

A lorry with a liquid air powered Dearman TRU providing cooling.

Camfridge's solid-state cooling solution for domestic refrigerators. Image courtesy Camfridge.

A drinks fridge employing Surechill's novel cold storage system. Image courtesy Surechill.

A retail refrigeration unit employing Simply Air refrigeration. Image courtesy Simply Air.

A number of servers mounted in a rack cooled with Iceotope technology. Image courtesy Iceotope.

- Sure Chill, a Welsh company, has developed a fridge that keeps its contents cool at a steady 4C for days or weeks without power through an ingenious energy storage system based only on ice and water. This means it works particularly well with solar panels or in countries with erratic grid electricity and is ideal for protecting vaccines in remote rural areas.[128]
- Dearman is in commercial trials of a piston engine driven by the phase change expansion of liquid air or liquid nitrogen for a variety of applications, the first of which is a highly efficient transport refrigeration unit that delivers both cooling and power from the same tank of cryogen. The technology recently won the Innovation Award at the Cooling Awards 2015.

Yet many of these companies are struggling to get their products to market or to expand. They and other expert witnesses cite a range of barriers, including a lack of grant funding at early stages; a lack of large scale demonstration facilities to prove technologies at scale; a lack of facilities and funding to develop the necessary manufacturing processes to commercialise products. Perhaps the most commonly cited barrier was the fixation of potential customers with capital cost rather than lifecycle cost. **In other words, if the developer could demonstrate that its product would save the customer money over its lifetime, but the up-front cost of buying it was higher than that of the incumbent technology, then no deal.** In transport refrigeration, this problem is exacerbated by the fact that the incumbent, highly polluting diesel TRU is subsidised through the use of duty-free red diesel in countries including Britain, Belgium, France and Spain.

Dearman Engine Laboratory at the University of Birmingham.

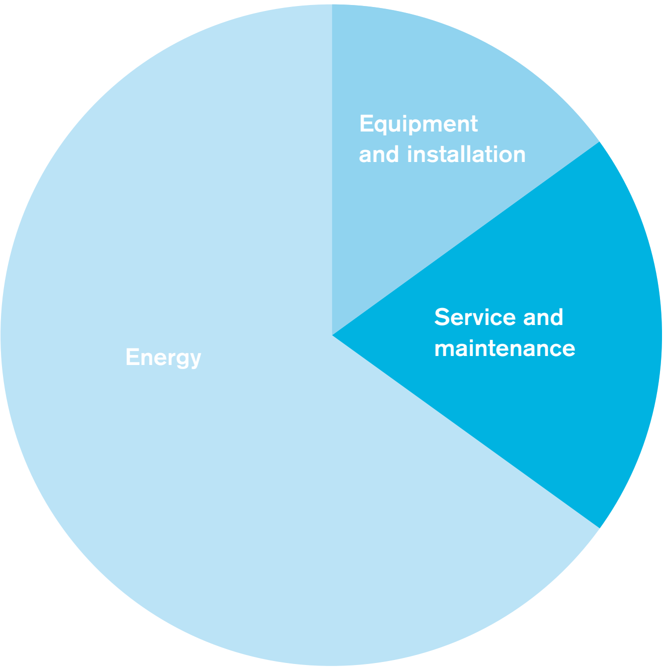


Figure 10: Total cost of ownership for refrigeration and cooling equipment: Source: Carbon Trust[130]

End users

A fixation with capital cost not only hinders the uptake of innovative technologies that may be perceived as riskier, but also that of well established products that would also deliver substantial energy and financial savings. This is often despite the fact that many cooling devices have operating lives of 10 years or longer, and energy will often be the overwhelmingly dominant cost on a lifecycle basis. A Carbon Trust study found that refrigeration systems typically cost seven to ten times as much to run over their lifetime as they do to buy (see Figure 10 above).[129]

An audit of cold storage facilities, for example, showed average potential energy reductions of 28% could be achieved on the basis of behaviour change, improved maintenance and off-the-shelf technologies only (see Figure 11).[131] The highest efficiency achieved by vapour compression refrigeration is 60%, but the average achieved is just 30%.[132] Although we have not conducted an exhaustive audit of cooling technologies, it seems likely that similar potential efficiency gains will be available in other applications. Some could simply be imported: Japanese air conditioning units are almost twice as efficient as European models (see Figure 12).

Some large users of cooling such as Britain's supermarkets do regularly trial new technologies, however, and some have improved the performance of their cooling significantly in recent years.[135] And so they should: we estimate they consume around 3.6TWh of electricity per year for cooling alone, or about 1% of UK electricity demand.[136] The Carbon Trust's Refrigeration Road Map presents scores of detailed suggestions of how supermarkets can improve the energy and emissions profile of their cooling through retrofitting in existing stores, or during store re-fits or while building new stores.[137] But supermarket cooling remains dominated by conventional vapour compression cycles, and competitive pressures sometimes prevent the adoption of some simple but effective measures: in a typical store, 85% of the cooling energy is consumed by chilled display cabinets, and installing doors would reduce this by 30% at a stroke, but supermarkets resist the change because it reduces impulse buying.[138] In other EU countries the fitting of doors on refrigerated cabinets is already mandatory.

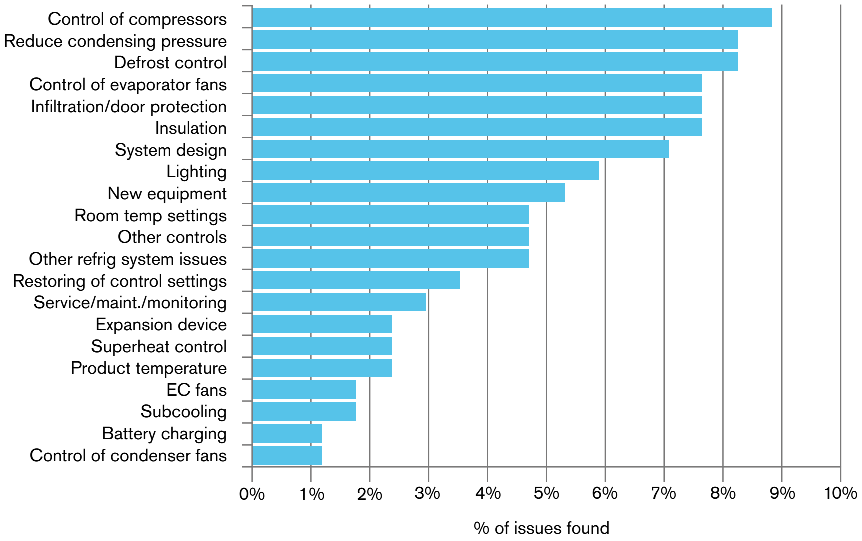


Figure 11: Potential to improve the efficiency of cold stores. Source: LSBU[133]

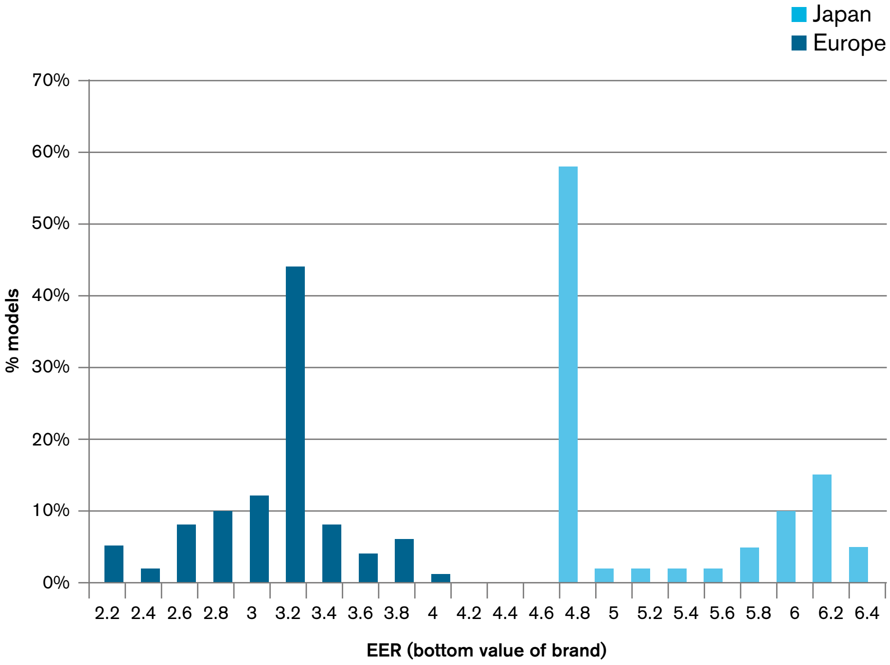


Figure 12: Coefficient of Performance (energy efficiency) of air conditioning units in Japan and Europe. Source: SIRAC[134]

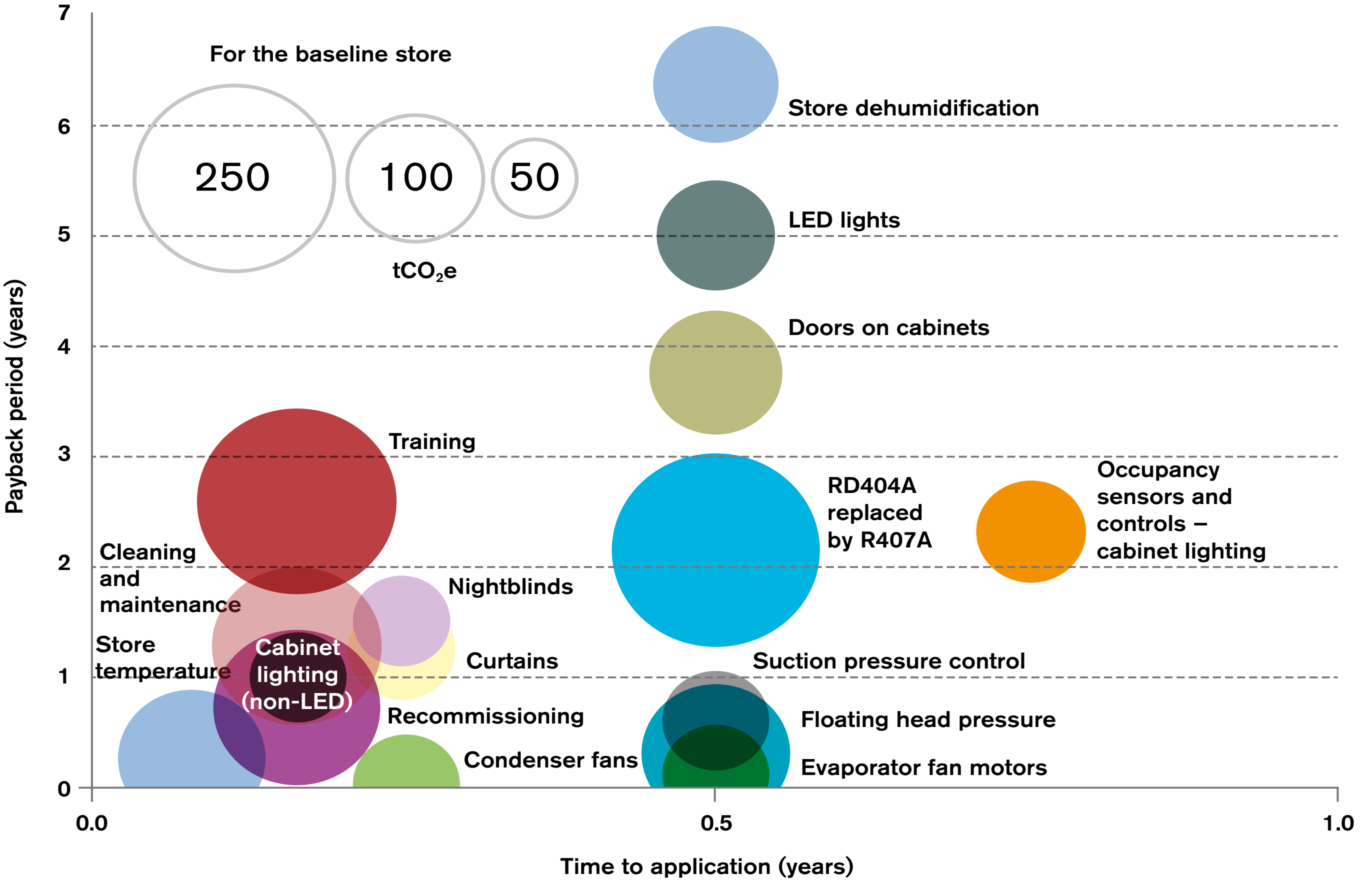


Figure 13: Results from the Carbon Trust Refrigeration Road Map. Source: Carbon Trust[139]

Problems of poor maintenance, customers' fixation with capital rather than lifecycle costs, and the consequent failure to adopt the most energy-efficient technologies, might be overcome if the industry were to adopt innovative business models such as 'product service systems' or 'functional sales', in which the manufacturer no longer sells physical equipment, but the services provided by that equipment. This gives the supplier an incentive both to develop efficient technologies and to maintain their products throughout their lives.

Examples of this approach are becoming more common across industry: Rolls-Royce no longer sells aero-engines,but miles in the air; Xerox sells photocopiers on a pay-per-page basis; and Atlas Copco offers a 'Contract Air Service' under which compressors are sold according to the quantity of compressed air delivered. But this approach is rare in the cooling industry, perhaps because of a generally conservative business culture.

WHERE DO WE GO FROM HERE?

While there are clearly large potential efficiency gains to be made by changing behaviours, investing in best-in-class technologies and inventing new ones, the chances of success must be seen in the context of three major issues.

First, cooling is not yet part of our thinking about how to make energy more sustainable and resilient. It is typically viewed as just another source of demand for electricity, rather than the start point being the service we require.

Second, there are major barriers among customers to both innovation and investment in efficiency, as discussed above, which clearly need government intervention to solve.

Third, even if all the barriers were cleared tomorrow, the sheer scale of future demand growth, especially in the developing world, looks likely to swamp any improvement in the environmental performance of traditional cooling technologies. If we assume for the sake of argument that the average efficiency of cooling worldwide could be doubled through smart investment and innovation, but the fuel sources remain the same, the reduction in emissions would still be utterly overwhelmed by, for example, the projected 33-fold increase in air conditioning energy demand this century.[140] Most of the growth will come in developing countries, which may be under even greater pressure to keep capital costs down and opt for conventional, highly polluting technologies promoted by well-entrenched incumbents.

THERE SEEMS TO BE AN IMPLICIT ASSUMPTION AROUND COOLING, IN COMMON WITH OTHER SECTORS SUCH AS TRANSPORT AND HEAT THAT MUCH OF THE HEAVY LIFTING OF EMISSIONS REDUCTIONS WILL BE ACHIEVED THROUGH DECARBONISATION OF ELECTRICITY

Finally, there seems to be an implicit assumption around cooling, in common with other sectors such as transport and heat, that much of the heavy lifting of emissions reduction will be achieved through decarbonisation of electricity. We question this assumption, because electricity decarbonisation will clearly be a multi-decade effort – particularly in some developing economies – and there is a huge amount of existing electricity demand to be satisfied before there is any 'spare' green electricity to supply incremental loads. This point was argued forcefully during our deliberations and accepted by the Commission. It is yet another reason why the primary energy consumption of cooling cannot be allowed to rise in line with projected demand.

We therefore conclude that while some technology developers are striving to bring radical, service driven, energy thoughtful products to market, there is an urgent need not only for government intervention to break the current log-jam, but also to catalyse a radically more efficient approach to cooling based on system-level thinking and the better recycling of waste or thermal resources, which has recently been coined the 'Cold Economy'.

WE QUESTION THIS ASSUMPTION, BECAUSE ELECTRICITY DECARBONISATION WILL CLEARLY BE A MULTI-DECADE EFFORT.

SECTION 3

DOING COLD SMARTER: THE COLD ECONOMY

DOING COLD SMARTER: THE COLD ECONOMY

A new framework

In evidence to the Cold Commission, the sustainable energy consultancy E4tech outlined its analysis of a new approach to greening cold developed by Toby Peters, Visiting Professor in Power and Cold Economy at the University of Birmingham, and the founder and CEO of Dearman. This stressed the importance of approaching the problem not simply in terms of the efficiency of individual technologies or applications, but of developing a *system-level* view of the production, consumption and wastage of cold, and understanding how this can relate to the wider energy system. Only then could we start to think about harnessing waste resources – of cold, heat and 'wrong-time' energy – to achieve dramatic reductions in the energy and environmental footprint of cooling. This approach is coined the 'Cold Economy'.

None of this is to decry the value of research, development and investment to improve existing cooling technologies, and develop new ones, but to place all these activities in a framework that allows us to capture far larger gains than are currently foreseen. For example, analysis commissioned from E4tech found that cooling in Britain has an overall Coefficient of Performance (or CoP, the ratio of cooling work performed to the energy consumed to achieve it, see Box) of about 1.6, making the system as a whole roughly half as efficient as a modern domestic fridge, with a CoP of 2.8. But if half the waste cold from projected imports of LNG were recycled, the UK system-wide CoP could be raised to 13. While capturing anywhere near half of this waste cold this would be impossible in practice, the comparison does illustrate the scale of the potential. Raising the system-wide efficiency to the level of a domestic fridge would roughly double Britain's cooling CoP; exploiting all the country's waste cold would raise it by almost an order of magnitude (from 1.6 to 13). Cooling system efficiency could also be raised through the recycling of waste heat, and its environmental impact reduced by the use of wrong-time energy (see The potential of untapped resources, page 22). There is a clear case to evaluate whether wrong-time energy could be better used directly for making and storing cold, where cooling is the service required, rather than creating an intermediary step of storage in a battery to then drive a vapour-compression cycle.

Measuring cooling efficiency

The efficiency of a cooling device is measured by its Coefficient of Performance or CoP. A new domestic fridge of average efficiency has a CoP of around 2.8. This means it can remove 2.8kWh of heat from its contents while consuming only 1kWh of electricity. On the face of it, an efficiency of 280% appears to break the laws of thermodynamics, but this is deceptive. The fridge is not converting the electricity it uses directly in to heat or cold. Rather it is using a thermodynamic cycle, involving the compression and expansion of a refrigerant gas, to push heat 'uphill' from a cold reservoir (the inside of the fridge) to a slightly warmer reservoir (the room). Because the heat must be pushed 'uphill' the transfer requires work, performed by an electric-powered compressor. For the small hill between the fridge and the room the amount of work needed to push the heat is less than the amount of heat that is transferred, resulting in a CoP greater than 1. The CoP of a refrigeration cycle can be increased further if energy consumption is reduced by integrating waste cold or heat.

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 'what source of energy is closest to hand and how can we convert it into what we need'. 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 evidently sub-optimal. 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 Cold Economy is also about looking at the entire environmental footprint of cooling – including carbon dioxide, refrigerant gases and toxic local air pollution – and doing so can lead to different conclusions. For example, the Commission heard that some companies are replacing high GWP refrigerants with CO_2 which has a GWP of 1, and is on the face of it far more environmentally benign. But CO_2 requires greater pressure to operate as a refrigerant than F-gases, meaning the emissions from increased energy consumption can outweigh the reductions gained from switching refrigerant. The Cold Economy is about making sure we do not swap one problem for another, or inadvertently worsen the problem we were trying to fix.

The first step – as with any energy or environmental hierarchy – is to reduce demand, in this case the cooling work that needs to be done, rather than to develop new technologies to supply additional cold. This could involve measures such as energy-efficient buildings, passive shading, computers that need less cooling, vaccines that survive ambient temperatures. The next step – offering good quick wins – is to reduce the energy required to do the remaining work, by raising the efficiency of cooling technologies, through measures such as improved maintenance and innovation.

