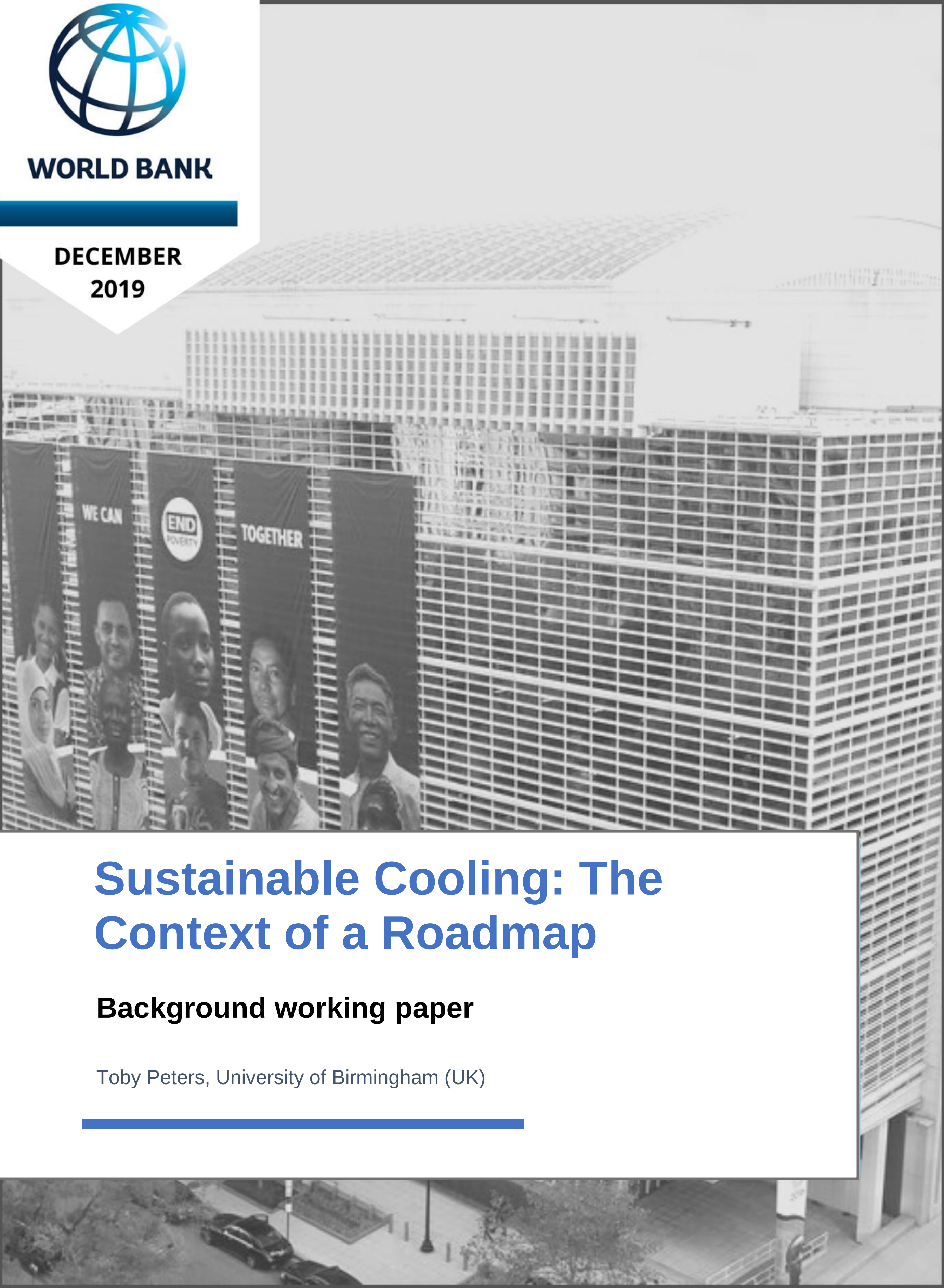
WORLD BANK

DECEMBER
2019



Sustainable Cooling: The Context of a Roadmap

Background working paper

Toby Peters, University of Birmingham (UK)

Table of Contents

Appendices

Figures

Tables

Context, Challenges and Possible Solutions to the Emerging Cooling Crisis

With climate change accelerating and increasingly impacting global development, the World Bank Group has identified “sustainable cooling”[1] as a new frontier, where several strands of the World Bank’s work intersect: (1) help client countries meet their national climate targets as part of their commitments under the Paris Agreement on Climate Change and the Montreal Protocol’s Kigali Amendment, (2) address adaptation and resilience challenges to the effects of climate change including increasing heat stress, and (3) foster income growth and raise productivity in poor countries to promote Sustainable Development Goals (SDGs), reduce poverty, protect people at risk and share prosperity among all.

Global action on sustainable cooling is now inevitable to achieve these goals. Not only the provision of cooling technology is a global challenge, but also the policies that guide the investments in cooling solutions and the industries that manufacture and supply these solutions are globally connected. The experience of the Montreal Protocol about restoring the ozone layer from climate-damaging refrigerants is a success story worthy to drawn on — it forged a sector plan approach that tackled for the first time the global supply of Ozone Depleting Substances (ODS).

The questions thus are: (1) which solutions are available to achieve sustainable cooling for all and (2) how can we collaborate – industry, governments, academia, and development institutions among others – to rapidly deploy these solutions and at scale? In short, how can we transform the cooling sectors and delivery access to cooling for all in the shortest possible time and in a sustainable manner.

With these questions in mind, the World Bank Group has embarked on an effort to (1) identify feasible solutions across all relevant sectors, (2) place these solutions in a development context, and (3) engage with various stakeholders to get their views and inputs on a Solution Roadmap for Sustainable Cooling.

This paper is an introduction to the context and status of the global sustainable cooling challenge. The paper was used as a basis for discussions during the kick-off stakeholders’ consultations workshop on the sustainable cooling roadmap in April 2019 in London. The paper will be used to develop sector specific studies and recommendations and contribute to the final sustainable cooling roadmap report.

The paper was authored by Toby Peters, Professor in Cold Economy at the University of Birmingham. This paper builds on the significant work that has been done in this area. It explores the implications of current projections in cooling demand, as well as a Cooling for All scenario in which global equitable access to cooling is achieved. The paper considers the current actions being taken by governments, industry, and others in expanding access to cooling while reducing climate impacts. Given that existing approaches to cooling are failing to adequately address the breadth and scale of the needs, the paper also explore the use of a holistic, system-driven approach that includes a radical reshaping of cooling provision and takes into account the cooling needs for all while addressing the challenges related to technology, operations, financing and consumer behavior to deliver universal access to cooling within the bounds of the Paris Climate Agreement targets. Recommendations are proposed as to how this could be achieved with appropriate support from the World Bank, governments, industry, and others.

---

[1] Cooling refers to any human activity, design or technology that dissipates or reduces temperatures and contributes to achieving: (i) reasonable thermal comfort for people, or (ii) preservation of products and produce (medicines, food), or (iii) effective and efficient processes (data centers, industrial or agricultural production). Sustainable cooling means cooling without climate impact in line with the objectives of the Paris Agreement on Climate Change. Measures that reduce the demand for artificial cooling (e.g. insulation, building design) are included in this definition.(UNEP and IEA (2019)

Executive Summary

Cooling for All – as means of achieving sustainable development

Universal access to clean cooling is critically important to the attainment of the UN Sustainable Development Goals. Access to vaccines and medicines is limited due to broken cold chains while more than 1.1 billion people are at risk of heat stress due to a lack of access to space cooling, with negative impacts on morbidity, mortality, cognitive function, productivity and economic outcomes.

Clean cooling can help to:

- Underpin health and keep homes, schools and workplace habitable and safe;
- Reduce post-harvest food loss – thereby protecting food volumes and quality, as well as facilitating efficient movement from farm to consumption center, to:
    - Increase economic growth and farmers' income;
    - Achieve nutritional security and deliver safe food to the wider population;
    - Improve resource efficiency.
- Meet essential demands for data centers.
- Reduce inequality.

The massive growth in demand for cooling needs to be managed within the constraints of natural resources and local economies, and underpins (not undermines):

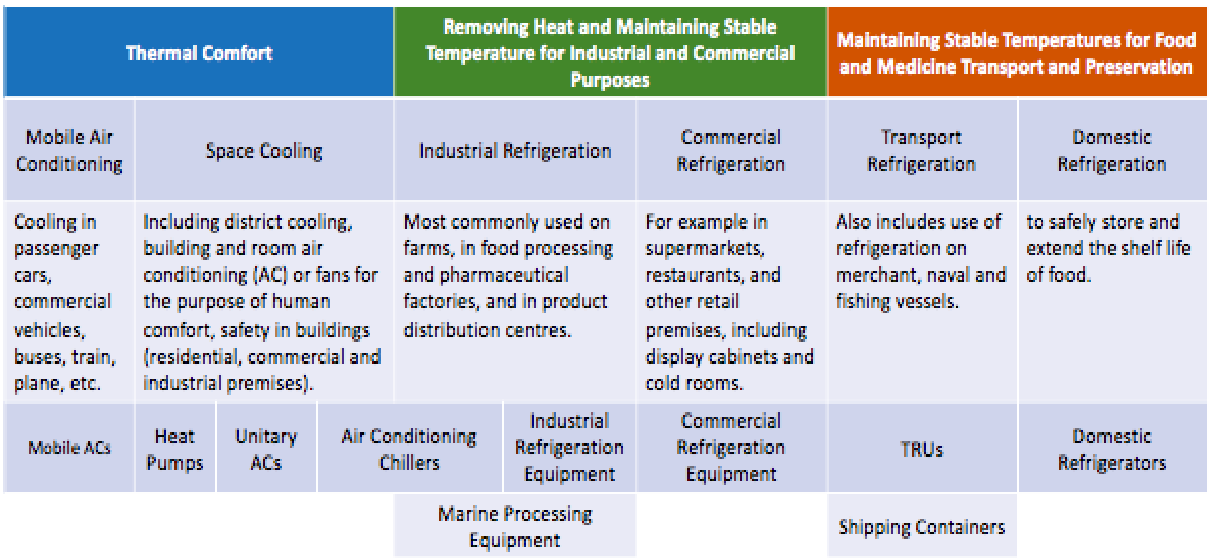
- Climate Change mitigation and pollution targets;
- Energy efficiency and resilience;
- Sustainable and affordable infrastructure.

However, penetrations of space cooling, industrial and commercial cooling, mobile cooling, and domestic refrigeration equipment vary widely across the world. Differences are especially pronounced in space cooling, domestic refrigeration, and mobile cooling equipment categories. Ownership of ACs has reached 90% among households in Japan and US compared to just 8% of the 2.8 billion people living in the hottest parts of the world.

It is estimated there are currently 3.6 billion pieces of cooling equipment globally. Current projections estimate that this will grow to nearly 9.6 billion cooling units by 2050.

This projection is likely to be conservative: to reach a cooling for all scenario we could see a further uplift of 56% on these figures (i.e. 14 billion cooling equipment units).

Main cooling applications and associated technologies



Thermal Comfort		Removing Heat and Maintaining Stable Temperature for Industrial and Commercial Purposes		Maintaining Stable Temperatures for Food and Medicine Transport and Preservation	
Mobile Air Conditioning	Space Cooling	Industrial Refrigeration	Commercial Refrigeration	Transport Refrigeration	Domestic Refrigeration
Cooling in passenger cars, commercial vehicles, buses, train, plane, etc.	Including district cooling, building and room air conditioning (AC) or fans for the purpose of human comfort, safety in buildings (residential, commercial and industrial premises).	Most commonly used on farms, in food processing and pharmaceutical factories, and in product distribution centres.	For example in supermarkets, restaurants, and other retail premises, including display cabinets and cold rooms.	Also includes use of refrigeration on merchant, naval and fishing vessels.	to safely store and extend the shelf life of food.
Mobile ACs	Heat Pumps Unitary ACs Air Conditioning Chillers	Industrial Refrigeration Equipment	Commercial Refrigeration Equipment	TRUs	Domestic Refrigerators
		Marine Processing Equipment		Shipping Containers	

Cooling technology today

Cooling technology has been used for thousands of years for a variety of applications. Cooling technologies can be divided into "cooling provision" and "cooling demand reduction".

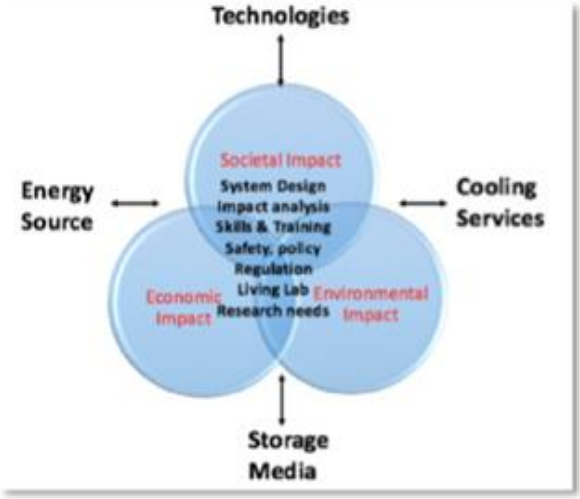
Cooling demand reduction technologies include:

- Thermal insulation
- Natural ventilation
- Shade and reduced solar gain
- Coatings and treatments e.g. in buildings and the food and drug sector

Within cooling provision electrically or mechanically driven Vapor Compression Cycle (VCC) has become the dominant technology in refrigeration and air conditioning (AC) applications due to its scalability, reliability and use of nontoxic and flammable refrigerants. VCC systems transport heat through a closed-loop cycle by compressing, condensing, expanding, and evaporating a working fluid (refrigerant). Most of the conventional refrigerants used in VCC based systems are potent greenhouse gases with significant ozone and / or climate impacts when leaked into the atmosphere.