The third step – the step-change – is to start to recycle waste and under-utilised resources – not just the waste cold of LNG, but waste heat, 'wrong-time' renewable or nuclear energy, and geothermal. This in turn requires energy storage to allow cold to be generated off-peak but consumed at peak times – or indeed moved (cold in motion), or used in transport applications. The key insight here is that energy can be stored efficiently in the form of cold rather than as energy in a battery. Step three represents the beginnings of the Cold Economy. The final step is then to convert the remaining primary energy requirement to low carbon sources. This approach could be broadly described as 'doing cold smarter', and can be summed up as:

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

2. **Reduce the energy required for cooling:** ie increase the efficiency cooling technologies – eg. cold stores could raise efficiency by an average of 30% using off-the-shelf solutions only[141] – 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 the buildings and transport;
   b. Cold energy storage to warehouse and shift wrong-time energy to replace peak electricity demand and diesel consumption in built environment and transport applications.

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

The primary focus of the rest of this report will be steps two and three, since the other elements are broadly understood, whereas nobody has previously investigated the system-level efficiency of cooling, and early work commissioned from E4tech suggests the gains from a Cold Economy approach are potentially huge. Another reason to focus on step three, the Cold Economy, is that even after all efforts have been made on steps one and two, we believe demand for cooling will continue to grow strongly, as a result of the factors discussed in Section 1. The final reason to focus on step three, is that much of the cold demand is going to come from new 'smart' cities yet to be built, and we have the chance to develop cold into properly planned and integrated energy systems.

Cold Economy

The Cold Economy is a new *system level* approach to cooling. If we invest in reducing cooling loads, harnessing renewable and 'waste' resources, and implementing novel clean cold technologies, we can reduce the electrical load and emissions, improve energy security and cut costs. These benefits accrue not just to the owner or user of cooling technology but across the value chain and energy system, so need need to be quantified and represented in system-level models. Key beneficiaries include transport, food, buildings, industry, energy and health.

A key aspect of the Cold Economy is energy resilience through better integration of renewable generation or natural resources with thermal energy storage and reduction in demand for peak-time electricity. The starting point is to understand the demand for cold across both transport and built environment and specifically district co-located cold users.

Features of the Cold Economy include:

- A service-oriented perspective, i.e. Consider cooling needs from a different perspective: What is the service I need: to keep cool in summer; to provide a cold chain for food *as opposed to provide electricity or diesel for cooling*?
- An energy system view that incorporates cold / thermal flows
- How can portfolio deployment of technologies best help a business or co-located group of businesses with potentially synergistic cooling demands (or indeed balance thermal loads across?)
- How can we use cooling demand (built environment and transport) as part of demand-side management solutions: grid buffering and stabilisation, district heating / cooling; system-level waste heat/cold recovery, storage and movement of wrong-time energy?
- Is there opportunity for LNG import terminal waste cold optimization? What is the most valuable use of the waste cold from the import terminal's perspective? How do you generate volume demand to justify capital investment and also harness the volumes of waste cold available?

These features help achieve:

- Reduction in cooling demand
- Greater integration between thermal and waste cold resources and cold needs
- Spatial and temporal balancing of dynamic needs
- Storing and moving cold to meet cold needs
- Use of more efficient technologies, materials and practices for meeting cold needs
- Use of cleaner energy to serve cooling energy demands

Benefits of the Cold Economy include:

- Meeting cold needs in a more resource efficient way
- Energy resilience
- Environmental benefits including reduced GHG emissions and improved air quality
- Lower overall cost
- New business opportunities and jobs

What would the Cold Economy look like?

Reducing the impact of existing technologies

The impact of existing cooling technologies can be reduced either by increasing their coefficient of performance (CoP, or efficiency) and so reducing the amount of energy consumed per unit of cooling, and/or by reducing the impact of refrigerant gases (so long as this does not worsen energy and emissions performance overall). This in turn can be achieved either by reducing leakage rates or reducing the global warming potential (GWP) of F-gases, or both. Taken together these actions constitute 'Step 2' of the Cold Economy hierarchy (above).

In Section 2, *Why does the problem persist?,* we identified several serious barriers to the adoption of readily available technologies and practices that could reduce emissions and cost substantially, and in Section 6, *Policy recommendations,* we suggest actions the government could take to clear them. If adopted, such measures could invigorate the take-up of existing technologies to achieve substantial incremental reductions in energy consumption and emissions. In cold stores, for example, potential energy reductions of 28% could be achieved through off-the-shelf technologies solutions only[142], and it seems likely that similar potential efficiency gains will also be available in other applications: Japanese air conditioning units are almost twice as efficient as European models, for example.

Substantial work is already going on to replace high-GWP refrigerant gases with lower- or zero-GWP alternatives such as ammonia, carbon dioxide, hydrocarbons and hydrofluoro-olefins (HFOs), and progress has been made at supermarkets in the UK, Europe and beyond. In Britain, the Co-op uses HFC-free cooling for 23% of its refrigeration, for example, Waitrose 36%, and Marks & Spencer is using natural refrigerants in 84 stores.[143] The pace of change should now accelerate with the introduction of new EU regulations earlier this year that will reduce the volume of high-GWP F-gases available to scarcely 20% of current levels by 2030, and which should help increase the production and reduce the cost of natural refrigerants.

Progress on F-gases will only increase the importance of tackling the energy consumption and emissions of cooling, however. Academics at LSBU estimate that energy accounts for around 75% of cooling emissions, compared to 25% for F-gas leakage, and the impact of the EU F-gas phase-down raise the energy share to over 90% of the sector's GHG emissions.[144] This suggests to us that while work on F-gases is important and must continue, the higher priority is now to tackle energy emissions of cooling through system-level analysis, the recycling of waste heat and cold and wrong-time energy, and the development of entirely new cooling cycles that eliminate refrigerant gases altogether.

This leads naturally to Step 3 of the Cold Economy hierarchy in which cooling is integrated with sources of waste cold; waste heat; 'free' cooling from air, water and ground; and renewable energy. Making the most of these sources requires new ways of moving cold, and one recent suggest we explore below is liquid air.

Recycling waste cold

A key feature of the Cold Economy would be to recycle waste cold to reduce the environmental impact and cost of cooling demand. By far the largest source or waste cold in Britain is that given off by the re-gasification of LNG at import terminals, as explained in Section 1: *The potential of untapped resources.* But the British LNG waste cold resource is dwarfed by that of developing countries such as India and China, where capacity is far greater and used more continuously, which could represent a major export market for technologies designed to exploit it. Some LNG import terminals do put some of their waste cold to use in so-called 'over-the-fence' applications, such as cooling the inlet air of a nearby gas-fired power station to increase its efficiency, or providing chilled water for industrial cooling. The problem with this is that the customer for the cold can only obtain large quantities when the import terminal is actually re-gasifying LNG and at some terminals, like the Isle of Grain in Kent, re-gasification has been infrequent – although 'boil off' gas is produced continuously, and at Grain this alone would be sufficient to drive a 350tpd air liquefier.[145]

Liquid air or nitrogen as a cold energy vector

Air can be turned into a liquid by cooling it to around −196°C in an industrial Air Separation Unit (pictured) 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 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 main text).

Liquid air provides an energy vector for storing and is valuable in applications where cold and power are required. Image courtesy: University of Birmingham

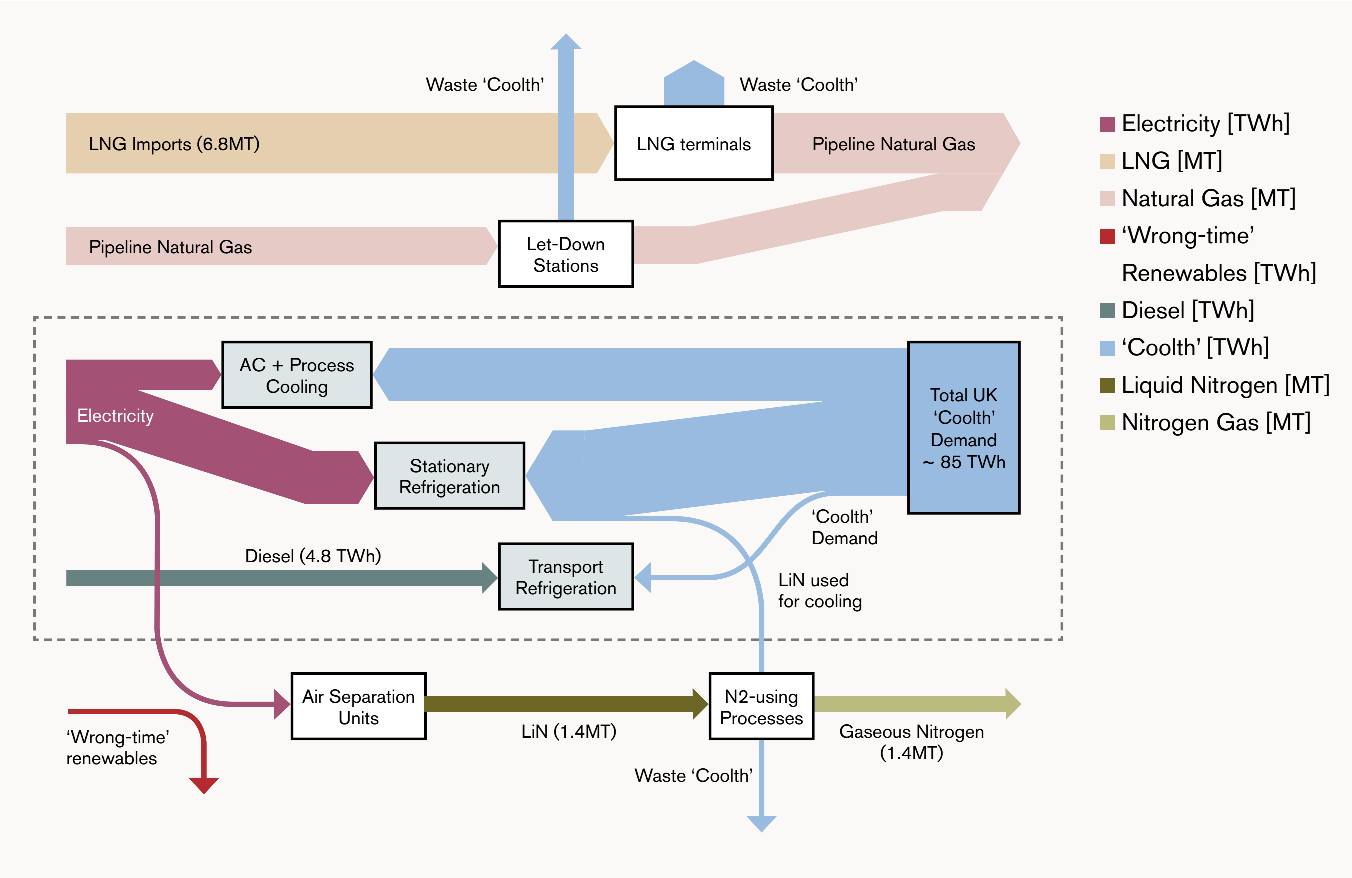


Figure 14: UK cooling energy system – current situation. Cooling system CoP is just 1.6, and operating costs are about £5.2 billion per year. Source: E4tech, ©Dearman

This constraint could be overcome with storage of cold in – for example – tanks of gravel, to give the customer more continuous supply. Even so, the cold would still only available in the immediate vicinity of the LNG terminal; gravel has excellent cold storage properties, but is hardly portable. Yet the largest sources of demand for cooling are highly dispersed – domestic refrigeration, office air conditioning, industry, refrigerated vehicles – and typically some distance from the LNG terminal. What's needed to make best use of LNG cold is a storage medium or 'vector' that is not only effective but also transportable. One recent suggestion has been liquid air or liquid nitrogen (see box).

Liquid nitrogen is already widely available from industrial gas producers, who have substantial spare production capacity (see Box). But these cryogens could be produced even more cheaply by building air liquefiers at LNG import terminals and integrating the waste cold from LNG re-gasification. The cold given off by LNG as it boils at –162°C could then be recycled to help produce liquid air at –194°C or nitrogen at -196°C, reducing the electricity required by about two thirds, and the cost by about half.

Waste LNG cold is already used to produce liquid nitrogen at a terminal in Osaka in Japan, and if practised more widely – and used as a vector to store and move cold and power – could become a key element of the Cold Economy. The LNG waste cold resource should grow significantly in future since the global LNG trade is expected to double to 500mtpa by 2025.[146]

Figure 14 above illustrates the energy flows in the UK cooling system as they exist today, and Figure 15 illustrates the potential energy and cost savings that could be obtained if the current recoverable waste cold (only half the actual resource) from LNG and gas let-down stations were recycled to help satisfy demand. The efficiency of cooling in Britain would rise from a CoP of 1.6 to 2.8, and operating costs would be reduced by around £1 billion or 20%. On the basis of projected LNG imports in 2030, system CoP would rise to 13.

Clean cold technologies are already being developed to run on liquid air or nitrogen. Dearman, for example, a British technology developer, 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. A recent report from the company, *Liquid Air on the European Highway*, found that waste cold from EU imports of LNG in 2014 could in principle provide over 27,000 tonnes of liquid air or nitrogen per day, enough to fuel refrigeration on almost 210,000 vehicles – equal to the entire projected German refrigerated fleet in 2025. It also found that 10 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. In principle, recycling just half waste the cold from the projected global LNG trade in 2025 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.[147]

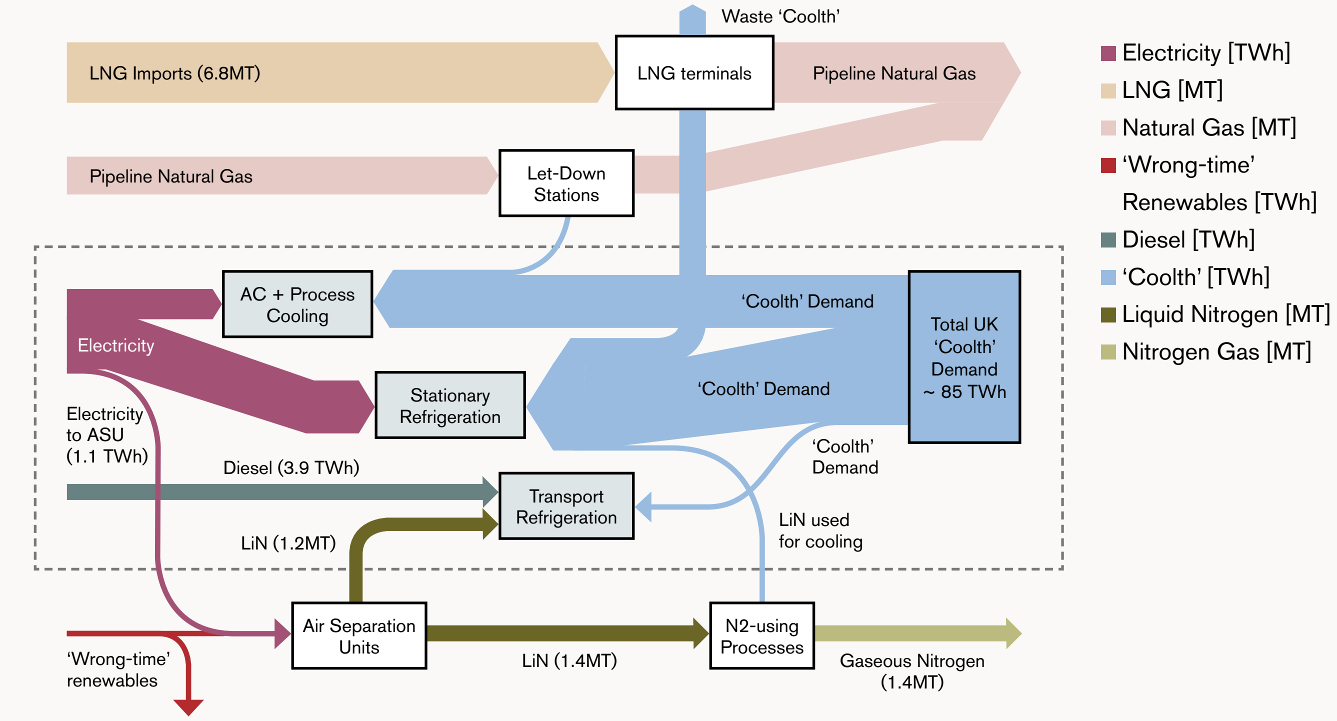
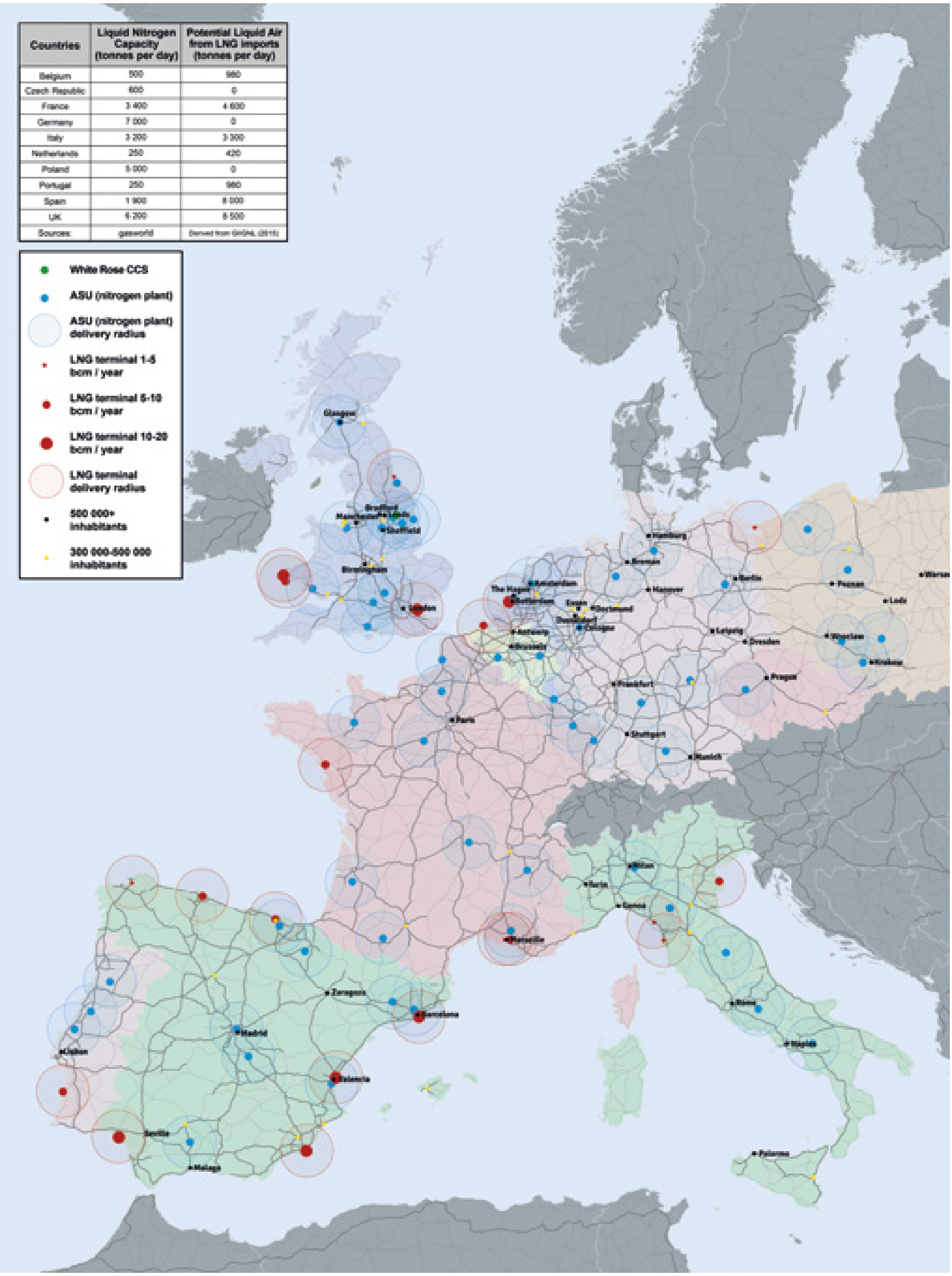


Figure 15: UK cooling energy system as it could be if waste cold from LNG re-gasification and gas pipeline let-down stations were recycled. Cooling system CoP rises from 1.6 to 2.8, and annual operating costs are reduced by £1.1 billion to £4.1 billion. Source: E4tech, ©Dearman



Countries	Liquid Nitrogen Capacity (tonnes per day)	Potential Liquid Air from LNG imports (tonnes per day)
Belgium	500	960
Czech Republic	600	0
France	3 400	4 600
Germany	7 000	0
Italy	3 200	3 300
Netherlands	250	420
Poland	5 000	0
Portugal	250	960
Spain	1 900	8 000
UK	6 200	8 500
Sources:	gasworld	Derived from GIIGNL (2015)

Liquid nitrogen production sites and LNG import terminals. Source: Dearman[148]

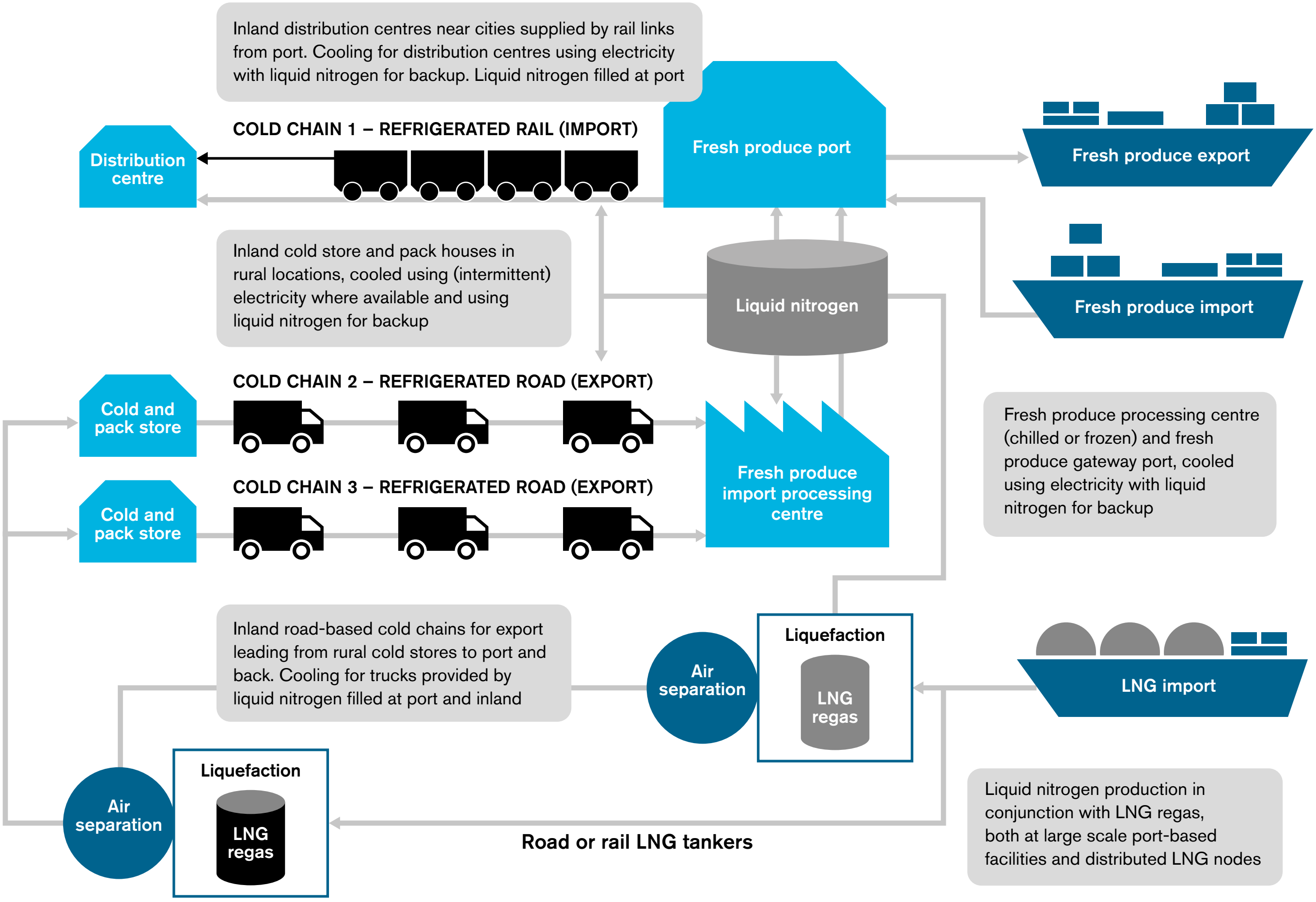


Figure 16. How waste cold from LNG re-gasification could power the 'Cold Economy' in India. Source: ©Dearman/E4Tech[151]

LNG waste cold potential in developing countries

In developing countries where energy demand is growing strongly, LNG import terminals are proliferating and are more likely to be used continuously as part of the country's baseload supply, meaning the available waste cold would be massively greater than at terminals such as the Isle of Grain in the UK. China is expected to be importing more than 60mtpa of LNG by 2020[149], for example, and India, with four LNG import terminals, is forecast to expand its import capacity from 25mtpa to 32mtpa – and a further 18 terminals have been proposed.[150] The idea of developing cold chains powered by waste cold from LNG re-gasification is now being pursued in India, where Petronet LNG recently invited expressions of interest from companies to help it develop an integrated cold store facility at its LNG import terminal at Dahej, Gujarat. The concept has already been explored by India's National Centre for Cold-chain Development (NCCD), following a report from the IMechE and with the help of analysis from Dearman and E4tech.

Other applications of LNG-assisted liquid air or nitrogen

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 low-cost liquid nitrogen made using LNG waste cold could solve both problems.

In countries with unreliable electricity grids, liquid air or nitrogen could also provide backup power and cooling for data centres, hospitals and other buildings with an absolute requirement for uninterrupted power and cooling. This 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 (see *Section 1: Feedback loops*). Conventional vapour-compression air conditioning systems work by expelling heat into their immediate surroundings, but for cryogenic cooling systems the only exhaust is clean cold air; most of the heat was expelled in Qatar or Australia when the LNG was produced. As a result, cryogenic cooling would tend to mitigate the heat island effect rather than reinforce it, reducing the load on other cooling systems nearby.

Not just liquid air – new materials and vectors

Liquid nitrogen is clearly not the only way to store and transport cold – although it does 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. It 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.

Yet liquid nitrogen is an accidental energy vector – an existing industrial product put to a new use – and the potential of the Cold Economy could be greatly enhanced if we developed new vectors with even greater cold energy density. Rather little research has been done in this area until recently, but the government has funded the new Birmingham Centre for Cryogenic Energy Storage (BCCES), led by Professor Yulong Ding, to pursue fundamental research into new cold storage materials with greater energy storage density and commercial life-spans, discharge and recharge speeds, and cost.

Other uses of LNG cold

Distributed LNG

Producing liquid air or nitrogen at LNG import terminals is not the only way to recycle LNG waste cold. Instead of re-gasifying LNG and feeding into the natural gas grid, it can be distributed by road tanker; National Grid Grain LNG opened a two-bay road tanker loading facility earlier this year.[152] And a Finnish company called Skolkovo has developed a system of distributing LNG in standard-sized shipping containers, called LNGTainer[153], meaning LNG can now be transported using standard container ships and terminals. Both forms of distribution mean that LNG can reach a far wider range of potential customers, and its waste cold can be applied directly to smaller-scale applications alongside the burning of the gas for power.

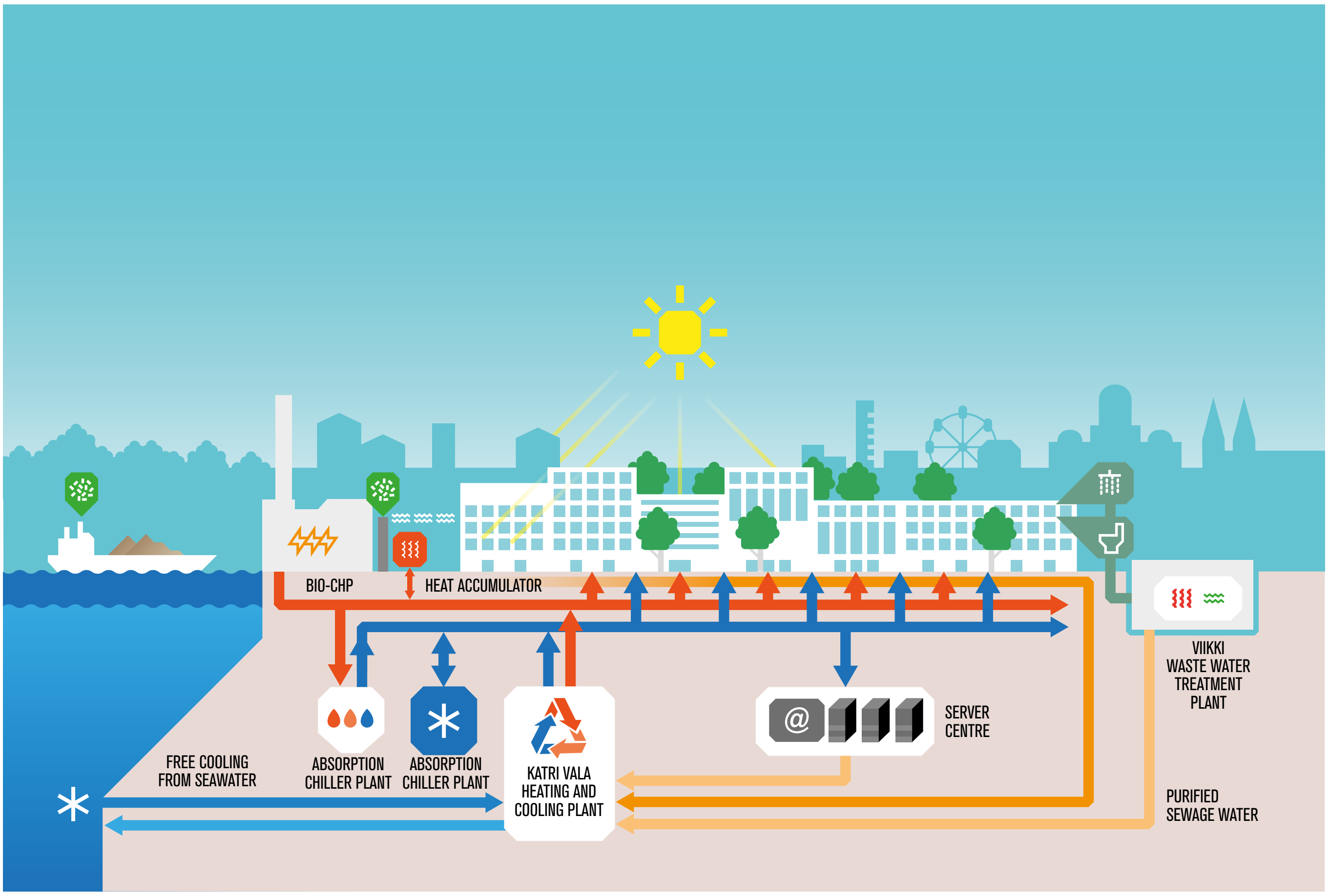


Figure 17: Tri-generation: district heating, power and cooling. Source: Stratego

Cold from waste or renewable heat

Tri-generation

The Cold Economy means not only integrating cold loads with waste cold, but also waste heat. This is already beginning to happen with the spread of district energy systems based on 'tri-generation', found extensively in Scandanavia, but also other European cities including Paris and Barcelona. In Britain, Cofely, the energy services subsidiary of Engie (formerly GDF-Suez), runs district energy schemes with cooling in Birmingham, Southampton and in London, the Olympic Park and Excel Arena.

The idea of Combined Heat and Power (CHP), where a small local gas or biomass generator provides both electricity and district heating from the generator's waste heat, is now commonplace. Tri-generation adds another layer of efficiency by providing cooling too. Cold is produced either from the waste heat of the generator through an absorption chiller, or sources of 'free' cold – river or sea water, and outdoor air in cooler climates or seasons – or in the last resort from high-efficiency electrical chillers, which are more efficient than small scale air conditioners. The cooling is then distributed to local buildings by a network of pipes carrying cold water.

This arrangement is even more efficient than CHP, and significantly reduces the environmental impact of cooling compared to electrical systems for individual buildings, and particularly individual room air conditioners. Cofely's Birmingham District Energy scheme in the city centre has saved 14,000tCO_2 per year since 2006. Its Southampton scheme, which provides electricity, heating and chilled water to 45 commercial and 800 residential customers and incorporates some geothermal energy, saves 11,000tCO_2 per year.

Tri-generation relieves pressure on electricity grids by displacing electrically driven air conditioning systems in individual buildings, which typically must run during peak periods, with a system powered by decentralised generating capacity and incorporating thermal (hot and cold) energy storage. It also mitigates the heat island effect, since buildings are no longer dumping the rejected heat in their immediate vicinity.

Sources of waste heat are widespread, however, and it is possible that absorption chillers could be more widely used, both in tri-generation schemes and for a wider range of applications, if the match between waste heat resources – estimated at 10–40TWh per year in Britain alone[154] – and localised cold loads were better understood. Waste heat and cold resources have been mapped in a handful of European countries – Britain, Croatia, Czech Republic, Romania and Italy – by the Stratego project, co-funded by the EU.[155] But cold mapping is far less advanced elsewhere, and this is an important area of future research in the EU and beyond. Article 14 of the EU Energy Efficiency Directive obliges member states to map their potential for high-efficiency cogeneration and efficient district heating and cooling.

Domestic refrigeration

Tri-generation schemes could eventually extend to providing not only heating and cooling but also refrigeration – even in a residential setting. Instead of fridges being powered by electricity, and dumping heat into their immediate surroundings – which in hot countries requires the building's air conditioning to work harder still – cooling could be provided by cold water produced centrally and distributed through a network of pipes. Such an arrangement could raise efficiency and reduce the heat island effect. The same approach could be taken to hot water for dish washers and washing machines.

This approach would probably not be so widely applicable in Britain, dominated as it is by existing infrastructure and Victorian housing stock, but could be highly effective in hot countries where huge amounts of high-density housing are expected to be built. India, for example, plans to build 100 'Smart Cities' with an average population of 1 million each in the next decades. The European Technology Platform on Renewable Heating and Cooling (RHC Platform) notes that white goods driven by district heating and cooling networks are already commercially available but still expensive, and recommends costs should be reduced through demonstration projects and mass production.[156] The RHC Platform roadmap recommends a target of reducing the average electricity consumption of white goods in homes operating with district heating and cooling from 850kWh in 2012 to 130kWh by 2030.[157]

Active solar thermal

Energy for cooling can also be provided by solar thermal systems.[158] Here the Sun's heat is harvested as hot water, which is then used to drive an absorption chiller for air conditioning. One major advantage of such systems is that the need for air conditioning and the sunshine to power it usually coincide. Solar cooling also produces minimal carbon emissions – those produced by the pumping and control systems – and can be built entirely off-grid, which is important for cold pack houses or cold storage in remote rural locations. They can also produce hot water and space heating from the same energy source. Such systems are not yet common, but have been installed on commercial buildings and school and university campuses in California, Europe, the Middle East and China.[159] In its heating and cooling technology roadmap, the IEA concludes that the main focus of R&D for such systems now should be cost reduction.[160]

'Free' cooling

Cooling can also be provided by sources of so-called 'free' cooling, such as cool ambient air, river or sea water and the ground. No energy source is ever truly free, of course, and each of these sources requires some work to exploit – usually pumping of air, water or heat – but can reduce the energy required for cooling substantially nevertheless. The British company Simply Air, for example, developed a system to refrigerate supermarket display cabinets that makes use of cool air from outside, which it says reduces energy consumption by 25% in the British climate, and far more in colder ones.[161] The company has 10 systems in operation across three British supermarket chains at present.[162] Free cooling from rivers or the sea is widely used in tri-generation projects, such as Helsinki. Another source of 'free' energy is the ground under our feet. Temperatures below ground are typically stable and moderate throughout the year, and rock has a huge capacity to absorb heat and cold. This property can be exploited to provide heating and cooling, either through a ground-source heat pump (GSHP), which operates exactly like a fridge but with a large underground pipe to absorb or reject heat, or a simpler borehole arrangement in which heat is transferred by means of a fluid that circulates but does not change phase.

Sainsbury's, for example, has 28 stores using twin boreholes to support both heating and cooling. In one borehole, warm fluid containing rejected heat from the store's refrigerators circulates to dissipate its heat and cool down. In the other, cool water is circulated to collect heat, which can then be used to help provide heating in the store – which is needed year-round because of the cold spilling from open fridge cabinets. In both cases the heat or cold from the boreholes is 'bumped up' to the necessary temperature by additional heat pumps. From time to time, as the temperature of the rock around the cooling borehole rises, and that surrounding the heating borehole falls, the functions are swapped.

In these stores, Sainsbury's has also replaced high-GWP refrigerant gases with CO_2. The average impact of the boreholes has been to reduce electricity required for store refrigeration by 30%, but on the other hand new parasitic loads including the additional compression required for the CO_2 refrigerant increase the electricity consumption by 20%, meaning the net reduction is 10%. The stores have also eliminated all gas consumption for heating, however, since this is now served completely by the boreholes and heat pumps.

There seems little doubt that ground-source cooling and heating is a massively under-exploited resource that could play a much larger role in the Cold Economy.

The EcoVap process harnesses the waste cold from the vaporisation of liquid gases and uses it to improve the efficiency of industrial cooling processes. Image courtesy: Messer

The re-gasification of LNG is by far the largest source or waste cold in Britain.

'Wrong-time' energy / thermal storage

Cooling can not only integrate waste or renewable heat or cold, but also 'wrong-time' energy – such as wind or nuclear power generated at night when demand is low – by means of energy storage. Storage has many benefits, including reduced carbon emissions as a result of displacing high-carbon fossil fuel generation with time-shifted zero-carbon energy, and improved grid security, since peak demand is satisfied by off-peak supply. One of the key insights of the Cold Economy is that this storage need not be in the traditional forms, such as batteries or pumped storage, which produce only electricity, but can also be thermal. If the energy service that's required is cooling, it may well make sense to eliminate unnecessary energy conversions and store wrong-time energy as cold throughout.

Energy storage is in inherent in many cooling technologies – simply through the inertia provided by insulation. In fridges, for example, the compressor operates only intermittently, as required by the thermostat. And it is this characteristic that has allowed the development of 'smart fridges' that adjust their duty cycles to help maintain the frequency of the electricity grid.[163] Large users of cold – such as industrial gas producers and supermarkets – already take part in 'demand-side management' of their cold loads to help with grid balancing. This could be a significant feature of the Cold Economy, although it has more to do with improving the reliability of electricity supplies than delivering clean cold.

Newer technologies can both improve energy security and deliver cleaner cold, however. One example in California is the Ice Bear, which makes ice at night, when power is typically cheaper and lower carbon, to deliver cooling to the building's air conditioners the following day.[164] The company recently won a contract with the Southern California Edison utility to provide 25.6MW of thermal energy storage to reduce peak electricity demand.[165]

Another example is Sure Chill, a Welsh company that gave evidence to the Commission, which has developed a fridge that keeps its contents cool at a steady 4°C for days or weeks without power through an ingenious energy storage system based only on ice and water.[166] The first application is a small portable fridge for safe storage of vaccines in remote parts of developing countries, part-funded by the Bill and Melinda Gates Foundation, but the company also builds larger walk-in sized fridges, and says the technology is well suited to large scale cold storage. The company is in discussions about building a larger cold store for a farmers' co-operative in a developing country powered by solar absorption chillers.[167] This technology could not only make targeted use of wrong-time or intermittent renewable energy, but would also raise the efficiency of refrigeration systems by allowing compressors to run less frequently but at full load.