- Alternate cooling methods have been developed, but with limited sector investment, and their use remains in niche applications. These include magnetic refrigeration; thermo-acoustic refrigeration; thermo-elastic cooling; Peltier effect cooling; absorption, adsorption, and vacuum cooling; and evaporative cooling.
- Some processes can harness "free" heat sinks such as bodies or water or novel approaches such as "sky cooling"; other technologies can harness waste heat of industrial processes, low grade geothermal and waste cold of LNG regasification. In addition to reducing demand for electricity, these technologies can reduce the urban heat island effect of AC units exhausting heat to the atmosphere. For instance, in Phoenix, USA, the outdoor night-time air temperature increases by up to 2°C because of the urban heat island.

  District cooling networks refers to the central provision of cooling within a defined service area. They provide a platform to aggregate cooling loads which is relevant for economy of scale and the use of business models such as "cooling as a service". These networks offer the opportunity for shifting to cleaner energy sources and for capturing available forms of waste resources (waste heat from industry for example) across multiple users.
- A range of storage devices that enable cold to be moved in space or time are available. They are "charged" by liquefying or freezing a substance and then absorb heat (provide cooling) by being melted or evaporated, i.e. ice, liquid nitrogen, or salt hydrates.



- Maintenance is essential to ensure technologies meet their performance targets; poor maintenance can increase energy consumption by up to 30%.

Environmental impact of cooling

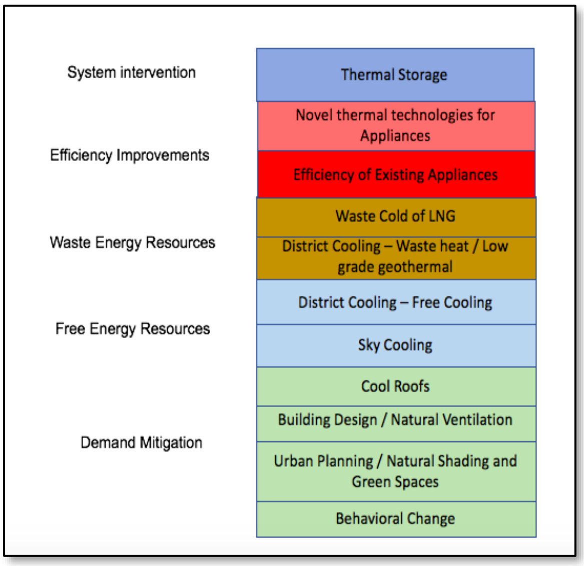
- Projected growth in cooling will currently have significant environmental impacts:
  - Directly, through increased levels of high global warming potential refrigerant leakage,
  - Indirectly, through increased energy consumption.
- The total energy consumption associated with cooling equipment today is estimated to be 3,900 TWhs – 15% of all electricity produced in 2017.
- In a business as usual scenario this is projected to rise to 9,477 TWhs by 2050. Associated CO2e emissions are expected to see 2.18 times increase and reach 8.971 GTCO2e, based on the current grid mix.
- In a universal access to cooling scenario, cooling related energy consumption could

be 19,600 TWhs and associated emissions would be 18.8GTCO2e based on the current technology mix.

- To green this volume of electricity would consume 68% of the IEA 2 Degree Scenario projected 2050 total global renewable energy capacity (solar and wind); and more than 100% of the IEA's Reference Technology Scenario.
- Cooling is also a major contributor to peak energy demand in many countries. Growth in cooling demand will have significant impact on the capacity needed for electrical systems worldwide.

Linkages to international agreements on climate change

- The United Nations Framework Convention on Climate Change was signed in 1992 and is designed to combat climate change by limiting CO2 emissions. To date, limited action on cooling has been taken by individual countries, with only 83 of the 197 signatories mentioning refrigeration or cooling in their nationally determined contributions, and only 29 countries have or are drafting National Cooling Action Plans.
- The Montreal Protocol on Substances that Deplete the Ozone Layer came into force in 1989 and includes the 2016 Kigali Amendment to phase down the use of hydrofluorocarbons. HFC phase down efforts are likely to be hampered by increased use of HFCs associated with a growth in the consumption of refrigeration technologies.



Intervention options

Achieving a goal of affordable access to cooling for all whilst meeting the targets of the Paris Climate Agreement will require action on both direct (refrigerant) and indirect (energy generation) emissions. The focus to date has been primarily on the impact of refrigerants on the ozone layer and climate.

Direct emissions from cooling and refrigeration are a result of the high global warming potential of refrigerants. Reductions in direct emissions can be achieved through:

- Reducing the number of refrigeration and air conditioning equipment,
- Reducing refrigerant leakage from cooling equipment during installation, servicing, maintenance, and disposal,
- Substituting current refrigerants with low or zero (natural) GWP alternatives.

However, direct emissions account for only 20% of the total GWP impact of cooling. Indirect emissions from refrigeration and cooling equipment account for 80% and are predominantly due to the electricity used to run this equipment, much of which is still generated from fossil fuels.

To reduce indirect emissions action is required across a range of factors:

- Energy demand mitigation – across all cooling applications via technical solutions for cooling equipment and building and urban design, and behavior change interventions towards equipment use and maintenance.
- Energy efficiency improvements - at the component level as well as at the overall system optimization and control.
- District cooling versus individual appliances.
- Preventive maintenance to ensure optimum performance of cooling equipment.
- Renewables and electricity network integration – particularly design of cooling equipment that enable demand management to limit peak load impact on electricity networks.
- Harnessing free and waste resources.

None of the above-mentioned, if implemented in isolation, will be sufficient to deliver access to cooling for all and simultaneously achieve the targets of the Paris Climate Agreement. What is required is a holistic system driven approach to:

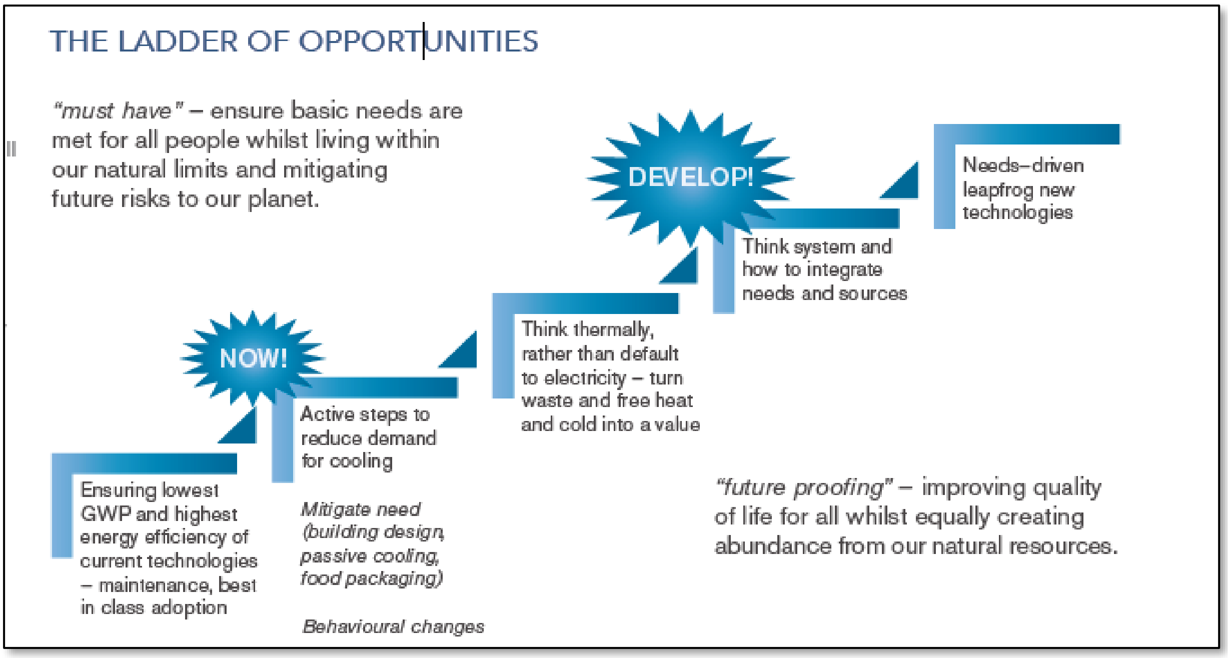
1. Identify cooling demand based on cooling services needed.in a driven manner.
2. Assess social and economic conditions and the energy landscape of the region under review.
3. Better consideration of the HVAC cooling loads within mobility; this will become increasingly important given both the projected growth in vehicles and the planned electrification of the transport network.
4. Highlight behavior change and demand mitigation strategies likely to be effective whilst maintaining required service levels.
5. Explore opportunities to harness free cooling and synergies between processes, waste resources and cooling needs that can further reduce the required cooling requirement.
6. Match technology characteristics to local conditions and residual cooling demand in a way that minimizes cost and carbon whilst maintaining the required service levels.

This should be reflected in a merit order of interventions based on a range of values including cost of mitigation or adaptation impact, likely starting with demand mitigation.

Ladder of opportunities

Given the current rapid growth in cooling demand and the life expectancy of major appliances which typically ranges from 10-20 years, there is a need for both short-term interventions to reduce energy demand now, deliver incremental efficiency improvements and embed the most energy efficient technologies as well as medium to long term interventions on system redesign. This step change interventions would first ensure access to cooling for all is within our climate and resource constraints, but also to future proof society.

With a series of projects focused on accelerated deployment of energy efficient air-conditioners, the focus of new work should include the system design.



Skills and maintenance

Poor skills of technicians are a factor in poor maintenance of refrigeration and cooling equipment. Poorly maintained equipment tends to cool less effectively, leak more refrigerant and use more energy. Utilizing badly maintained systems at large scale can increase direct and indirect emissions across the sector by 10-30%.

In the "cooling for all scenario", the number of trained refrigeration technicians needed for maintenance of total installed cooling units is projected to be 3.8M in 2050 compared to 975,000 technicians currently in the cooling market.[2] It is worth noting that 80% of RAC equipment is projected to be deployed in the developing markets by 2030.

Commercial and policy options

Market failures currently limit access to cooling and do not incentivize the uptake of climate-friendly cooling solutions. Several business model innovations and policy interventions have been identified, which, if implemented, could address these failures.

Access to cooling

In many countries there are several market failures that limit access to cooling, these include:

- Insufficient financial resources to mitigate demand or purchase, install and operate cooling equipment,
- Lack of access to electricity,
- Lack of integration of non-electric resources,
- Access to technology.

There are also additional barriers to deploying energy efficient cooling. Business model innovations could contribute to tackling investment and energy access challenges, for example:

- Aggregate individual demands to create “time of use” trading groups.
- Multiple stakeholders whose production volumes are small could pool resources to access cooling infrastructure, i.e. farmers at time of harvest.
- Cooling as a Service, where clients are charged per unit of cold air consumed.
- Financing schemes for purchasing efficient appliances/home improvements/ commercial renovations.

Policy interventions implemented in parallel could expand access and overcome barriers to uptake, these include:

- Renewable thermal incentives, not just electricity generation,
- Policy makers capacity building e.g. through awareness raising, best practice needs assessment and policy intervention tools,
- Information and Communication with relevant stakeholders to build understanding of the importance of cooling to societal and development goals,
- Education and Skills Development to ensure effective installation, maintenance and use of cooling equipment,
- Financing Provision, e.g. coordinating provision of finance or bulk procurement to overcome initial investment challenges to purchasing cooling equipment
- Incentives, e.g. preferential import tariffs, reduce interest rate loans or direct subsidies.

These however must be focused on clean cooling resources, not simply access to cooling.

Emissions reduction

Market failures that are currently barriers to emissions reduction in the cooling sector include:

- Lack of awareness amongst users of cooling equipment energy consumption, emissions impacts and true running cost,
- Lack of skills - insufficient numbers of properly trained technicians, leading to low equipment take up and poor maintenance,
- Dominance of first cost considerations in purchasing decisions,
- Lack of stakeholder cohesion (split incentives) regarding purchase, maintenance and operating costs in commercial settings,
- Lack of political interest in energy efficiency regulations, e.g. Minimum Efficiency Performance Standards,
- Lack of knowledge or interest in system solutions including free and waste energy resources,
- Market structure where significant power is held by a small number of organizations, limiting innovation,
- Lack of data, limiting understanding of scale of challenge and efficacy of proposed measures,
- Insufficient research and development funding,

---

[2] This figure is based on data for the EU which is likely to be modified with a high-level current gap analysis, awaiting new data points.

- Lack of integrated system tools and demonstrators.

Private sector role

To promote sustainable cooling, the private sector plays a key role in driving sustainable cooling deployment through the development, manufacturing of climate-friendly cooling technologies as well as through its procurement and investment decisions.

Private sector entities can facilitate the servitization concept of cooling through innovative business model, which include:

- Purchase or leasing combined maintenance contracts with efficiency incentives,
- District cooling systems,
- Cooling as a service.

A wide variety of policy interventions are identified, the correct mix of which would be country specific, but could include:

- Renewable thermal incentives (free cooling, harnessing waste, and natural resources),
- Training capacity development and provision,
- Provision of funding and development of financial instruments, including loans, enhanced capital allowances, co-opetition funds, coordination of access to capital for Cooling as a Service providers, R&D funding,
- Regulation and building codes or other standards to force purchasing and behavioral changes,
- Urban planning and design.

A focus on energy efficiency (MEPS) of driven appliances must not preclude the longer-term integration of free and waste thermal resources essential to meet 2030 and 2050 goals.