Eutectic beams and plates – which work rather like a picnic box cooler – can also provide cold for buildings and vehicles on the same principle. As renewable generating capacity continues to expand, so will the opportunities to absorb and store this energy efficiently until needed in the form of cold. The opportunities will also increase if energy storage materials and technologies can be developed that are cheaper, more compact and have longer storage durations.

Liquid air – cold in motion

Most of the cooling technologies discussed above can move cold in time but not place. Liquid air or nitrogen can do both with technologies such as the Dearman engine delivering cold and power on demand (see Recycling waste cold, above). Production of liquid nitrogen is already well placed to take advantage of lower carbon off-peak electricity.

Industrial gas production is an energy intensive process, consuming around 3% of Britain's electricity. Industrial gas companies are therefore acutely aware of electricity prices, and typically produce liquids such as nitrogen overnight and at weekends when wholesale power prices are lowest. This is also when grid electricity is least carbon intensive, since wind and nuclear generation make up a bigger proportion of the national supply when demand is low. The difference between overnight and average carbon intensity is not yet great, but will become bigger as offshore wind capacity continues to grow. A report from the Centre for Low Carbon Futures found that by 2030 the emissions factor during periods of low demand fall to 53gCO_2/kWh, for a system that on average still emits 93gCO_2/ kWh.[169] As a result the carbon intensity of liquid nitrogen or air will fall, even more so if the process integrated with waste cold from LNG re-gasification. It is also possible that ASUs (Air Separation Unit plants, used in liquefaction) may be managed even more actively in future: the ramp up times of ASU plants coincide quite well with the horizons of short-term wind forecasting.[170]

Direct liquefaction from renewable generation

In future, the production of liquid air or nitrogen could be directly powered by renewable energy. In the US, for example, the wind developer Keuka Energy is developing a novel *Rimdrive* wind turbine to power air liquefaction mechanically, with no electrical stage, which it believes should reduce the cost of production significantly.[171] A report from the Institution of Mechanical Engineers, *A Tank of Cold: Cleantech Leapfrog to a More Food Secure World,* found that an air liquefier driven by solar power could provide the basis for an economic cold chain in rural Tanzania and other remote locations in developing countries.[172]

Benefits of the Cold Economy

To summarise, the Cold Economy means a far greater and more rapidly achieved system-level integration of cold demands with sources of waste cold and heat, and 'wrong-time' low carbon energy; the use of cryogens as vectors to store and transport cold and power; and the development of more efficient technologies, practices and materials. We believe the benefits of this approach – 'doing cold smarter' – will be to reduce costs, CO_2 and local air pollution; improve energy and food security. Given the rapidly rising global demand for cooling, it will also create business opportunities, growth and jobs. The direct benefits to Britain appear significant, but are likely to be dwarfed by those to the developing world, because of the sheer scale of projected cooling demand growth, and the severity of the environmental impacts of a business as usual approach in those countries. The potential export market for clean cold technologies and know-how looks vast, and the question now is how much of it Britain might capture.

TES technology	Capacity kWh/t	Power kw	Effeciency (%)	Storage time	Cost (USD/ kWh)
Hot water tank	20–80	1–10 000	50–90	day–year	0.1–0.13
Chilled water tank	10–20	1–2 000	70–90	hour–week	0.1–0.13
ATES low temp.	5–10	500–10,000	50–90	day–year	Varies
BTES low temp.	5–30	100–5,000	50–90	day–year	Varies
PCM-general	100	100–1,000	80–90	hour–week	6–20
Ice storage tank	100	100–1,000	80–90	hour–week	6–20
Thermal chemical	120–150	10–1,000	75–100	hour–day	10–52

Table 3: Thermal energy storage characterised. Source: IEA[168]/Roth, Zogg and Brodrick.

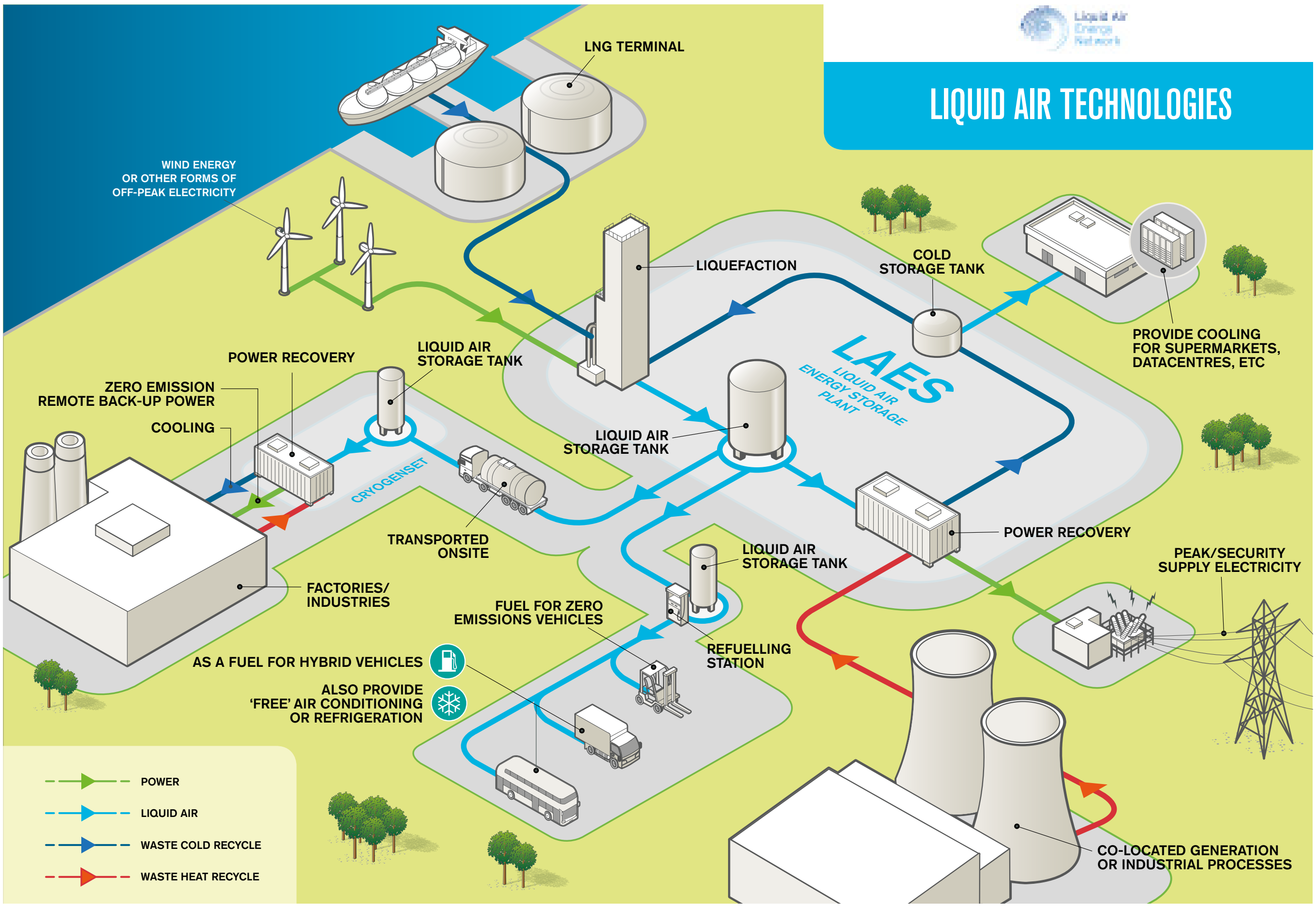
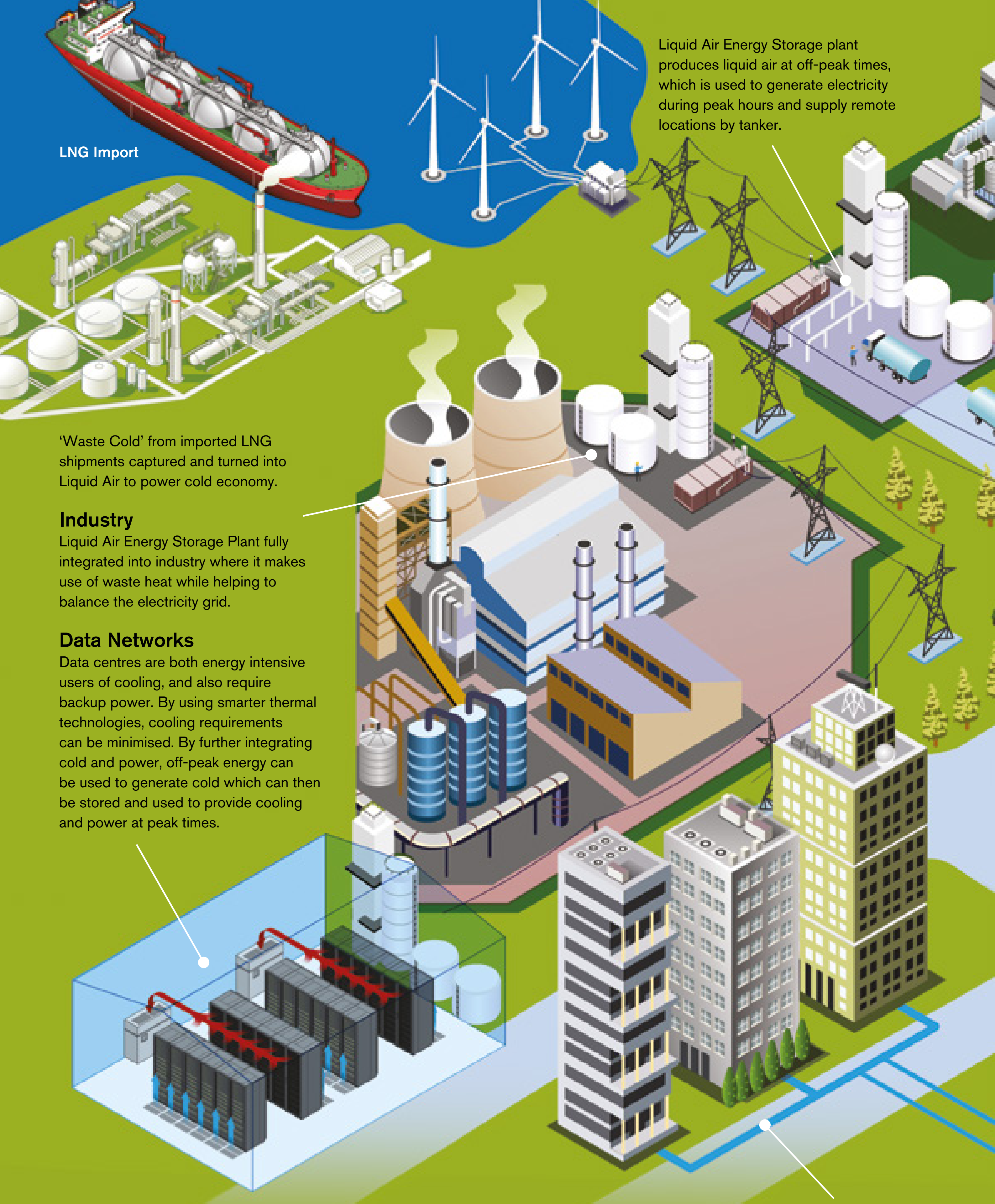


Figure 17: A future cold economy could make significant use of liquid air technologies



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

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

Industry

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

Data Networks

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

District Cooling

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

DOING COLD SMARTER:
THE FUTURE COLD ECONOMY

Waste heat from a nearby biomass power station raises the LAES plant's efficiency.

Supermarket refrigeration is upgraded to promote efficiency. With cold storage, the supermarket uses it's cooling loads to help balance the grid.

Liquid air also provides fuel for refrigerated lorries.

Supermarket receives and makes deliveries by liquid air refrigerated lorries and vans.

Bus depot receives liquid air by tanker to use in 'heat hybrid' buses with 'free' air conditioning. The depot also has a liquid air generator to help balance the grid.

In the home

By being able to store cold energy in thermally efficient refrigerators, the grid can be balanced through demand-side management.

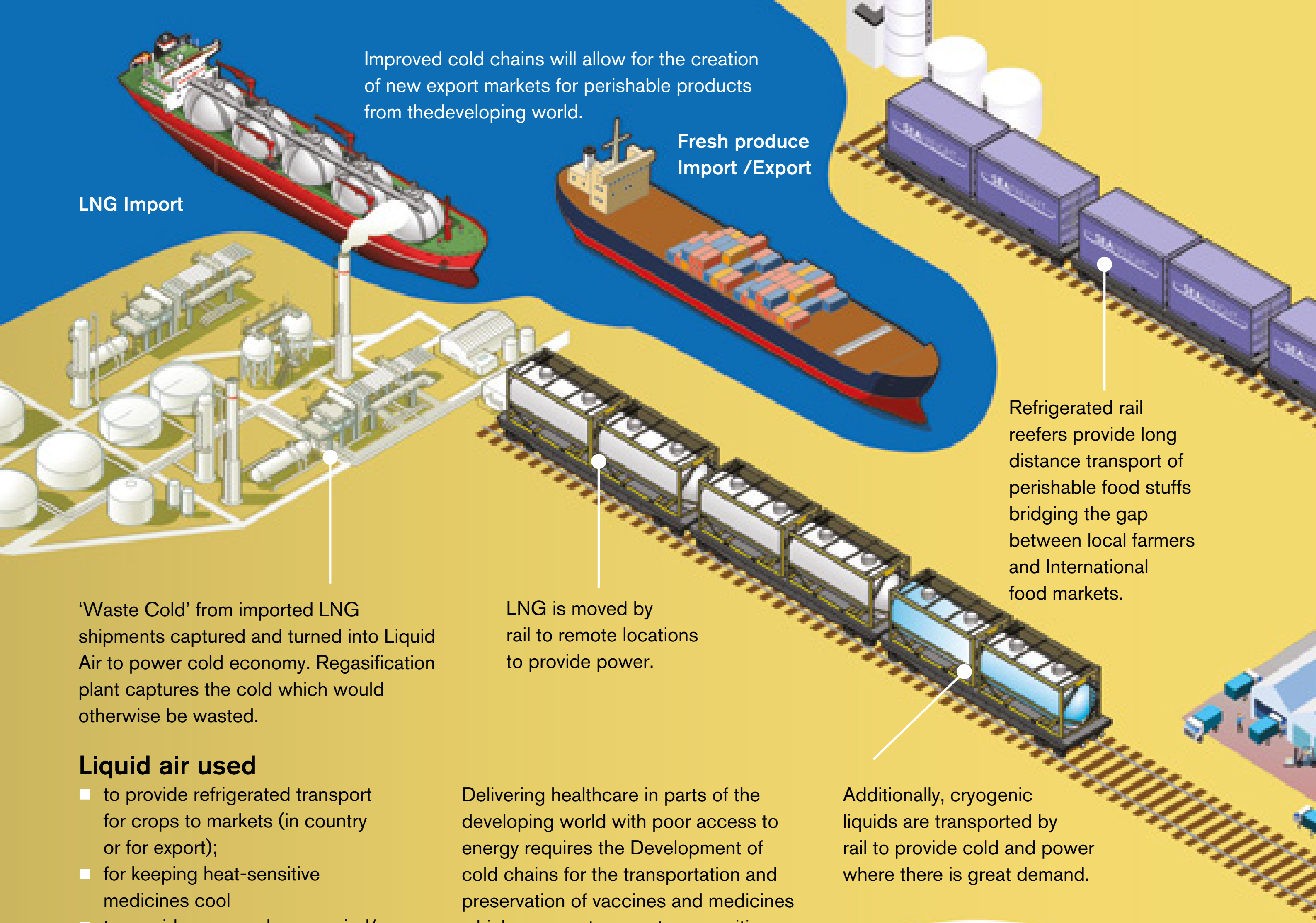
Fridges work as 'batteries' for the grid. Novel technologies such as solid-state cooling may become important in the future yielding step-change efficiency improvements.

Water Source Cooling

Efficient cooling can be achieved using natural bodies of water as a heat sink to provide cooling.

Ground-Source Heat Pump Heating and Cooling

As heat pumps play a more important role in delivering thermal comfort, the ground becomes a useful source and sink for heat.



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

Fresh produce Import /Export

LNG Import

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

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

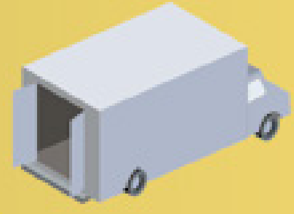
LNG is moved by rail to remote locations to provide power.

Liquid air used

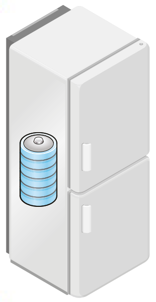
- to provide refrigerated transport for crops to markets (in country or for export);
- for keeping heat-sensitive medicines cool
- to provide power when no wind/sun, alongside sources of waste heat
- for local domestic/business cooling and refrigeration

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

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



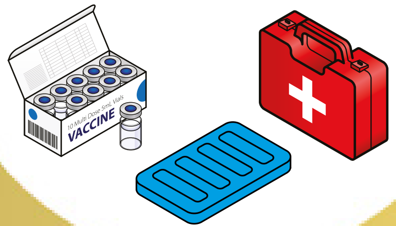
Refrigeration



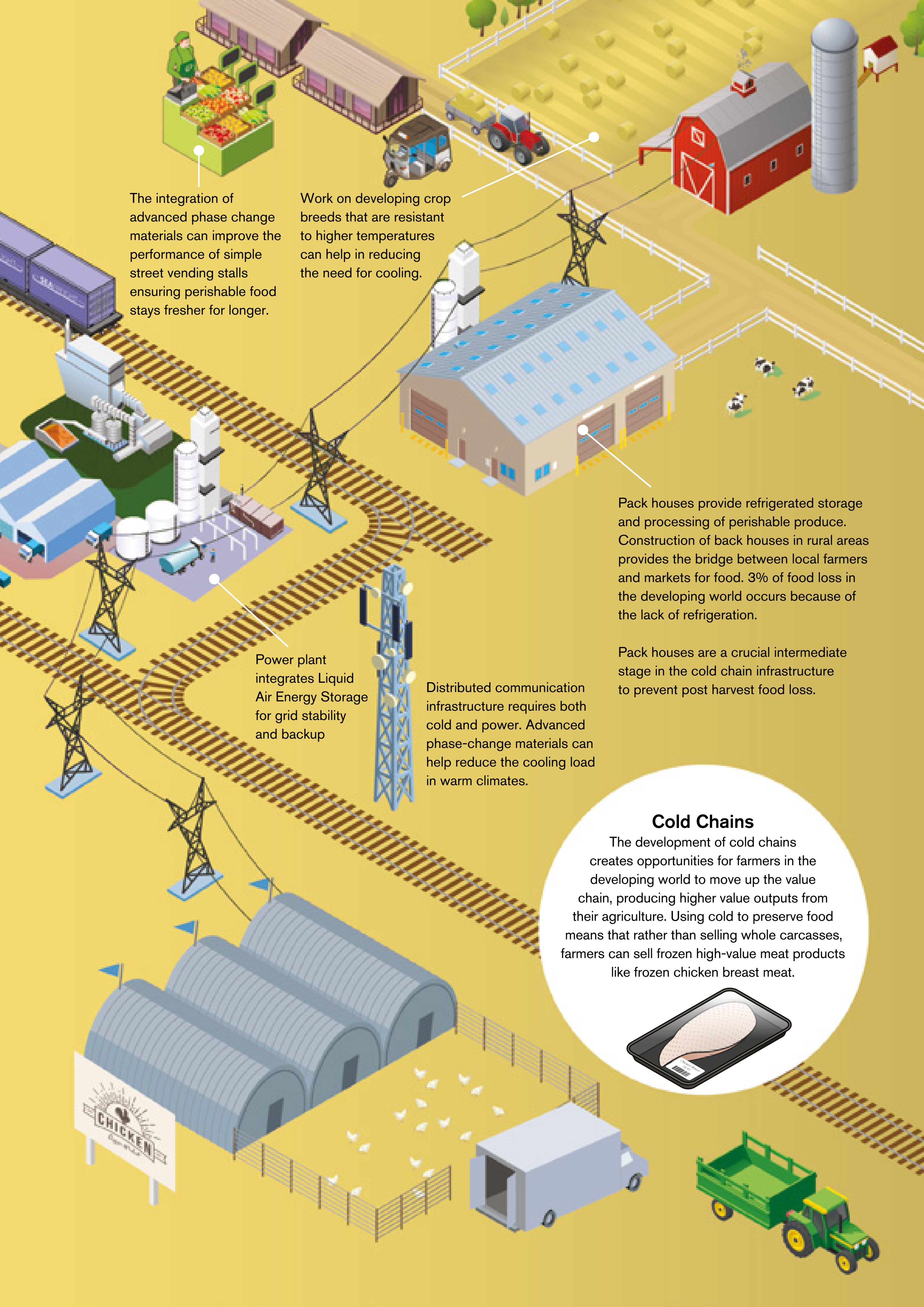
In remote areas without electricity, solar photovoltaic panels are used to generate electricity. The electricity is intermittent. Some electricity is stored in batteries for powering lighting and small electrical devices. The cooling energy needed is stored in the form of ‘ice’. Fridges work as ‘batteries’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

Ice packs

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



DOING COLD SMARTER:
IN THE DEVELOPING WORLD



The integration of advanced phase change materials can improve the performance of simple street vending stalls ensuring perishable food stays fresher for longer.

Work on developing crop breeds that are resistant to higher temperatures can help in reducing the need for cooling.

Pack houses provide refrigerated storage and processing of perishable produce. Construction of back houses in rural areas provides the bridge between local farmers and markets for food. 3% of food loss in the developing world occurs because of the lack of refrigeration.

Pack houses are a crucial intermediate stage in the cold chain infrastructure to prevent post harvest food loss.

Power plant integrates Liquid Air Energy Storage for grid stability and backup

Distributed communication infrastructure requires both cold and power. Advanced phase-change materials can help reduce the cooling load in warm climates.

Cold Chains

The development of cold chains creates opportunities for farmers in the developing world to move up the value chain, producing higher value outputs from their agriculture. Using cold to preserve food means that rather than selling whole carcasses, farmers can sell frozen high-value meat products like frozen chicken breast meat.

SECTION 4

THE OPPORTUNITY FOR UK PLC

THE OPPORTUNITY FOR UK PLC

UK leadership in the development of cooling and refrigeration

Britain can rightfully claim parenthood of many of the critical early innovations in the development of refrigeration and cooling. It was William Cullen who first applied the evaporative cooling technique using diethyl ether in the 1750s, and Faraday who deployed high pressures and low temperatures to achieve the liquefaction of ammonia soon after. The first vapour compression refrigeration cycle was developed in Britain in the 1830s – albeit by an American – and the first working system was built by James Harrison, a British journalist!

Yet as so often happens, British inventions were commercialised by others. In 1882, William Soltau Davison, an immigrant to New Zealand, faced with a decline in the world wool markets, fitted a ship with a compression refrigeration unit to export New Zealand lamb to Britain and its colonies. British leadership was further undermined following the development of industrial refrigeration by the American company GE, which introduced a gas powered refrigerator in 1911 and then an electric version in 1927. It was another American company, Frigidaire, that introduced synthetic refrigerants such as Freon. It seems Britain's frequent failure to exploit its own inventions – from computing through to graphene[173] – has deep roots.

This is no historical curiosity, however; it matters because Britain continues to innovate in cooling technologies, and the global market is huge. We saw in Section 2 how British companies including Simply Air, Iceotope, Camfridge and Sure Chill are developing exciting clean cold technologies but struggling to commercialise them. At the same time, the global refrigeration and cooling market is forecast to be worth $38 billion by 2018.[174] The largest market today is China, worth $10 billion, followed by the US at $6 billion. India's refrigeration market in 2012 was less than $1 billion[175], but the future market potential is huge – the investment required in cold chain alone is estimated by the country's National Centre for Cold-chain Development at $21 billion. It is therefore essential that the benefits of this new wave of British innovation are not lost overseas; we need to break the cycle. One recent success story is the opening of Dearman's new product development centre in Croydon, with £2 million of funding support from Local Enterprise Partnership, Coast to Capital. This is the world's first industrial Cold and Power product development centre, with facilities for testing, low volume manufacture, training and demonstration.

The coordination of this sector is provided by the Sustainable Innovation in Refrigeration Air Conditioning and Heat (SIRACH)[176] forum. SIRACH is a networking organisation for promoting new technology in refrigeration, air conditioning and heat pumps – increasing the flow of information between those with problems to solve and those with the ideas to solve them – and has had strong links to universities such as LSBU's Centre for Refrigeration and Air Conditioning. Despite its excellent work, we are not convinced SIRACH has sufficient clout to catalyse the necessary step-change, which will require wider policy and institutional reform.

UK leadership in cryogenics

One area of cooling in which British leadership is still unrivalled, however, is cryogenics – loosely defined as the science of temperatures below around -153°C – which dates back to 1959 when Oxford Instruments became Oxford University's first spin-out company. Oxford Instruments and the Rutherford Appleton Laboratory (RAL) did pioneering work to develop superconducting magnet technology, which requires extreme cold to function, and is today found in MRI scanners, satellites, and the world's largest particle physics experiments at CERN. Other potential uses of cryogens span manufacturing and materials, defence, space, and in particular food, healthcare and transport and energy. Oxford is now the centre of a world-class concentration of cryogenics-related businesses – often set up by former employees of Oxford Instruments – including Thor Cryogenics, Magnex (ElScint), AS Scientific, Thames Cryogenics, Scientific Magnetics, ICEoxford, Cryophysics, and Siemens

Magnet Technology – the world's largest supplier of magnets for MRI scanners. These companies are now represented by the British Cryogenics Cluster, which estimates[177]:

- Sectors broadly associated with cryogenics represent 17% of the UK economy.
- The total (direct and indirect) GVA contribution of cryogenics-related activities to the UK economy is £324 million per year.
- Cryogenic-related economic activities could contribute between £1.6 billion and £3.3 billion to the UK economy in the next 10 years, and up to 6,000 jobs.

Britain's leadership in cryogenics – built on close co-operation between universities, SMEs and national laboratories – creates a significant opportunity to leapfrog international competitors in the development of clean cold technologies, which must not be squandered.

UK academic leadership

Despite the low levels of public R&D spending on cold overall, Britain also shows surprisingly strong academic leadership in thermal energy – both hot and cold – through a number of funded projects:

- CryoHub: a €7 million European grant for pan-European consortium of researchers led by Professor Judith Evans, LSBU to investigate integrating cryogenic energy storage (CES) with refrigerated warehouses and food processing plants.
- Birmingham Centre for Cryogenic Energy Storage: 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 government's '8 Great Technologies' initiative.
- i-STUTE: an interdisciplinary centre for Storage, Transformation and Upgrading of Thermal Energy. i-STUTE, funded through the research councils Energy programme, brings together cutting-edge engineering advances with economic, behavioural and policy expertise to produce solutions that are both technically excellent but also appealing to business, end-users, manufacturers and installers. The Centre involves the University of Warwick's School of Engineering and Warwick Business School together with LSBU, the University of Ulster and Loughborough University.
- 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 University, 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.
- The new government funded Energy Research Accelerator led by the Midlands Universities, which will invigorate the search for new cleaner technologies including around heating and cooling (t-ERA). It will alsolook at productionisation and manufacture to help to bring those technologies to market at affordable prices, and help deliver the skills and training to support deployment.

This small core of internationally leading researchers creates the springboard for accelerated technology development in cooling technologies, should elevated investment flow into this sector from EPSRC, InnovateUK, H2020 and industry.

Britain may have lost its historic leadership in cooling technologies over a century ago, but today it has a good number of SME clean cold technology developers, a world leading cryogenics sector, and substantial academic muscle despite the low levels of public R&D funding overall. In short, Britain has all the elements required to achieve international success if properly co-ordinated. Since the world appears to be on the verge of a renewed wave of innovation and expansion in cooling, it is vital that Britain should not let this opportunity slip from its grasp.

The Birmingham Energy Institute is leading the way in developing next generation cooling technologies as a partner in the government funded Energy Research Accelerator led by Midlands Universities.

SECTION 5

ROADMAP

ROADMAP

We have made the argument that cooling is both vital and highly polluting, and that if nothing is done, its environmental impact will soon multiply many times over because of the huge projected demand growth worldwide – but especially in developing countries. But that growth suggests an equally large opportunity – a new global market for clean cold technologies – and Britain has inherent strengths that could allow it to capture a significant slice. The question of whether Britain will be successful is still open, however, because of the barriers identified in Section 2, and a thriving domestic market in clean cold to serve as a showcase for exporters is probably a minimum precondition to become a credible exporter. To secure this we need not only supportive policy (see next section) but also an industry roadmap.

Roadmaps are a means of developing a consensus among stakeholders about the R&D and commercial needs of a particular technology or an entire industry, and typically plot the drivers for change, short- and long-term goals and deadlines for progress, and provide a means of measuring success. A good roadmap will inform planning and investment by both industry and government, allowing each to focus on the areas of greatest need and to avoid duplication of effort.

The Automotive Council roadmap for the British car and truck industry is a good example of one that has worked extremely well. It was designed to plot the industry's course towards low-carbon and low-emission transport, and how to progress from incremental improvements to the internal combustion engine to electric and hydrogen vehicles, and formed the centrepiece of a broader government strategy which embraced investments covering R&D, supply chain and skills. The impact of this investment was to transform the industry's fortunes and political profile through targeted interventions and the founding of supporting initiatives such as the Centre of Excellence (CenEx), Low Carbon Vehicle Partnership (LowCVP), and Advanced Propulsion Centre (APC). Government R&D funding was raised from just £3 million per year to £ several billions over the course of a decade. By contrast, the government published its Offshore Wind Industrial Strategy in August 2013[178], by which time Britain already had the largest offshore wind capacity in the world, and most of the equipment had been manufactured in countries like Germany and Denmark.

The present roadmap for cold is intended to describe what is required to develop 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. It is a high-level industry roadmap, developed by the Commission and external experts. It is technology agnostic and resolutely practical: it does not fix its eyes solely on what might be achieved in from blue-sky technologies in 15 years, but is equally occupied with the significant short-term gains from improved maintenance of existing equipment – and all the steps in between. Like the Automotive Council's roadmap, we hope it will help guide investment in R&D, and the development of new business models, and help forge new relationships between stakeholders in disparate industries who until now have had no cause to co-operate.

The aims of the roadmap are to reduce consumption of non-renewable natural resources, pollutant emissions, greenhouse gases (CO_2, refrigerants) and the total cost of ownership for equipment operators, but at the same time generate economic value to UK plc through improved productivity and exports, and social benefits for emerging economies through the creation of clean cold chains.

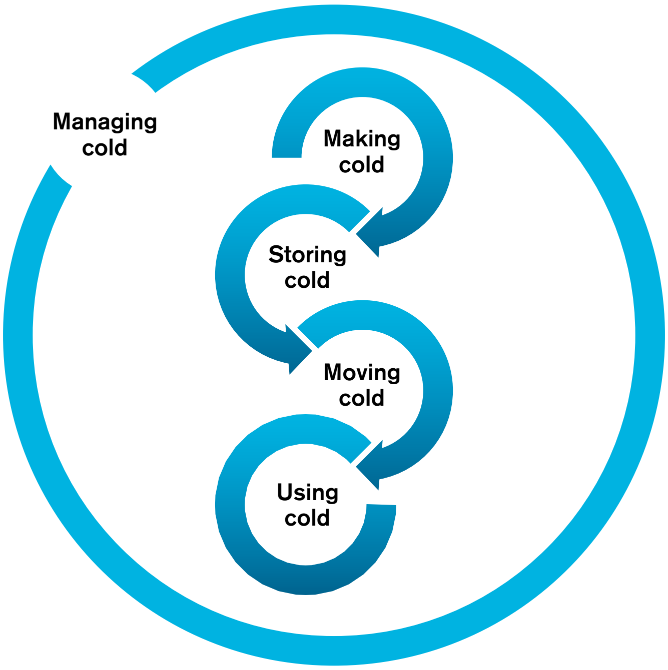


Figure 19: System-level approach to cold

The roadmap takes a system-level view of cooling, reflecting the Cold Economy described in Section 3, but for the sake of clarity divides cooling activities into **five themes: making cold, storing cold, moving cold, using cold** and **managing cold**.

Under **making cold**, the Cold Economy approach would involve conventional and future cooling technologies, recycling waste resources such as LNG waste cold or wrong-time renewable energy such as wind power generated at night when demand is low.

Under **storing cold**, it would involve thermal energy storage, storing energy efficiently as hot or cold rather than energy stored in a battery, in order to deliver cooling whenever needed without worsening peak demand.

Under **moving cold**, the Cold Economy requires new energy vectors to help shift cold not only in time but also place. This role could be played by liquid nitrogen or liquid air in the short-term, but R&D should be directed towards developing vectors with greater energy density and distribution versatility.

Using cold reflects the hierarchy described in Section 3: first reduce the amount of cooling needed, with thermally efficient buildings, improved products etc; then increase the efficiency of cooling equipment and reduce its emissions intensity; and finally develop new technologies to harness novel thermal stores and energy vectors.

The final theme, **managing cold**, describes the role that ICT could play in raising efficiency through monitoring and managing cold from production through to consumption.

Themes	Enablers		Value creators	Impacts for UK plc
Making cold	Technology demonstration	Skills development	Innovation	Jobs
Storing cold	Measurement and data	Business models	Manufacturing	Revenues (tax)
Moving cold	Export support	Manufacturing techniques/ high value supply chain	Sales	Exports
Using cold	Advocacy	UK and EU regulation	Services	Environment/ reduction in societal cost of pollution
Managing cold	Behavorial changes	Being on the agenda		Energy security

Table 4: Elements of the Cold Economy

Progress on any of these five themes could produce benefits for UK plc in the form of exports, jobs, tax revenues, energy security and the environment, as shown in column four of Table 4. The enabling factors that would allow this to happen are listed in the second column, and the channels through which it could happen in the third. This Table illustrates the many different pathways through which Britain could benefit from a global market in clean cold technologies.

The roadmap is relevant to a wide range of industries, many of which would not necessarily think of themselves as closely connected:

- Energy Systems: grid buffering and stabilisation, district heating cooling, system-level waste heat/cold recovery, storage and movement of cold
- Food: packing, processing, manufacturing
- Cold Chain: transport refrigeration, depots, retail and medical, domestic refrigeration
- Built Environment: building energy, local-scale energy buffering and power generation, air conditioning, data centre cooling, warehouse refrigeration
- Transport: propulsion, waste heat recovery, interaction with ICE and electrochemical systems, LiAir, LN$_2$, LH$_2$ LNG or NH$_3$ as a fuel, provision of a/c from cold
- Industrial process: industrial Gases and Processes, LNG and LH$_2$ import and distribution, industrial-scale chilling and freezing processes
- Advanced: superconductors, nanotechnology, other fundamental or advanced concepts

The roadmap shows that actions to advance the Cold Economy can begin immediately, and that rapid progress could be made over the next 10 years:

	Here Now 0–3 YEARS	Short-term 3–5 YEARS	Medium-term 5–10 YEARS	Long-term 10 YEARS +
Making Cold	**Sources of cold** Better use of presently available low temperature sources including: Geothermal sourced cooling; River and sea water cooling sources; adiabatic/evaporative cooling; Night time stored energy; Co-locating large consumers of cold and cooling (e.g. data centres) near waste cold centers (e.g. LNG); Evaporative Cooling.	**Sources of cold** Sources of cooling in early stages of deployment or development: Integration of geothermal heat with cooling capability; Waste cold from LNG capture; Better use of ambient air temperature as part of cooling system.	**Sources of cold** Key development: Small-scale liquefaction for wide scale deployment of LN_2.	**Sources of cold and far future technologies** Developments likely to be of great importance in the longer term: Wind powered liquid air production; Direct drive liquefaction; Optical cooling; Baro-caloric refrigeration; Ice nucleation proteins; Ultrasound assisted freezing; Hydraulic refrigeration
	Efficiency and integration Significant energy savings can be made by enhancements in current technologies and the way they are used: Increasing efficiency/coefficient of performance (COP); Utilization and sharing of heat and cold between applications; Optimised deployment of heat pipes and targeted cooling (e.g. district cooling). Booster heat pumps for district heating and cooling.	**Efficiency and integration** Next step opportunities for enhanced efficiency and systems integration: Development of gas-electric hybrid heat pumps to reduce electricity peak usage integrated into cooling systems; Development of combustion-engine powered heat pumps that make use of waste heat from engine to generate heat and cold.	**Efficiency and integration** Potential for the development of new solid state refrigerant materials with high cooling power.	
	Refrigerants Deployment of existing high-efficiency, low environmental impact refrigerants is key: Investment in research into lower GWP refrigerants, particularly azeotropes; Replacement of R134a with near drop-in replacement HFO-1234yf; Conversion of R22 systems to R290 (propane); Conversion of R410a systems to R290 (propane); Development of techniques to reduce refrigerant leakage.	**Refrigerants** Developments in new refrigerants and associated adoption include: Increased use of Hydrocarbons in household refrigerators and freezers and food retail refrigeration; CO_2 for supermarket applications; Industrial refrigeration relying on ammonia; Need for fast development of standards to support the roll out of flammable refrigerants; Improvement of safety technologies for use of flammable refrigerants; Development to reduce costs of production of some low-GWP refrigerants (e.g. HFOs).	**Refrigerants** Novel technologies with the potential to deliver cooling at scale: Electro-caloric; Magneto-caloric; Air cycle refrigeration; Pressure shift freezing; Thermionic refrigeration; Thermoelectric generation; Vortex tube cooling; Commercialisation of gas-electric hybrid heat pumps to reduce electricity peak usage; Thermoelectric cooling used in automotive (converting some of the waste heat of an internal combustion engine); Active solar thermal used to drive refrigeration cycles (Supply and demand of energy well synchronised); Improvement of sorption cooling from renewable energy sources; Optimisation and integration of renewable energy sources into district heating and cooling networks.	**Refrigerants** Long term aim to phase out of HFCs in all refrigeration applications.
	Developing technologies There exist a number of emerging technologies that can be deployed on a small scale, but require further R&D for scale up: Thermoelectric coolers used in consumer goods (portable coolers, replace heat sinks for microprocessors) and electronic and scientific equipment; Small scale magnetic cooling-based technology.	**Developing technologies** Technology developments with the potential to have a near (some longer) term impact: Sorbtion cooling systems driven by hot water at moderate temperature; High capacity heat pump for simultaneous production of hot and cold water; Optimisation of thermally driven heat pumps; Thermoelectric; Perfusion; Use of nanoparticles in cooling systems; Vortex tube cooling; Ejector or jet pump; Stirling cycle for cooling; Electronic expansion valves; Borehole Condensing; Magnetic cooling in domestic cooling appliances; Proof of concept for electro-caloric cooling unit; Eutectic packaging of cold/cooling.	**Developing technologies** Novel technologies with the potential to deliver cooling at scale: Electro-caloric; Magneto-caloric; Air cycle refrigeration; Pressure shift freezing; Thermionic refrigeration; Thermoelectric generation; Vortex tube cooling; Commercialisation of gas-electric hybrid heat pumps to reduce electricity peak usage; Thermoelectric cooling used in automotive (converting some of the waste heat of an internal combustion engine); Active solar thermal used to drive refrigeration cycles (Supply and demand of energy well synchronised); Improvement of sorption cooling from renewable energy sources; Optimisation and integration of renewable energy sources into district heating and cooling networks.	