An integrated set of interventions

How we manage our growing demand for cooling will have enormous implications for our society, economy, energy demands and climate change. In order to achieve sustainable cooling that is affordable, financially sustainable and accessible to all we need a new needs-driven, integrated system-level approach that incorporates 'thinking thermally' into our energy strategies, including: mitigating demand; understanding the size and location of the thermal, waste and wrong-time energy resources; understanding novel energy vectors, thermal stores, clean cooling technologies and new business models; and integrating these resources optimally with various cooling loads.

A set of interventions that both mitigates demand today and ensures more fundamental system changes will be needed. Key actions have been identified to achieve this:

- Assessment of cooling needs to meet SDG goals and climate change mitigation targets, including development of cooling related services, or demand-based outcome models.
- Joined-up merit order understanding of interventions based on energy requirements, emissions, and cost factors (system / total cost of operation) to provide an ascending order of cost of impact. Deploying solutions in this way could minimize infrastructure requirement, cost of generating more electricity.
- Using data analytic and modeling capabilities to map and predict temporarily varying social, economic, health, etc. cooling demands of the community and explore technology and operational changes with the goal of meeting those needs whilst reducing emissions and costs.
- Acceleration of behavior change and demand-side management, including building an improved understanding of user needs, an inventory of available technologies and cost-benefit assessments of different technologies and their associated emissions.
- Technology acceleration: a framework that includes research, investment, product development and demonstration and deployment of innovative technologies.
- Demonstration of new solutions, e.g. piloting of representative market-embedded multi-service Community Cooling Hubs and Clean Cold Chain Living Lab to test, validate and demonstrate innovative and integrated solutions (technology and business model) in real world-based controlled environments.
- A cross-sector skills roadmap that identifies and addresses the training and skills needs for product development, installation and

  maintenance, and improved usage practices.
- Business model innovation, including business model definition and funding for business model simulation, innovation development, demonstration and scale-up.
- Integrated policy intervention frameworks relevant to OECD, Upper Middle Income, Lower Middle Income and Least Developed Countries. This will include segment specific policy recommendations, capacity building, education and skills development, funding and financial instruments, regulation, and engagement of industry.
- Financing, both for accelerated technology development and deployment of cooling infrastructures that can harness under-utilized thermal and waste resources.
- Customer and policymaker information dissemination: leveraging current efforts, design, and dissemination of a program of information that:
  - raises awareness among customers and policy makers of cooling issues and possible actions,
  - stimulates development and adoption of nationally determined contributions (NDCs) and nationally appropriate mitigation actions (NAMAs) for cooling related emissions,
  - makes available information on total-cost-of-operation and models that are intelligible to domestic and commercial consumers.

Unintended consequences

Introducing more affordable and readily available means of cooling in food supply chains and the built environment is not just a matter of adding cooling to the status quo; it will introduce major shifts to dynamic socio-technical systems as well as the wider environment and eco-systems. These could result in several unintended and sometimes negative, as well as positive, effects. It is important to try to identify and plan for these in advance.

For example, a cold chain will help reduce food loss, in itself a major source of CO2 emissions, and thereby potentially reduce the need for deforestation by ensuring an increased proportion of production reaches the market from existing land resources utilized for agriculture. It could equally allow farmers in developing economies to transition from staple to high value (but temperature sensitive) horticulture. The latter shift could have implications for water resources where farmers move to more water demanding produce. Equally, cold chain-enabled food processing at the farm can capturing value, but also increased local CO2e emissions, environmental pollution, and packaging – with implications for waste streams and resource use.

Refrigeration in homes can change cooking habits, lifestyles and health outcomes. As fridges and microwaves become more common in kitchens, traditional cooking appliances and methods are less used. Over time this affects kitchen architecture, building design, diets and health. Domestic refrigeration can change shopping habits and affect local marketplaces.

Drawing on a broad and cross-disciplinary analysis of the impact of refrigeration to-date, we can anticipate many of the consequences of a widespread adoption of cold chains and cooling for all across the developing world.

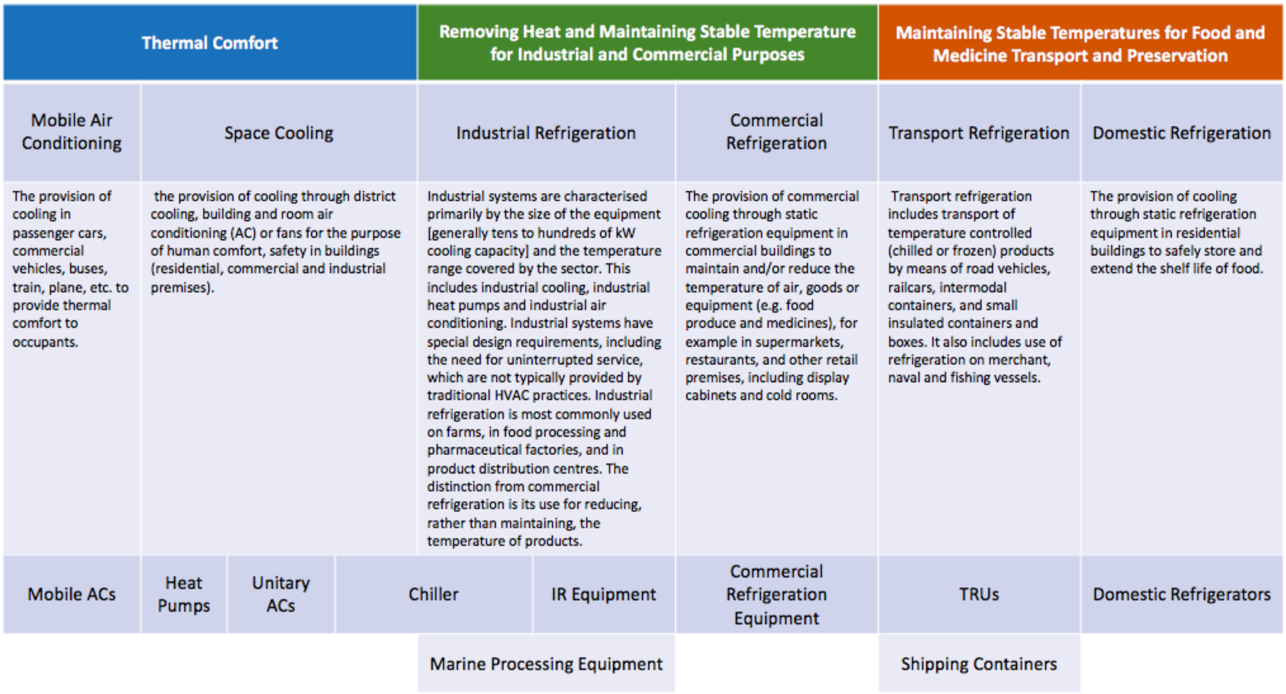
Introduction

Cooling has been used for thousands of years and evolved out of our need to preserve food as well as create comfortable environments in which to live and dates back thousands of years. (See Appendix 1 for a summary of the history of cooling).