Table 5: Tasks and targets for the Cold Economy

	Here Now 0–3 YEARS	Short-term 3–5 YEARS	Medium-term 5–10 YEARS	Long-term 10 YEARS +
Storing Cold	**Current technologies/media deployed for storing cold** Cryogens; Ice; Water; Glycol; Water-ethylene glycol mixtures; Propylene glycol; Propylene glycol – water; Paraffin wax based storage materials; Eutectic salt based solutions; Fatty acid based formulations; Other phase change materials; Gravel bed; aquifer thermal energy storage (ATES); Underground thermal energy storage (UTES); Thermal piles; Large natural energy stores.	**Developing technologies/ opportunities for cold as an energy storage medium** Composite cold storage materials; Cold storage components and devices; Heat transfer intensified storage components and devices; Novel building fabrics; Development of new installation technologies for retrofitting district cold with minimal disruption; Cold storage heat exchangers.	**Next generation cold energy storage possibilities** Inter-seasonal cold storage; High power density high grade cold storage materials; High power density cold storage components and devices; Combined cold storage and power devices; Low-cost and economic solutions for low usage cold storage devices; Compact domestic and district scale storage devices; Zero boil off cryogenic systems.	**Disruptive cold storage opportunities** Thermochemical storage for cold and power; Development of bespoke phase change materials for very low temperature applications; Composite cold storage materials with tunable boiling point through microstructures and surface forces; Smart cold storage components and devices.
Moving Cold	**Current technologies for moving cold (e.g. in district cooling networks and cooling applications)** Cryogens; Ice; Water; Glycol; Water-ethylene glycol mixtures; Propylene glycol; Propylene glycol – water; Phase change materials.	**Developing technologies/ opportunities for cold as an energy vector** Containerised LNG.	**Next generation cold energy transportation possibilities** Harnessing waste cold from cryogenic fuels.	**Disruptive cold mobility opportunities** Novel materials with high energy density, low production cost and readily transportable. District cryogen networks.
Using Cold	**Actions to immediately improve the use of cold and cooling** Maintain and repair existing equipment to ensure optimum performance; Better exploitation of natural opportunities e.g. ice; Reducing loads vacuum insulation, use of LEDs etc; Cryogen evaporation systems; Eutectic plates; Further development of air conditioning and refrigeration technologies; Better development of food cold chain; Exploitation of heat pumps; Doors on cabinets in supermarkets; Occupancy sensors for retail cabinet lighting.	**Opportunities for widening use of cold** Cryogenic ‘cold and power’ engines; Need for better cryogenic ancillaries – transition from cottage industry to manufacture at scale; Low-cost systems for low utilisation systems; Need integrated plan for recycling end of use of cooling with embodied energy and carbon costing; Super chilling; Tri-generation.	**Next generation exploitation opportunities for using cold** Cold & Power Systems; Systems integration in automotive – e.g. air conditioning and aux power; Passive air conditioning; Passive systems employing eutectic plates; Develop and roll out white goods suitable for integration into district heating and cooling scheme.	**Horizon for exploitation of cold** Harnessing the waste cold from liquid hydrogen infrastructure; Full integration of advanced cold technologies (Magnetic, Peltier). Electro-calorics, acoustics; Thermoelectric devices that can generate electricity directly from waste cold.
Managing Cold	**Immediate opportunities and requirements for better management of cold and cooling** Need for data capture on cold usage; Big data processing and interpretation; Intelligent control; Variable speed compressor drives; Thermal management in vehicles; Thermal management of power electronics; ‘Smart’ loads that are responsive to grid frequency variations to improve grid stability by acting as a flexible load; Development of systems to monitor and maintain temperature accurately across large supermarket chiller volumes.	**Emerging opportunities for better management of cold** Devices for cold production; Smart fridges – grid sensing – linked to internet of things; Cold chain optimization; Climate robust cooling; Weather prediction linked to cold production and utilization; De-superheating / Heat Recovery.	**Longer term management of cold** Fully integrated cold chain with energy vectors, with optimization of all system components.	
Technology Demonstration	Ad-hoc tech demonstration driven by commercial firms that can raise capital. Large scale demonstration of thermal (heating and cooling) grids.	Demonstration and proof of concepts of elements of integrated schemes. Demonstration systems capable of providing validation data, essential for commercialization.	District schemes with integrated demonstration of technologies.	A whole city-scale UK integrated cold demonstrator.
Modular Manufacturing and Export Models	Immediate actions required to build manufacturing capability: The UK’s position on the cold chain needs to be clarified. There exists opportunities from manufacture to export. There may also be the capability to export and franchise manufacturing. Need for better cryogenic ancillaries – transition from cottage industry to manufacture at scale. Mapping of UK capabilities throughout the supply chain.	Development of manufacturing capability linked to thermal energy technologies to solve some of the common manufacturing challenges. Development of the appropriate scale of skills in the UK to take advantage of the growing market.	Development of a manufacturing franchise capability (Factory in a Box) model, capable of creating UK manufacturing capability in emerging markets. Implementation of best manufacturing practice (e.g. Industry 4.0) in thermal energy technologies. Embedded intelligence in manufacturing and products to create service market.	Fully integrated cold/refrigeration manufacturing process with UK supply chain and UK skills and servicing underpinning the growing export market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Expressed graphically, the actual roadmap combines drivers, technology development and the kinds of new interactions between different parts of the energy system that represent the core of the Cold Economy:

Drivers for Change	Reduction in CO_2 footprint
	Increased pollution from NO_x and PM
	Transition to lower GWP 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 goods 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-gasification and liquid air liquefaction
	Grid balancing and district cooling and heating
	Vehicles: Liquid air – LN_2 – LH_2 systems
	Advanced superconductor technologies in power systems
	Food refrigeration and transport with liquid air generation and use
Interventions	Development of cold and cooling as a 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
	Develop@ UK skills base linked to state-of-the-art cold systems

Figure 20: Steps towards a cold economy

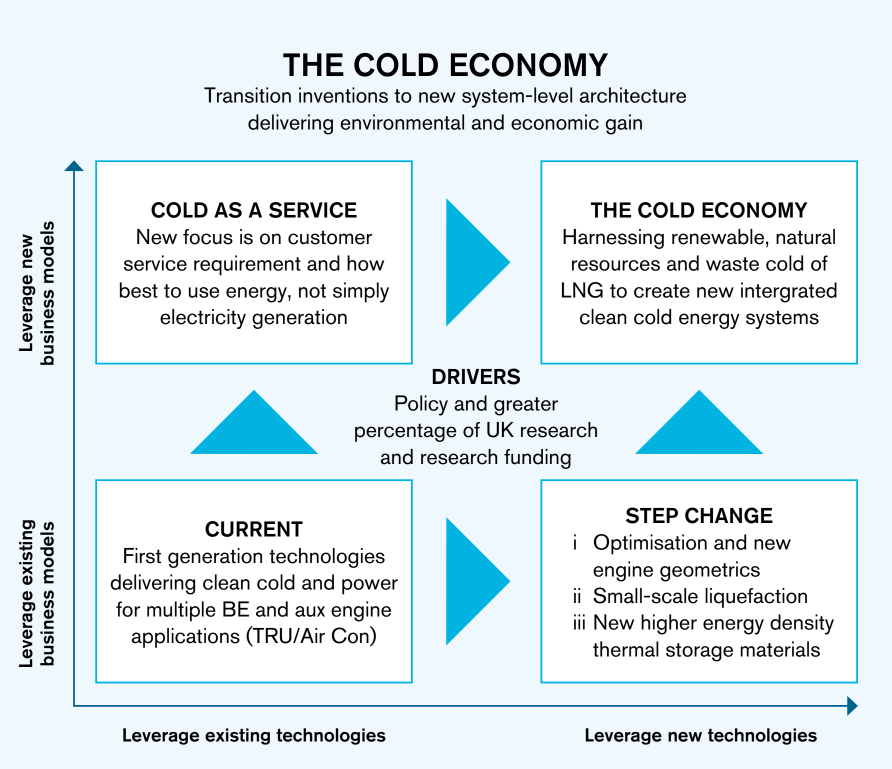


Figure 21: The Cold Economy: evolution of a new system.

The range of technologies and sectors covered by the Cold Economy means the spread of stakeholders that could benefit is unusually wide:

- **Energy Sector:** Grid, power generation, liquid air and hot-cold storage players
- **Urban planners:** district cooling networks, heat island effect, integration of services and utilities
- **Energy Users:** Liquefaction, users with cold processes, industrial parks, city authorities
- **Cold dependent businesses:** agriculture and food industry (Post Harvest food Loss community); medical; data centres
- **Vehicle manufacturers:** Technology developers especially urban trucks and buses, refrigerated transport, light urban vehicles, goods handling, marine and mining
- **Equipment manufacturers:** commercial and domestic refrigeration manufacturers – built environment, transport and mobile refrigeration plant and the providers of power in emission-sensitive environments
- **Transport and Logistics operators:** Including cold-chain, buses, urban delivery and haulage
- **Component suppliers:** Including heat exchangers, refrigeration compressors, electrical systems, ICEs, fuel cells and other future technologies with waste heat / cooling need
- **Industrial gas suppliers:** Embracing liquefaction and distribution of LN_2, LiAir, LH_2, LNG
- **Superconductor innovators:** Magnets, electrical conductors, motors
- **Policymakers:** In Energy, Energy Storage, Transport, Air Quality and Environment
- **Finance community:** venture capital, asset finance, novel financing models, shared risk

We believe the roadmap – which we acknowledge is at this stage a hand-drawn sketch of unfamiliar territory – will prove useful not only to government but to all stakeholders – universities, innovators, industry, customers – and will contribute to the rapid development of clean cold technologies and the Cold Economy. We also hope that it will now be adopted by an existing institution – such as the Energy Systems Catapult (see next section) – and developed further.

SECTION 6

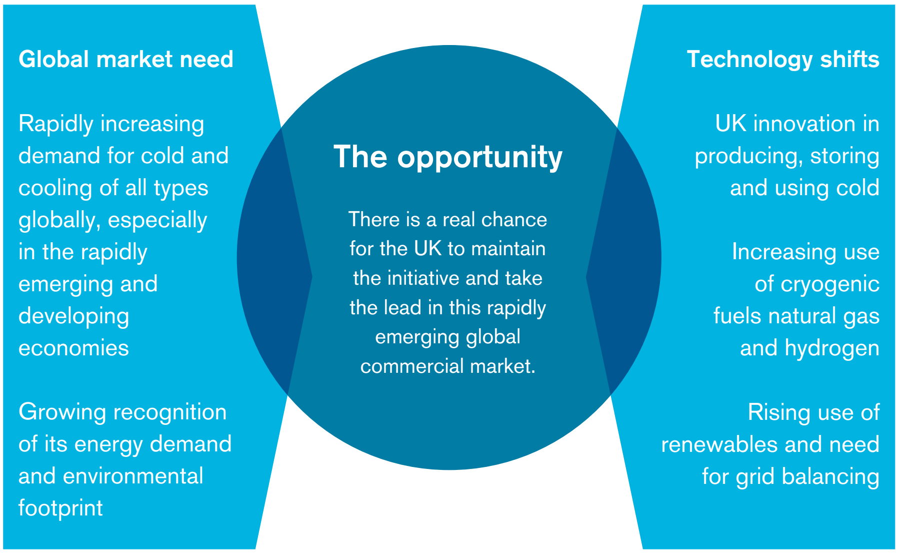
POLICY RECOMMENDATIONS

POLICY RECOMMENDATIONS

We noted in Section 2 that for most governments cold is still a policy-free zone. Yet there is every reason for the government to develop a comprehensive policy around clean cold, not only to support its wider domestic policies on CO_2 reduction and air quality, but also to create a platform for innovation and exports that could help Britain secure a lead in what promises to be a major global market.

The environmental benefits of clean cold technologies are likely to be significant in Britain, but those in the developing world will be enormous, and the economic value of satisfying those needs equally large. Developing policy to support clean cold strategies and technologies at home could create an export shop window for UK plc, whereas not doing so risks losing this opportunity, and being forced to import clean cold technologies for our own needs. The rationale for developing clean cold technologies, and policy to support that innovation, is summarised in Figure 22.

> THE ENVIRONMENTAL BENEFITS OF CLEAN COLD TECHNOLOGIES ARE LIKELY TO BE SIGNIFICANT IN BRITAIN, BUT THOSE IN THE DEVELOPING WORLD WILL BE ENORMOUS AND THE ECONOMIC VALUE OF SATISFYING THOSE NEEDS EQUALLY LARGE.



Global market need

Rapidly increasing demand for cold and cooling of all types globally, especially in the rapidly emerging and developing economies

Growing recognition of its energy demand and environmental footprint

The opportunity

There is a real chance for the UK to maintain the initiative and take the lead in this rapidly emerging global commercial market.

Technology shifts

UK innovation in producing, storing and using cold

Increasing use of cryogenic fuels natural gas and hydrogen

Rising use of renewables and need for grid balancing

Figure 22: Why clean cold?

Developing policy on cold would help deliver many of the government's wider strategic aims, including:

- **Reduced costs to industry and consumers:** E4tech estimates that doubling Britain's cooling efficiency through the Cold Economy could save the country around £1 billion;
- **Reduced CO_2 emissions;** key is deploying more efficient, low carbon technologies;
- **Energy security:** raising cooling efficiency reduces the electricity required, and would therefore improve capacity margins, which are forecast to fall to a ten year low of just 1.2% this winter[179];
- **Grid balancing:** some clean cold technologies incorporate thermal energy storage, meaning they can help reduce peak electrical loads on hot days;
- **Food security:** improved cold chains would reduce food waste worldwide, so helping to constrain food price rises in both developing and developed countries;
- **Air quality and health:** existing transport refrigeration and diesel generators emit grossly disproportionate amounts of NO_x and PM; the profile of toxic air pollution is rising rapidly following the Volkswagen emissions testing scandal, while recent court judgements that oblige Britain to submit a new air quality strategy to Brussels by the end of this year;
- **Exports, growth, jobs and skills:** if the immediate benefits from greening Britain's cooling are worth £1 billion as E4tech estimates, we would expect potential value of supplying clean cold to the global market to be many times higher. Based on the estimated value of clean cold to Britain, scaling by GDP produces a global value of £43 billion, and scaling by population gives a global value of £112 billion.[180] Even at the lower figure – which takes no account of projected cooling demand growth in developing countries – the opportunity is enormous.

RECOMMENDATIONS

Many areas of policy clearly need work, particularly in light of the barriers to clean cold explored in *Section 2*. There is a strong argument to be made for each of these barriers to be cleared by government intervention. But although the case for developing detailed policies is compelling, we believe there are more fundamental issues to resolve first. Awareness of the need for clean cold is woeful, for example, and the data around cooling demand is poor. For this reason our five key recommendations are intended to raise awareness of the importance of clean cold and improve the data and analysis of the cooling system in Britain. If these are accepted, we propose a further series of more detailed proposals.

1 Raising awareness and long term commitment

We believe government has a major role to play in raising awareness of the environmental and economic importance of cooling. If the government makes clear its recognition of the strategic importance of cold for our energy resilience, food security, medicine and even our aspirations for the UK space industry, and its long term commitment to the adoption of clean cold technologies, it will increase the confidence of investors. We urge the government to:

Establish a lead department with responsibility for clean cold. Since cold touches so many aspects of the energy system, the environment and the economy, the development of policy should involve several arms of government: the Department of Energy, Environment, Food and Climate Change for energy security and CO_2; the Department for Environment Food and Rural Affairs (Defra) for air pollution; the Department for Business, Innovation and Skills for exports and growth; the Department for Transport (DfT) and of course the Treasury. We recommend that a single department should take ownership of this issue and co-ordinate with the others.

Appoint an institutional champion for clean cold: we recommend the Energy Systems Catapult should adopt clean cold as one of its themes, and act as a co-ordinating body for analysis and development of clean cold technologies in Britain.

Review National Policy Statements: The Government should review the existing national policy statements to ensure that the importance of cold and cooling is properly recognised as the UK's energy priorities and infrastructure are defined.

Develop a concordat for the UK cooling and refrigeration industry: that encourages the development of system-level thinking and associated products with high-efficiency, low levels of pollution and carbon impact, establishing UK industry as best in class.

2 Technology Innovation Needs Assessment for cooling

Technology Innovation Needs Assessments (TINAs) are carried out by the Low Carbon Innovation Co-ordination Group (LCICG), whose core members include DECC, BIS, the Engineering and Physical Sciences Research Council (EPSRC), the Energy Technologies Institute (ETI), the Technology Strategy Board and the Carbon Trust. TINAs are intended to identify and value the main innovation needs of specific low-carbon technology families to inform the prioritisation of public sector investment in low-carbon innovation. Each TINA analyses, estimates or identifies:

- the potential role of the technology in the UK's energy system
- the value to the UK from cutting the costs of the technology through innovation
- the value to the UK of the green growth opportunity from exports
- the case for UK public sector intervention in innovation
- the potential innovation priorities to deliver the greatest benefit to the UK

These are precisely the questions that need to be answered around clean cold. TINAs have already been conducted for bioenergy, carbon capture and storage, industry, domestic buildings, non-domestic buildings, electricity networks and storage, hydrogen for transport, marine energy, nuclear fission, off-shore wind and heat. The heat analysis concluded:

Innovation in these heat technologies could reduce UK energy system costs by £14–66 billion to 2050, with heat storage also offering additional value by enabling other system adjustments. Innovation can also help create a UK industry with the potential to add £2–12 billion to UK GDP to 2050. Significant private sector investment in innovation, catalysed by public sector support where there are market failures, can deliver the bulk of these benefits with strong value for money.[181]

Similar conclusions seem entirely possible for cold, but given the likely size of the future global clean cold market, the value of potential exports to UK plc could be much higher. While data around cooling is still poor, this Commission has certainly gathered sufficient to justify early investigation of the sector through a TINA.

3 System-level model of UK cold

This Commission has produced a first-take analysis of cooling demand and resources in the UK. But a proper understanding of the potential of the Cold Economy requires a more detailed and definitive model to be developed. This model should use whole-system methodology to evaluate the reduction in system cost – financial and environmental – that could be achieved by deploying new cooling technologies and harnessing waste resources to meet cooling loads. The whole-system approach is required because the potential benefits stretch far wider than those enjoyed by the individual owner or user of clean cold technologies. These benefits span transport, food, buildings, industry and energy, and include: lower costs; reduced emissions of greenhouse gases, NO_x and PM; and improved grid resilience resulting from reduced cooling loads and increased use of wrong-time renewable energy and waste heat and cold.

We recommend that Research Councils, Innovate UK and the government jointly fund a study to assess the social benefits of implementing the measures outlined in this report. We expect this work would take a two-step approach: first to understand the cold value chain in more depth, and second to integrate this into whole systems models.

In the first stage, a specific ‘cold value chain model’ should be developed that stretches across sectors, including energy, food and industry and includes a full lifecycle assessment (LCA). The value of interventions in this ‘sub-system’ can be quantified by comparing the costs and benefits of existing processes and technologies, primarily powered by grid electricity, with the new processes and technologies outlined in this report, which mitigate cooling demand for fossil fuels and peak electricity. Potential benefits including reductions in operating cost and avoided investment in electricity grid infrastructure would be netted off against the cost of the new cooling technologies.