Today, artificial, or mechanical cooling is used in a wide range of industrial, commercial, and domestic applications. It underpins several critical services on which we rely, and is a key enabling technology for a wide range of industries. Cooling refers to any human activity, design or technology that dissipates or reduces temperatures and contributes to achieving:

- Reasonable thermal comfort, which is needed for people's wellbeing and for productivity. Growth in space and mobile cooling has been increasing, driven by global warming/climate change, and increasing levels of urbanization around the world.
- Effective and efficient processes, through delivery of stable temperatures— critical to several industrial or agricultural processes and mining, datacenters, etc.
- Preservation of food and medicines, which is essential to ensure that the quality is maintained when they are processed or manufactured, as well as transported from production site to consumers. Safe transit of food and medicine allows access to these goods and prevents wastefulness.

Sustainable - or "clean" - cooling means cooling that uses climate friendly refrigerants and without other environmental damage including climate impact, in line with the objectives of the Paris Agreement on Climate Change and the Montreal Protocol. Clean cooling necessarily must be accessible and affordable to help deliver our societal, economic and health goals.



Thermal Comfort		Removing Heat and Maintaining Stable Temperature for Industrial and Commercial Purposes		Maintaining Stable Temperatures for Food and Medicine Transport and Preservation	
Mobile Air Conditioning	Space Cooling	Industrial Refrigeration	Commercial Refrigeration	Transport Refrigeration	Domestic Refrigeration
The provision of cooling in passenger cars, commercial vehicles, buses, train, plane, etc. to provide thermal comfort to occupants.	the provision of cooling through district cooling, building and room air conditioning (AC) or fans for the purpose of human comfort, safety in buildings (residential, commercial and industrial premises).	Industrial systems are characterised primarily by the size of the equipment [generally tens to hundreds of kW cooling capacity] and the temperature range covered by the sector. This includes industrial cooling, industrial heat pumps and industrial air conditioning. Industrial systems have special design requirements, including the need for uninterrupted service, which are not typically provided by traditional HVAC practices. Industrial refrigeration is most commonly used on farms, in food processing and pharmaceutical factories, and in product distribution centres. The distinction from commercial refrigeration is its use for reducing, rather than maintaining, the temperature of products.	The provision of commercial cooling through static refrigeration equipment in commercial buildings to maintain and/or reduce the temperature of air, goods or equipment (e.g. food produce and medicines), for example in supermarkets, restaurants, and other retail premises, including display cabinets and cold rooms.	Transport refrigeration includes transport of temperature controlled (chilled or frozen) products by means of road vehicles, railcars, intermodal containers, and small insulated containers and boxes. It also includes use of refrigeration on merchant, naval and fishing vessels.	The provision of cooling through static refrigeration equipment in residential buildings to safely store and extend the shelf life of food.
Mobile ACs	Heat Pumps Unitary ACs	Chiller IR Equipment	Commercial Refrigeration Equipment	TRUs	Domestic Refrigerators
		Marine Processing Equipment		Shipping Containers	

Table 1 - Main Cooling Applications (NB: See Appendix 2 for more details of the cooling market segments)

A lack of access to cooling is now recognized as a major constraint on people's daily lives, especially poor people in areas of hot climate, for example:

Heatwaves kill about 12,000 people annually across the world,[3] and this figure is forecasted to rise to 255,000 by 2050.

---

[3] WHO (2014)

In developing countries, around 40% of harvested food is lost before it reaches the consumer due to a lack of the cold chains needed to preserve fresh food. This has a significant negative impact on farmers' incomes and malnutrition as well as a significant waste of resources.[4]

Nearly 50% of freeze-dried and 25% of liquid vaccines are wasted each year primarily because of broken cold chains.[5]

With populations growing, rapid change in demographics, continued urbanization and climate change, the need for cooling is expected to increase. By 2050, projections suggest that there could be more than 9.5 billion cooling appliances worldwide – more than 2.5 times today's ~3.6billion.

Under these projections though, much of the world would still only have low penetration levels of cooling. We would still have unacceptable levels of food loss; many of the world's population would be experiencing life threatening temperatures, and medicines and vaccines would be spoiled in the supply chain.

Furthermore, without a radical new approach to addressing the cooling challenge our global demand for cooling energy could increase five times over the next 30 years.[6]

---

[4] UNFAO

[5] WHO

[6] University of Birmingham (2018)

1. Cooling for All – as Means of Achieving Sustainable Development

Universal access to clean cooling is critically important to the attainment of the UN Sustainable Development Goals. More than 1.1 billion people face immediate risks including malnutrition and extreme poverty due to a lack of access to cooling. Access to vaccines and medicines is limited by broken cold chains while increasingly larger percentages of the world's population are at risk of heat stress due to a lack of access to space cooling, with negative impacts on morbidity, mortality, cognitive function, productivity and economic outcomes.

Global access to sustainable, affordable, and resilient cooling is achieved to

- Underpin health and deliver habitable, safe housing and workplace.
- Reduce post-harvest food loss – thereby protecting food volumes and quality, as well as facilitating efficient movement from farms to consumption centers, so as to
    - Enhance economic growth and farmers' income.
    - Achieve nutritional security and deliver safe food to the wider population.
    - Improve resource efficiency.
- Meet essential demand for data centers (be it for health centers, weather apps or trading platforms for farmers, or rural education and day to day communication, electronic banking etc.)
- Reduce inequality.

The massive growth in demand for cooling is managed within the constraints of natural resources and local economies, and underpins (not undermines)

- CO2, Climate Change mitigation and pollution targets.
- Energy efficiency and resilience.
- Sustainable and affordable infrastructure.

The Sustainable Development Goals (SDGs) are a collection of 17 global goals set by the United Nations General Assembly, which came into force on 1st of January 2016. The SDGs aim to end all forms of poverty, fighting inequalities, resource management and tackling climate change by 2030, ensuring that no one is left behind.

Cooling sits at the nexus of this challenge: a report published by the University of Birmingham Energy Institute in January 2017 pointed out that achieving all 17 of the SDGs would depend to a greater or lesser extent on developing clean cooling strategies[7] – and for many Goals, clean cold would be vital. But to date cooling has been largely ignored and as stated in the Sustainable Energy for All report: "Given that millions of people die every year from lack of cooling access, whether from food losses, damaged vaccines or severe heat impacts, this is a glaring omission".[8]

Universal access to cooling or Cooling for All is becoming an issue of equity, and as temperatures hit record levels it will threaten the life of many. There are already more than 1.1 billion people globally who face immediate risks including malnutrition and extreme poverty due to a lack of access to cooling.[9] This includes an estimated 470 million people living in poor rural areas without access to electricity and cold chains for food and medicines,[10] and 630 million slum dwellers living in hotter-climate urban areas where electricity services do not exist, are intermittent, or are too expensive.