This approach can also be used to quantify the performance and cost parameters required of new technologies such as novel materials for moving waste coolth to high demand locations.

From this more detailed understanding of the value chain, the Cold Economy can then be integrated into whole systems models to quantify the wider social benefits. In Britain we recommend this should involve organisations such as the Whole Systems Energy Modelling Consortium (wholeSEM)[182] and the RCUK National Centre for Sustainable Energy use in Food chains (CSEF)[183]. So-called ‘whole systems’ models are often still restricted to individual sectors such as energy or food, but by having developed a specific Cold Economy model in the first stage, this analysis will ensure that there is a common understanding of the wider linkages.

A truly system-level model of cooling in Britain would inform decisions in policy and research funding and provide the evidence to ensure interventions are directed where beneficial impacts are most likely. Building and integrating such models would start with the UK, but could then be extended to other markets. It would therefore highlight the value of clean cold technology innovation in developing export opportunities for business.

4 Support demonstration projects

The environmental benefits of clean cold technologies are likely to be significant in Britain, but those in the developing world will be enormous, and the economic value of satisfying those needs equally large. For this reason government should consider supporting clean cold demonstration projects, both in Britain and abroad, as a platform for future exports. In Britain, such projects could explore ways of measuring cooling demand and aggregating cooling loads – for instance between a hotel, data centre and logistics business – to build a viable business case. In Africa, they could simultaneously demonstrate effective ways to reduce post-harvest food loss – and the consequent waste of land, water and energy, and needless emission of CO_2 – while laying the foundations for future economic growth and British jobs.

5 Measurement and management of clean cold

It is axiomatic that `you cannot manage what you cannot measure’, and many users of cooling have very little idea about how much energy they are consuming, the efficiency or inefficiency of their equipment, and how much pollution they are causing. This is true for individual cooling applications but probably even more so at the level of an entire company. Some large consumers of cold may have a clear idea of their cooling energy consumption but perhaps much less of their cooling requirement (coolth). We believe this requires 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, which may also help them identify cooling loads that could be aggregated and therefore supplied more efficiently through district cooling schemes. The Coefficient of Performance (CoP) used for individual appliances is too narrow a measure, and we favour a broader indexed approach capturing energy consumption, emissions (CO_2, NO_x, PM) and whether the energy source worsens or mitigates peak load. The government should consider leading the development of a broad metric of the energy and environmental impact of cooling and promoting it among companies on a voluntary reporting basis.

In the longer term, the development of clean cold technologies could be hastened by the introduction of a trading scheme through which companies could exchange the energy and environmental benefits of efficient clean cold technologies. Such a scheme could help the industry invest in the most cost effective measures soonest.

6 Other recommendations

We expect that the TINA and system model would confirm our broad conclusions about the value of clean cold technologies and the Cold Economy approach, in which case we make a series of further recommendations:

Research and development

Public funding of R&D into refrigeration and cooling technologies attracts just over £20 million in research funding, just 0.2% of total UK funding for engineering research, despite the fact that cooling consumes 16% of UK electricity and by one estimate responsible for 10% of global CO_2 emissions. **Public funding of cold R&D should be increased to better reflect its environmental and economic weight and global market opportunity.**

Witnesses also complained that funding calls, even those nominally addressed to both heating and cooling, were often couched in terms that effectively exclude cooling technologies or projects from bidding for public funds. **The government should review the terms and language of all relevant future funding calls to ensure that cooling is not inadvertently excluded from thermal bids.**

Several technology developers told us that their efforts to commercialise were hampered by a lack of facilities to demonstrate their technologies at scale – such as a novel cooling system for an entire supermarket, for example. The Catapult centres funded by Innovate UK provide just such facilities for innovation in areas as wide-ranging as cell therapy, digital technologies, future cities, high value manufacturing, offshore renewable, satellites, transport, precision medicine and energy systems. **The Energy Systems Catapult should add cold as one of its themes and develop it by collaborating with the offshore renewable energy, future cities, high value manufacturing and medicine Catapult centres.**

Research at the Birmingham Centre for Cryogenic Energy Storage into novel cold storage materials.

Skills Development

The refrigeration and cooling industry employs 100,000, but the age profile of the workforce is rising rapidly and recruitment is difficult, and witnesses told us skills are poor – particularly in terms of handling new lower GWP refrigerant gases, for example.[184] The government has recently established an apprenticeship standard for refrigeration and heat pump engineers[185], but the knowledge it requires reflects the current dominance of conventional vapour compression cycles. Developing the Cold Economy will create the opportunity to recruit thousands of young new cooling engineers with enhanced skills, including, for example, an understanding of cryogenics and the ability to deal safely with new energy vectors such as liquid nitrogen. **The government should consider financial support for apprenticeships in the sector, and in any event should work with Summit Skills, the Skills Council responsible for building services engineering, to monitor and update training and apprenticeship standards to reflect the needs of the developing Cold Economy.**

Financing

The barriers most commonly cited among technology developers was customers' fixation with capital cost of new equipment rather than lifecycle costs, and the higher risk profile of innovative technologies, both of which slow the take-up of more energy-efficient technologies. **We urge the government to review the problem and consider how it might help clear these barriers, perhaps through:**

- **Extending existing schemes:** for example, by extending the technological and geographical reach of schemes such as the London Energy Efficiency Fund[186];
- **Encouraging innovative business models** such as product service systems;
- **Modifying existing tax incentives:** the rules for schemes such as the Enterprise Investment Scheme, Seed Enterprise Investment Scheme, and Venture Capital Trusts, currently preclude leasing, whereas allowing it would reduce risk and upfront cost for prospective customers;
- **Government-assured asset financing:** another way to reduce risk and upfront cost might be for government to underwrite asset financing of new technologies, so eliminating the risk premium in leasing deals. The government would not have to commit any cash, simply assume a contingent liability. This could be a more efficient approach than conventional subsidies of capital cost;
- **Export assistance via UKTI.**

GLOSSARY

Term	Definition
Absorption Chiller	A chiller unit that employs a brine solution and water to provide refrigeration without the aid of a compressor. This process is driven by heat which makes these devices useful as they can employ low grade waste heat to provide cooling.
Absorption Refrigerator	Refrigerator which creates low temperatures by using the cooling effect formed when a refrigerant is absorbed by chemical substance. This process is driven by heat which makes these devices useful as they can employ low grade waste heat to provide cooling.
Air conditioner	A unit used to regulate the temperature, humidity, quality and movement of air in a building envelope.
Carbon dioxide (CO_2)	Compound of carbon and oxygen that can be used as a refrigerant. Refrigerant number is R-744. Also, emissions resulting from the burning of fossil fuels. A greenhouse gas that contributes to climate change.
Chlorofluorocarbons (CFCs)	Refrigerants that are composed of chlorine, fluorine, and carbon. CFCs deplete the ozone layer and so their use as a refrigerant was phased out under the Montreal protocol.
Coefficient of Performance	Ratio of work performed (measured in terms of amount of cooling or heating generated) divided by the energy input to the device.
Cold chain	A temperature-controlled supply chain of goods (often produce).
Cryogenic Energy Storage	The storage of wrong-time energy (e.g. from renewable sources) by liquefaction of air, storing the energy in the form of cryogenic gas. This gas can then be expanded to produce cooling and power.
Demand-Side Management	The process whereby energy demand is regulated (by switching off or throttling back loads) in response to changes in available energy supply.
District Cooling	A system arrangement for cooling, whereby a centralised plant produces chilled water, which is then distributed over a wide area (often encompassing a number of buildings and facilities) using an insulated pipe network. District cooling may involve the provision of heat to a range of different customers – in this case it is often metered to assess each customers' consumption.
Embedded greenhouse gas emissions (GHGs)	The emissions produced in the manufacture and disposal of equipment such as vehicles or engine.
Energy vector	A medium of moving, storing, and releasing energy.
Euro 6 (VI) lorry	A vehicle complying with the most recent European Union exhaust emission regulations (NO_X emissions of 0.46g/kWh, PM of 0.01g/kWh)
Eutectic Beams	A system whereby a beam containing a eutectic mixture (a phase change material, which is able to remain cold for a long time) is brought to temperature whilst the vehicle is stationary using electricity (often this is cheap, overnight wrong-time energy). This beam is able to maintain the temperature whilst the vehicle makes deliveries.
Evaporative Cooling	Evaporative cooling is accomplished when moisture evaporates, absorbing heat in the process. Works best in warm, dry environments.
F-gas	Fluorinated gases ('F-gases') are a family of man-made gases used in many applications in cooling and refrigeration. They do not damage the ozone layer, this has led to their substitution in place of ozone-depleting substances. F-gases are powerful greenhouse gases, with a high GWP, up to 23 000 times greater than carbon dioxide (CO_2). Because of this, F-gases are increasingly regulated.
Heat pump	Often designed to be reversible, heat pumps are a heating or cooling system whose 'work' is to extract heat from a cooler place and deliver heat to a warmer place. As the temperature difference between the warm and cold places increases, greater amounts of work are required to 'pump' the heat, leading to decreased COP. Heat pumps may use the ground, bodies of water or the air as their sources / sinks of heat. Refrigerators and chillers are all 'heat pumps', however the term heat pump can also be applied specifically to devices which are used to pump heat into and out of buildings providing heating and cooling.
Hydrochlorofluorocarbons	Compounds containing hydrogen, chlorine, fluorine and carbon. Used as a refrigerant. Have a deleterious effect on the ozone layer and so are being phased out.
Isothermal	Maintaining a constant temperature.
Liquefaction	The process of cooling a gas to the point of becoming liquid (-194C for air).
Liquid air	A cryogenic fluid comprising an atmospheric mixture of nitrogen, oxygen, and the trace gases.

Term	Definition
Re-gasification	The process in which a liquid becomes a gas.
Reefer	Refrigerated trailer or shipping unit.
Technology Readiness Level (TRL)	A technology readiness level denotes a technology's maturity and viability in the marketplace, Technology Readiness Levels between 1-9 are assigned.
Thermoelectric Cooling	A cooling or refrigeration device that employs a Peltier junction to create a temperature differential from a DC electrical supply.
Transmission System Operators	Our energy infrastructure is divided between the 'Transmission System' which conveys natural gas or electricity at a national or regional level, and the 'Distribution System' which distributes electricity or gas to consumers at a local level. The Transmission System Operator is responsible for the 'backbone' of the system which distributes energy over regions and nations.
Tri-generation	A system which produces electricity, heat and cooling efficiently.
Well-to-wheel emissions	The combined emissions from the production, processing, distribution and end-use of a unit of fossil fuel from its point of origin (oil well) to its consumption by an engine.
Wrong-Time Energy	When there is a surplus of either heat or electricity produced at a time when there is insufficient demand. This can be stored for use when demand rises.
Zero Boil Off	Cryogenic liquids can be used to 'store cold'. One of the challenges is that heat in the atmosphere causes cryogenic liquids to boil resulting is a loss of cryogenic gas and therefore stored cold. Zero Boil Off technology, which is in development, employs advanced insulation techniques to reduce the quantity of boiled of liquid to as near to zero as possible improving energy efficiency.
Zero-emission vehicle	A vehicle which produces no emissions such as PM or NO_X at the point of use.

Acronyms

ACHR	Air Conditioning, Heating & Refrigeration
APC	Advanced Propulsion Centre
ASU	air separation unit
BCCES	Birmingham Centre for Cryogenic Energy Storage
BIS	Department for Business, Innovation and Skills
BSRIA	Building Services Research and Information Association
CenEx	Centre of Excellence
CES	cryogenic energy storage
CFC	Chlorofluorocarbon(s) [a type of refrigerant]
CO_2e	Carbon Dioxide equivalent: (CO_2e allows other greenhouse gas emissions to be expressed in terms of CO_2 based on their relative global warming potential (GWP).)
CoP	Coefficient of Performance
CSEF	National Centre for Sustainable Energy use in Food chains
DECC	Department for Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
EPSRC	Engineering and Physical Sciences Research Council
FAO	Food and Agricultural Organisation of the United Nations
F-gases	Fluorinated gases
GDP	Gross Domestic Product
GWP	Global Warming Potential
GVA	Gross Value Added
HFC	Hydrofluorocarbon(s) [a type of refrigerant]
HFO	Hydrofluoroolefin(s) [a type of refrigerant]
HFO-1234yf	2,3,3,3-Tetrafluoropropene refrigerant
ICE	internal combustion engine
iSTUTE	interdisciplinary centre for Storage, Transformation and Upgrading of Thermal Energy
km^3	kilometres cubed
KTP	Knowledge Transfer Partnership
LCICG	Low Carbon Innovation Co-ordination Group
LiAir	Liquid Air
LH2	Liquid Hydrogen
LN2	Liquid Nitrogen
LNG	Liquefied natural gas
LowCVP	Low Carbon Vehicle Partnership
LSBU	London South Bank University
mtpa	Metric tonnes per annum, which is a typical measurement unit in liquefied natural gas (LNG) markets for production and facility capacity.
$mtCO_2$	million tonnes of CO_2
$mtCO_2$	million tonnes of CO_2 equivalent
$mtCO_2e$	million metric tons of carbon dioxide equivalent
MW	megawatt
MWh	megawatt hour
MRI	Magnetic Resonance Imaging
NO_X	nitrogen oxides
PM	particulate matter
R-125	pentafluoroethane refrigerant
R-134a	1,1,1,2-Tetrafluoroethane refrigerant
R-22	Chlorodifluoromethane refrigerant
R-290	Propane (when used as a refrigerant)
R-32	difluoromethane refrigerant
R410a	near-azeotropic mixture of difluoromethane (CH_2F_2, called R32) and pentafluoroethane (CHF_2CF_3, called R-125) refrigerants
RAC	Refrigeration and Air Conditioning
RACHP	Refrigeration, Air Conditioning and Heat Pumps
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
R&D	research and development
SME	Small and Medium Enterprises
t-ERA	Thermal Energy Research Accellerator
TINA	Technology Innovation Needs Assessment
tpd	tonnes per day
TRU	transport refrigeration unit

COOLING AND REFRIGERATION TIMELINE

1600

1619
James I has the first modern 'Ice House' constructed for the storage of winter ice and the preservation of food in Greenwich Park. Before refrigeration, ice houses were used to store ice throughout the year.

1700

1748
William Cullen, a Professor at Edinburgh University demonstrates artificial refrigeration for the first time.

1800

1803
Thomas Moore receives first US patent on refrigeration.

1820'S
Britain begins the process of importing 'cool' in the form of ice from Norway.

1824
Michael Faraday discovers the principle of vapour absorption, during experiments to liquefy gases. This principle underpins absorption refrigeration technology which converts refrigerant gas back into a liquid using only heat with no moving parts.

1834
Jacob Perkins an American inventor demonstrates a refrigeration unit in London's Fleet Street which can cool fluids and produce ice. This is based on Oliver Evans' earlier unpatented ideas.

1875
Thomas Mort of Australia develops the first 'Cold Storage' plant.

1883
Zygmunt Wróblewski and Karol Olszewski are the first to liquefy nitrogen, oxygen and carbon dioxide to a stable state.

1890
Ferdinand Carre demonstrates a refrigeration machine based on vapour absorption.

1900

1902
Willis Carrier invents air conditioning.

There were 460 refrigerated ships (Reefers) at sea, many built in Glasgow.

1907
Pierre-Ernest Weiss the French Physicist undertakes work that underpins understanding of the magneto-caloric effect. This principle underpins future solid-state cooling devices.

1914
The first air conditioning unit is installed in the Minneapolis mansion of Charles Gates.

1921
Britain receives its last import of ice from Scandinavia as mechanical production of ice becomes well established.

1928
Thomas Midgely was commissioned by GM to find a less risky alternative to methyl methanoate used in their Monitor Top refrigerators as a refrigerant. He discovers CFC's.

1930
Electrolux launch the first widely available domestic refrigerator.

1935
Frederick McKinley Jones designs a portable air-cooling unit for trucks carrying perishable food (Jones went on to co-found the U.S. Thermo Control Company – later the Thermo King Corporation.

1939
Two million American homes now own a refrigerator.

1940
Packard launches the first vehicle with factory air conditioning as an option.

1941
The first commercial LNG liquefaction plant was built in Cleveland, Ohio.

1942
In America, the load that air conditioning is placing on the electrical grid has become apparent, and the first 'summer peaking' power plant is constructed to help deal with this load.

1951
In the early part of the twentieth century, the majority of US residents lived in the North of the US. In 1951, the household air conditioner came to market. This radically changed the distribution of growth of the American population.

1959
A heatwave in the UK, with temperatures reaching 34 degrees Celsius, kickstarts the UK market for domestic refrigerators as much food is spoiled in the heat.

The 'Methane Pioneer' carries the first experimental shipment of Liquified Natural Gas from Lake Charles, Louisiana to Canvey Island.

Diesel powered refrigeration units for refrigerated transport are introduced.

1965
Only a third of UK households own a fridge.

1974
The link between CFC refrigerants and the hole in the ozone layer is proposed by Frank Sherwood Rowland and Mario J. Molina

1980
Air conditioning makes hot southern cities more habitable in the Summer leading to population growth fuelled by the influx of older wealthy people. Author Stephen Johnson asserts that this is a contributory factor in the election success of Ronald Reagan, who can build a 'sunbelt coalition' of voters that would not have existed before.

1994
Freon as a refrigerant, linked to ozone depletion and banned in several countries.

2000

2001
Peter Dearman patents a novel piston engine that uses liquid air or nitrogen to produce both cooling and power.

2008
Kraft foods build their 'Springfield Underground' cold storage facility in a disused Limestone mine, using the thermal mass of the ground to help provide efficient cooling.

2010
Chinese consumers bought 50 million air conditioning units – equivalent to half the entire US domestic air conditioner fleet.

2022
The Qatar world cup due to take place in air conditioned stadiums.

2025
Demand for trus could quadruple to 15M which would emit same pollution as more than 800M cars more food secure world' The report notes that 40% of fresh food produce in India is lost annually because of the lack of cold chains.

2030
UK LNG imports projected to reach 500 million tonnes per year, enough to produce 184 million tonnes of low-cost, low-carbon liquid air.

The European Commission expects cooling demand in EU buildings to rise by a further 70% by 2030.

2060
Global energy demand for cold in built environment exceeds global energy demand for heat.

2080s
Defra projects that the average British summer temperature is likely to rise by 3°C to 4°C.

2100
The IPCC projects that global air conditioning energy demand will grow 33-fold from 300TWh in 2000 to more than 10,000 TWh in 2100. The IPCC says most of the growth will occur in developing economies, and 25% will be due to climate change. 10,000TWh is roughly half the total electricity generated worldwide in 2010.

APPENDIX 1 – COMMISSION WORK PROGRAMME




The Policy Commission heard and deliberated on evidence from a range of sources, agreed conclusions and recommendations, and explored these through a variety of tools, including consultation group discussions.

Scoping Phase

Activities included:

- Appointing the Commissioners
- Developing the idea for the Policy Commission with Birmingham Energy Institute academics and Commissioners
- A commissioner meeting to agree the content and process of the Policy Commission held at the Royal Institution.

Expert Witness Session

- To catalyse the discussion around Doing Cold Smarter a panel of expert witnesses was assembled to present to Commissioners at the Royal Institution.

Evidence Gathering

- Researching literature and data in the public domain.
- Global consultation exercise, inviting written evidence from interested parties

Evidence Gathering Workshops

Two evidence days were held, each split into two sessions.

Sessions 1 and 2 were held at the Royal Institution.

- Session 1– Understanding the Scale
- Session 2 – Resources

Sessions 3 and 4 were held at the Institution of Mechanical Engineers

- Session 3 – Technology and Innovation
- Session 4 – Manufacturing, skills and what it means for UK plc

Technology Roadmapping Event

A technology roadmapping workshop was held at the University of Birmingham to bring together academics and industry practitioners to discuss the future innovation trajectory of a range of cold and cooling technologies.

Review and Writing Phase

- Reviewing written evidence submitted to the commission
- Commissioners' meeting at the Royal Institution to reflect on the issues raised in the workshops and consultations, and to deliberate on policy options.
- Commission findings and recommendations finalised at Commissioners' meeting.

Policy Commission Launch

Launched at One Whitehall Place on 28 October.

APPENDIX 2 – THE COMMISSION

Commissioners

CHAIR
Lord Robin Teverson – (Lib Dem) Spokesperson for Energy and Climate Change, House of Lords

Robin Teverson spent some 20 years in the freight industry, much of that time managing multi-temperature distribution operations. He was a member of the European Parliament in the 1990s where he spoke on marine, transport, and regional issues. After a spell in the financial sector - he is a fellow of the Chartered Institute for Securities and Investment – he was appointed to the House of Lords in 2006. He is energy and climate change spokesman in the Lords for the Liberal Democrats. In 2015/2016 he chaired the House of Lords Select Committee on the Arctic. He lives in Cornwall.

Professor Toby Peters – Visiting Professor in Power and Cold Economy, University of Birmingham; Chief Executive, Dearman

Toby Peters is long-time advocate of UK-based innovation in energy systems. He co-founded both Highview Power Storage (2004) and the Dearman (2011), and with them established the concept of liquid air as an energy storage solution for both grid and transport delivering clean cold and power. Toby has helped secure more than £20 million of UK grant funding for liquid air development, as well as commensurate levels of industrial and private equity investment for technology and commercial development.

He was appointed to the position of Visiting Professor in Power and Cold Economy within the Birmingham Energy Institute in 2014, contributing to energy strategy, policy and system-level thinking and supporting engagement with key external stakeholders and industry around the need to produce and harness cold and the need to create a sustainable cold infrastructure.

Toby is the co-academic lead of the 2015 ‘Doing Cold Smarter’ Policy Commission.

Professor Martin Freer – Director, Birmingham Energy Institute (BEI)

Professor Freer is Director of the Birmingham Energy Institute, Director of the Birmingham Centre for Nuclear Education and Research, and head of the Nuclear Physics Group at Birmingham.

His main research area is the study of the structure of light nuclei using nuclear reactions. This research is performed at international facilities worldwide and in 2010 he won the Rutherford Medal and Prize which is awarded once every two years by the Institute of Physics for distinguished research in nuclear physics or nuclear technology.

In addition, he is actively engaged in promoting research and educational programmes to support the UK’s investment in nuclear power generation. His expertise are in the areas nuclear physics; nuclear education; nuclear power research; pure nuclear science; waste management; decommissioning and energy.

Martin is the co-academic lead of the 2015 ‘Doing Cold Smarter’ Policy Commission.

Dr Jonathan Radcliffe – Senior Research Fellow, University of Birmingham

Dr Jonathan Radcliffe is a Senior Research Fellow at the University of Birmingham, and works across the Engineering and Physical Science College, and the Business School. His research interests lie in technology, policy and market options for energy system flexibility, in particular the role of energy storage.

Jonathan has extensive knowledge of policy-making, having worked in Government and Parliament for 13 years. He has worked directly with policy makers, academics and business leaders at the highest level.

He has written reports on future energy innovation priorities, the role of energy storage, and flexibility options for the UK’s energy system. He has experience of working within Europe and China, and is leading a comparative analysis of UK and Korea energy systems funded by the FCO.

Jonathan regularly presents at national and international conferences, and contributes articles to journals and magazines.

Professor Lenny Koh – Director, Centre for Energy, Environment and Sustainability Logistics
Professor Lenny Koh is Director of the Centre for Energy, Environment and Sustainability (CEES) and Director of Logistics and Supply Chain Management (LSCM) Research Centre, University of Sheffield.

She is an Associate Dean, Chair Professor in Operations Management, Founder and Director of the Logistics and Supply Chain Management (LSCM) Research Centre at the Management School and the Faculty's Centre for Energy, Environment and Sustainability (CEES), at the University of Sheffield. She is also the co-founder of Supply Chain Management and Information Systems (SCMIS) Consortium, a global network of leading academic and practitioners driving research and knowledge exchange on supply chain and information systems.

A World leading mind recognised amongst FRSs and Nobel Laureates within the University, Professor Koh is a Senior Chair Professor, an internationally renowned and established authority in supply chain especially on low carbon and sustainability, with a high H-index (World number 2) and high research income generation in her discipline internationally. She is active in leading a 2022 Futures initiative advancing resource efficiency and supply chain disciplines, navigating a new translational model for connecting invention/basic science at lower TRLs to higher TRLs.

Professor Koh's leadership and management role involves leading alumni, external relations and championing partnerships with industry, government and other top institutions. She is a member of the strategy executive leadership board.

Professor Tim Benton – UK Champion for Global Food Security, University of Leeds
Professor Tim Benton is the 'Champion' for the UK's Global Food Security (GFS) programme, leading, facilitating and coordinating its activities, and acting as a spokesperson for the programme and the challenges of food security.

GFS is a partnership of the UK's main public funders of research in food security, including the research councils and government departments (including Department of Health, Defra, DFID, FSA and the devolved administrations). The role of GFS is to ensure that strategically important research in this area is undertaken, and to add value to research via interdisciplinary collaboration, alignment and engagement of different communities of stakeholders.

He is also a leading researcher, based at the University of Leeds, on agri-environment interactions and finding ways to make agricultural production more sustainable.

Dinah McLeod – Director of Strategic Development, Overseas Development Institute
Dinah McLeod is Director of Strategic Development, Centre for Aid and Public Expenditure, at the Overseas Development Institute.

Before joining ODI she lived in Germany where she was CSR director for Sandoz, a Novartis-owned pharmaceuticals company; she also researched green growth issues for Allianz. Prior to this she headed the BT Global Services sustainability practice in London, where she worked with customers to adopt more sustainable modes of business operation.

In her previous role as an independent consultant, she worked on aid effectiveness issues; before that, she was a policy adviser in the Prime Minister's Strategy Unit. Dinah began her career as a Social Protection Specialist at the World Bank, focussing on community-based development and financing issues. Dinah holds a Master's degree from Princeton and a BA from Columbia University.

Dr Sally Uren – Chief Executive, Forum for the Future
Sally is Chief Executive at Forum for the Future, and works with leading global business, including Unilever, Kingfisher, M&S, Nike and PepsiCo, to deliver their mission of creating a sustainable future, as part of multi-stakeholder collaborations designed to address system-wide challenges, particularly in food and energy.

Sally is Chair of Kingfisher plc.'s Advisory Council and acts as an independent advisor on advisory boards for several other global businesses. She is also Chair of the advisory board overseeing Forum for the Future's growing operations in the US and an Advisory Board member for Sustainable Brands.

She speaks regularly at international and national conferences on topics as diverse as future trends in retail and food, sustainable business models and brands, and scaling up for system change. She also writes for a range of publications, with recent articles in the New Statesman, Huffington Post and Management Today. Before joining Forum in 2002, Sally set up the Sustainability Group at private consultancy Casella Stanger (now owned by Bureau Veritas).

Sally obtained her PhD from Imperial College, London in environmental science, later securing a DfID sponsored Post-Doctoral Fellowship in Borneo identifying optimal nitrogen conditions for logged forests.

Professor Rob Elliot – Director of Education, University of Birmingham
Professor Robert Elliott is an applied economist who works at the intersection of international economics, development economics, environmental and energy economics and international business.

He has a particular interest in the Chinese economy, firm behaviour, the impact of regulations on competitiveness and exports, energy efficiency, natural disasters and the impact of globalisation on the environment. Other research areas include multinationals and foreign direct investment; urban and spatial aspects of firm behaviour and the economics of climate change.

Rob currently holds the position of Director of Education in the economics department at the University of Birmingham.

Professor Peter Fryer – Professor, Chemical Engineering, University of Birmingham
Professor Peter Fryer is Professor of Chemical Engineering at the University of Birmingham and is currently investigating approaches and technologies for use in the reduction of energy at all stages of the food chain after being awarded a substantial grant from EPSRC.

The EPSRC Centre for Sustainable Energy Use in Food Chains will bring together multidisciplinary research groups of substantial complementary experience and internationally leading research track record from the Universities of Brunel, Manchester and Birmingham and a large number of key stakeholders to investigate and develop innovative approaches and technologies to effect substantial end use energy demand reductions. The Centre will engage both in cutting edge research into approaches and technologies that will have significant impacts in the future, leading towards the target of 80% reduction in CO_2 emissions by 2050, but also into research that will have demonstrable impacts within the initial five year lifetime of the Centre.

Professor Fryer is a Council Member at the Biotechnology and Biological Sciences Research Council (BBSRC), and is also member of the Editorial Board, 'Journal of Food Engineering', Innovative Food Science and Emerging Technologies, Soft Matter. He is an IChemE representative for the International Conference on Engineering and Food.

Peter Braithwaite – Director, Engineering Sustainability, Birmingham Centre for Resilience Research and Education
Peter Braithwaite is Director of Engineering Sustainability at the Birmingham Centre for Resilience Research and Education, University of Birmingham and an Examining Inspector with the Planning Inspectorate for Nationally Significant Infrastructure Projects.

He has had a varied international career in the construction industry and in built environment, gaining expertise in sustainability, urban regeneration, and geotechnical engineering, mining and environmental services. During his 27 years with Arup, he reached Director level and successfully developed both environmental and then sustainability businesses.

In 2008 he joined CH2M HILL to take on the role of Head of Sustainability for the London 2012 Olympic Development Agency Delivery Partner, with special responsibility for delivering energy, waste, water, materials, biodiversity and environmental impact sustainability targets.

Peter has special interests in sustainable urban regeneration, in particular investigating the cross discipline impacts of sustainable regeneration from planning, design, infrastructure, biodiversity and social impacts as well as the built form.

He has particular interest in developing frameworks, key performance indicators and monitoring and assurance tools for a variety of applications including cities, such as Masdar in the UAE and for strategic sustainability programmes for corporate business as part of organisational change to a more sustainable model.

He graduated from The University of Strathclyde, with a BSc (Hons) degree in Civil Engineering. After two years working for a site investigation contractor, he continued his studies gaining an MSc and DIC in Engineering Rock Mechanics from Imperial College, London.

He was conferred as Honorary Professor in the School of Engineering at the University of Birmingham in 2006 and joined the academic staff on a part-time basis in November 2012.

David Sanders, Director Innovation, The Carbon Trust
David has over 25 years' experience in strategy consultancy, corporate advisory and as a technology entrepreneur with a focus on energy, clean technology and telecoms. As Director of Innovation at the Carbon Trust, David works with early stage and corporate customers on venturing, strategy and innovation delivery in the energy and resource efficiency space.

Prior to joining the Carbon Trust, David spent 12 years running businesses that provided both strategic consultancy to large corporates and also commercialisation support to early stage companies, as well as launching new ventures. David has co-founded several technology businesses in food production, composite materials, internet telephony, and mobile telephony software.

He has an MBA (Finance) from Wharton and a degree in Mathematics from New College, Oxford.

Clive Hickman – Chief Executive, Manufacturing Technology Centre (MTC)

Prior to joining MTC in January 2011 Clive Hickman had over 35 years engineering experience in several roles within the automotive industry, culminating in the position of Head of Engineering for Tata Motors in India.

Born in Dudley in the West Midlands, he gained a first class honours degree and PhD in Mechanical Engineering and an MBA. He was a senior engineer with Rover Group before becoming Engineering and Group Operations Director at the Motor Industry Research Association working on product development and later joining Ricardo Consulting Engineers, where he held a seat on the board of Ricardo Plc and was managing director of Ricardo UK Ltd. During his career he has worked on a wide range of vehicle programmes including the development of a unique Bentley, which, along with Dr Phaefgan of VW, he presented to HM the Queen in 2002.

In 2005, he was approached by Ratan Tata with the idea to set up an engineering function for the Tata Motors in the UK and to manage the entire engineering operation for Tata Motors in India, responsible for some 6,000 engineers. During this period of extraordinary development in the automotive sector he was responsible for the ‘peoples car’ the Nano in India and the introduction of the Vista electric vehicle in UK.

Nick Winser – Chairman of the Energy Systems Catapult

Joining the Board of National Grid in 2003 responsible for UK and US transmission operations and becoming its UK and European CEO in 2011, until he left the company in 2015. In January 2015, Nick was appointed as Chairman of the Energy Systems Catapult, one of the latest technology and innovation centres set to open in the UK this year. Nick is also a Non Executive Director of Kier Group, Chairing its Safety, Health and Environment Committee.

Nick Chairs The Power Academy and CIGRE UK and is President of the European Network of Transmission System Operators for Electricity.

Nick serves on a number of charity boards – Way Ahead Support Services (affiliated to the Royal Mencap Society) and the Multiple Sclerosis Society. He is Vice President and Trustee to the Institution of Engineering and Technology Board of Trustees, Chairing its Membership and Professional Development Board.

Nick holds a BSc in Electrical Engineering and is a Fellow of The Royal Academy of Engineering, The Institution of Engineering and Technology, The Institution of Gas Engineers and Managers and The Energy Institute. He holds the rank of Major in the Engineer and Logistics Staff Corps (RE) V.

Co-ordinator

Co-Ordinator: Gavin Harper

Gavin Harper is Energy Development Manager for the Birmingham Energy Institute. His research concerns sustainable business models in the automotive industry. Gavin obtained his PhD from Cardiff University and MBA from Keele University. He sits on the Advisory Council of the National Energy Foundation. He has been published internationally by Mc Graw-Hill, New York, with books translated into Chinese and Korean and Italian.

Editor

Editor: David Strahan

David Strahan is an award-winning investigative journalist and documentary film-maker who specialises in business and energy. For a decade he reported and produced extensively for the BBC’s Money Programme and Horizon strands, and is the author of *The Last Oil Shock: A Survival Guide to the Imminent Extinction of Petroleum Man*, published by John Murray. He has edited several reports on cold and power.

APPENDIX 3 – WITNESSES

Andrew Atkins Chief Engineer, Technology Ricardo

Michael Ayres Deputy Chief Executive Officer, Dearman

Stephen Barker New Markets Associate, Siemens

Zoe Bengherbi Associate – New Markets, Dearman

Dr David Boardman Head of Strategic Projects, University of Birmingham

Mikele Brack Founder and Chief Executive Officer, City Impact Challenge

Sylvia Broadley Green Fleet Change Manager, Birmingham City Council

Adam Chase Director, E4Tech

Paul Coates Manufacturing Director, Iceotope

Professor Yulong Ding Founding Chamberlain Chair of Chemical Engineering, Highview-RAEng Chair of Cryogenic Energy Storage, University of Birmingham

Jeff Douglas Smart Systems and Heat Strategy Manager, Energy Technologies Institute

Professor Philip C Eames Professor of Renewable Energy, Director of the Centre for Renewable Energy Systems Technology, Loughborough University

Ian Ellerington Head of Innovation Delivery, Department of Energy and Climate Change

Professor Judith Evans Researcher, Air Conditioning and Refrigeration, London South Bank University

Tim Evison Senior Vice President, International Key Accounts, Messer Group

Tim Fox International Ambassador, Dearman, Previously Head of Energy, IMechE

Professor Jane Francis Director, British Antarctic Survey

Professor Colin Garner Perkins/Royal Academy of Engineering Professor of Applied Thermodynamics, Loughborough University

Professor Richard Green Alan and Sabine Howard Professor of Sustainable Energy Business, Imperial College, London

Matthew Hannon Research Fellow, Centre for Environmental Policy Imperial College, London

Gavin Harper Energy Development Manager, University of Birmingham

Robert Hurley Group Head of Refrigeration and HVAC Standards, Tesco

Pawanexh Kohli Chief Executive Officer and Chief Advisor, National Centre for Cold Chain Development

Professor Graeme Maidment Professor of Air Conditioning and Refrigeration, President Institute of Refrigeration, London South Bank University

Professor Tony Marmont Chairman, Fuels From Air

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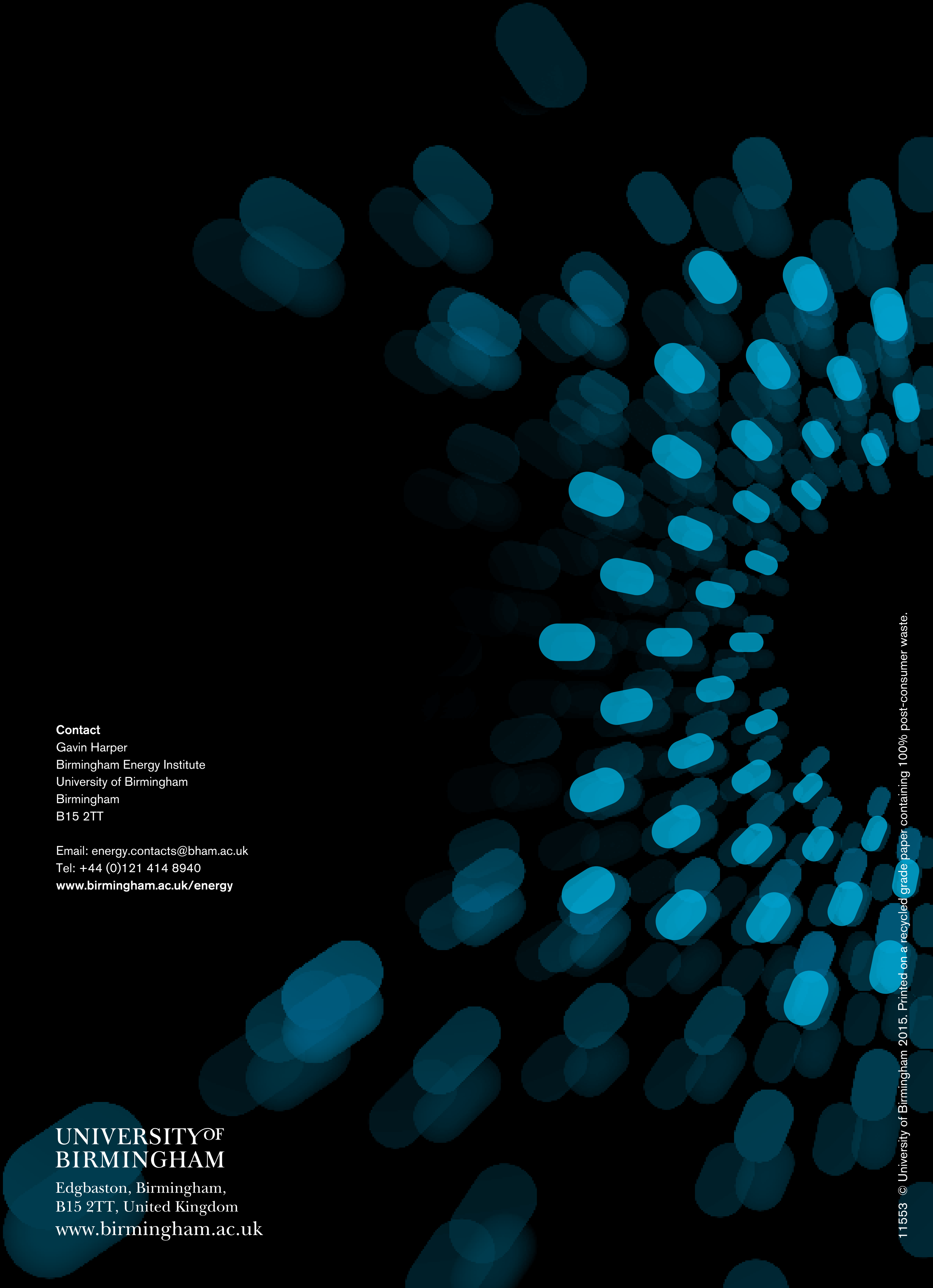

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