1.1. Cold Chains for Health and Wealth Promotion

The Cold Chain is an integrated, seamless and resilient network of refrigerated and temperature-controlled pack houses, distribution hubs and vehicles used to maintain the safety, quality and quantity of food, while moving it swiftly from farm gate to consumption center.

The cold chain could enhance economic wealth, cash flow and security for farmers and improve food quality, safety, and value to the customer. Effective cold chains are needed to address rural poverty and global health. In developing markets, 40% of food is lost post-harvest - in the global context of 750 million subsistence farmers and where more than 820 million vulnerable people are malnourished. Indeed, malnutrition is the largest single contributor to disease in the world,[11] more children die each

---

[7] Clean Cold and the Global Goals: www.birmingham.ac.uk/Documents/college-eps/energy/Publications/Clean-Cold-and-the-Global-Goals.pdf

[8] Chilling Prospects: Cooling for All

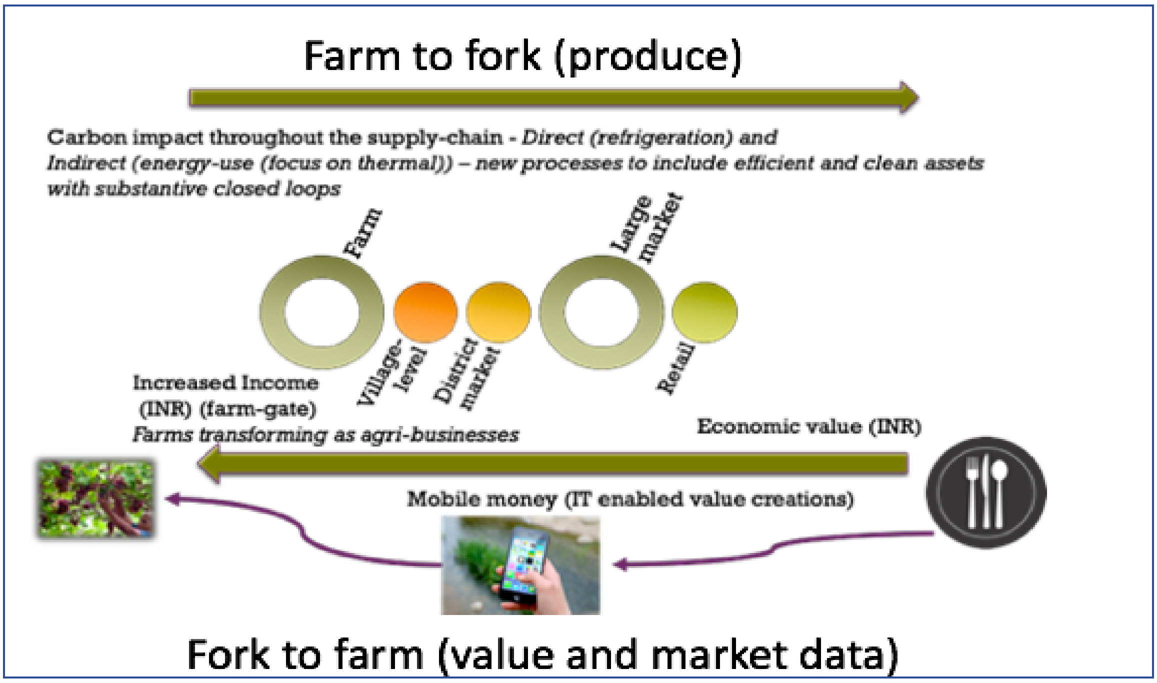
[9] ibid

[10] it should be noted that globally 75% of the billion people living in extreme poverty are rural dwellers dependent on agriculture

[11] UN Standing Committee on Nutrition

year from malnutrition than from AIDS, malaria and tuberculosis combined. The WHO estimate that 600 million people – almost 1 in 10 worldwide – fall ill every year after eating contaminated food, and 420,000 die.[12] Furthermore, ineffective cold chains are also hampering global vaccination programs. The World Health Organization estimates that nearly 50% of freeze-dried and 25% of liquid vaccines are wasted each year primarily because of broken cold chains.

Cold chains do not just enhance food security, they also allow farmers to earn more by maintaining the quality of their produce and selling it further afield, especially when this means they can reach more distant cities and major centers of consumption. This is only true if the farmer can get their produce to market in the same condition as one imported by airfreight from a highly developed global agri-business and cold chain. What is more, the market connectivity afforded by a cold chain enables and incentivizes farmers to raise their output because they can earn more from what they produce.



Post-harvest food loss due to the lack/inefficiencies of cold chains is also a major contributor to greenhouse gas emissions. In 2011 this accounted for about 1 G ton of CO2 equivalent; more than the total GHG emissions of road transportation in the EU in 2012 (0.9Gtons).[13] The IFC Creating Markets for Climate Business report refers to "given that most food loss and waste in developing countries occurs during production and after it is harvested, the greatest potential for reduction is investment in infrastructure related to storage, transport, cold chains, and distribution."[14]

1.2. Space Cooling in a Changing Climate

More and more people are being put at risk of heat stress due to climate change. It is that between 1.8 billion and 4.1 billion people in the Global South do not have adequate access to space cooling and may need AC to avoid heat related stresses under current climate and socio-economic conditions.[15] Heat stress is associated with increased morbidity and mortality, cognitive impairment, limited productivity, and economic losses.[16] It is often the poorest who are most vulnerable to heat stress due to inadequate housing conditions, the inability to afford cooling solutions and a lack of electricity access.

Today heatwaves kill an estimated 12,000 people annually across the world. The World Health Organization forecasts that by 2050, the annual death toll could reach 260,000 unless governments

---

[12] WHO (2015) report

[13] http://www.foodcoldchain.org/wp-content/uploads/2016/07/Reducing-GHG-Emissions-with-the-Food-Cold-Chain-NOV2015.pdf

[14] Creating Markets for Climate Business, IFC

[15] Mastrucci et al. (2019)

[16] Ibid

(primarily cities) adapt to the threat.[17] Already 30 percent of the world's population, are at risk of potentially deadly heat exposure for more than 20 days per year; and by 2100, up to three-quarters could experience this risk.[18]

1.3. The Energy and Climate Challenge

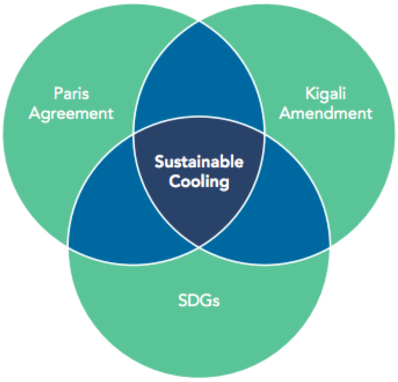
Global demand for cooling is already straining electricity grids and causing high levels of greenhouse gas (GHG) emissions; double that of aviation and maritime combined. By 2050, projections suggest that there could be more than 9.5bn cooling appliances worldwide – more than 2.5 times today's ~3.6bn. However, even at this rate the world will still not achieve Cooling for All by mid-century. Cooling for All could require closer to 14bn cooling appliances by 2050 – an additional 4.5bn appliances compared to the current forecast. Our global demand for energy for cooling could, without intervention, increase more than five times over the next 30 years.

Traditional cold chain infrastructure places a burden on the environment since refrigeration equipment is energy intensive and a source of greenhouse gases. Also, food waste due to lack of refrigeration causes significant GHG emissions

Keeping products cold throughout the mobile portion of the cold chain (such as trucks, trains, and ships) accounts for 7% of global hydrofluorocarbons (HFC) consumption. This contributes to 4% of the total global warming impact of moving all freight (refrigerated or not).[19] Furthermore, diesel-powered transportation refrigeration units consume up to 21% more than a non-refrigerated diesel powered truck,[20] which will have significant implications on climate change with the rapid roll-out of new cold chains in developing countries.

As we migrate from fossil fuels to renewables, we need to reshape the cooling landscape; combining technology, operations, financing, and consumer behavior in a system perspective, which is both inclusive and environmentally sustainable.

Clean cooling has the potential to advance three internationally agreed goals simultaneously: the Paris Climate Agreement; the United Nations' Sustainable Development Goals; and the Montreal Protocol's Kigali Amendment. In other words, it could address poverty, reduce food loss, improve health, raise energy efficiency, manage our natural resources, support sustainable cities and communities, phase out refrigerants and combat climate change - concurrently.



The challenge now is how to embed this approach quickly enough to avoid lock investment in highly-polluting conventional equipment – or sub-optimal alternative approaches –for years or decades to come. The following chapters of this report examine how this might be achieved.

---

[17] WHO (2014)

[18] Mora, C et al. 2017. "Global risk of deadly heat"

[19] Greenbiz, October 18, 2013. How Coke, UTC are cooling the cold chain's climate impact

[20] ADEME (French Agency) 2012, 'Comité de gouvernance de la base d'impacts ACV pour l'affichage' présentation, Slide 20

2. Cooling Technology Today

Cooling technologies can be divided into “cooling provision” and “cooling demand reduction”. Cooling demand reduction technologies include:

- Thermal insulation
- Natural ventilation
- Shade and reduced solar gain
- Coatings and treatments e.g. in buildings and the food and drug sector

Within cooling provision electrically or mechanically driven Vapor Compression Cycle (VCC) based technologies dominate refrigeration and air conditioning applications.

- Alternate cooling methods have been developed but remain for use in niche applications because they have not achieved the scale need to lower costs. These include magnetic refrigeration; thermo-acoustic refrigeration; thermo-elastic cooling; Peltier effect cooling; absorption, adsorption and vacuum cooling; and evaporative cooling.
- Some processes can harness “free” heat sinks such as bodies or water or novel approaches such as “sky cooling”; other technologies can harness waste heat of industrial processes, low grade geothermal and waste cold of LNG regasification. Along with reducing demand for electricity, these can reduce the heat island effect of AC units exhausting heat to atmosphere. Today AC units in Phoenix, USA, increase the night-time air temperature outside by up to 2°C.
- District cooling networks which exploit economies of scale to offer building cooling as a service are in use in some countries. Aside from the scale economy advantage, these networks offer the possibility of sharing the benefit of free or waste resources across multiple users.
- A range of useful technologies are available that can store cold and enable it to be moved in space or time. They are “charged” by liquefying or freezing a substance and then absorb heat (provide cooling) by being melted or evaporated i.e. ice, liquid nitrogen or salt hydrates.

Maintenance is essential to ensure technologies meet their performance targets; poor maintenance can increase energy consumption by up to 30%.

A few cooling technologies dominate the marketplace. The most common used cooling device is the electric fan. There are 2.3bn fans are in use around the world (IEA, 2018), compared to~1.6bn domestic refrigerators, 1bn stationary air conditioners of various types and 1bn pieces of mobile air conditioning equipment (GCI). However, fans are a transitional technology (as incomes rise, people often shift to different technologies like air conditioning) and their energy consumption though significant (~80TWh in 2016) is exceedingly small compared to other forms of cooling.

Ownership of ACs has reached 90% among households in Japan and US,[21] however, among the 2.8 billion people living in the hottest parts of the world, AC ownership is only 8%. Likewise, refrigerators are the most widely owned appliances among households in developed countries. In much of the developing world, they are still considered luxury products and ownership is low.

2.1. Vapor Compression Cycle

The Vapor Compression Cycle (VCC) dominates both refrigeration and air conditioning applications. VCCs exploit the fact that nearly all gases cool (absorb energy or heat) when they expand and get hot when they are compressed (expel energy or heat).

A VCC moves heat from one place to another and has the following key steps (see figure 1):

1. A refrigerant gas is compressed causing its temperature and pressure to rise
2. Heat is rejected to the environment via a heat exchanger called a condenser. This causes the temperature of the gas to fall whilst the pressure is more or less maintained.
3. The gas is expanded across a thermal expansion valve (TXV). This causes a further decline in temperature and large pressure drop in the gas to the point where it becomes a liquid.
4. The liquid is then passed through a heat exchanger that absorbs heat from the object being cooled (such as food in a refrigerator), which raises the liquid’s temperature so that it boils and becomes a gas again. i.e. the cooling is provided when the rejected heat is absorbed.
5. The cycle repeats from step 1.

---

[21] IEA, Future of Cooling

Historically, technology development focus has been on component and system level optimization of VCCs.

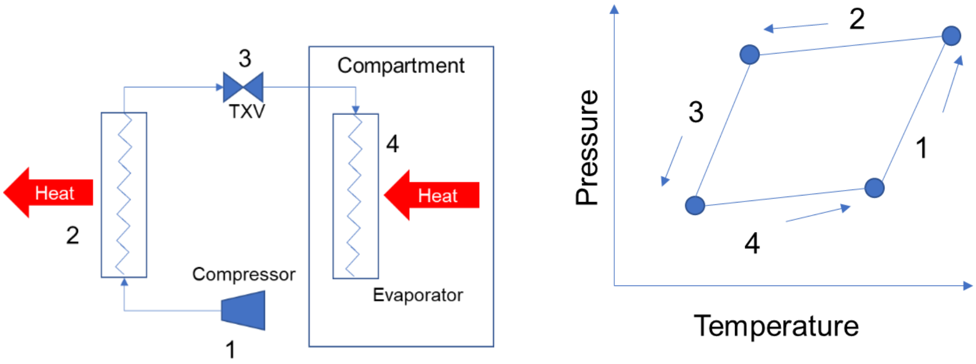


Figure 1 - Vapor Compression Cycle Operation

2.2. Other Cooling Technologies and Solutions

A wide range of other cooling technologies exist which have more niche applications, figure 2 provides an indication of the breadth of options available. However, none of these technologies have yet challenged the market dominance of VCCs.

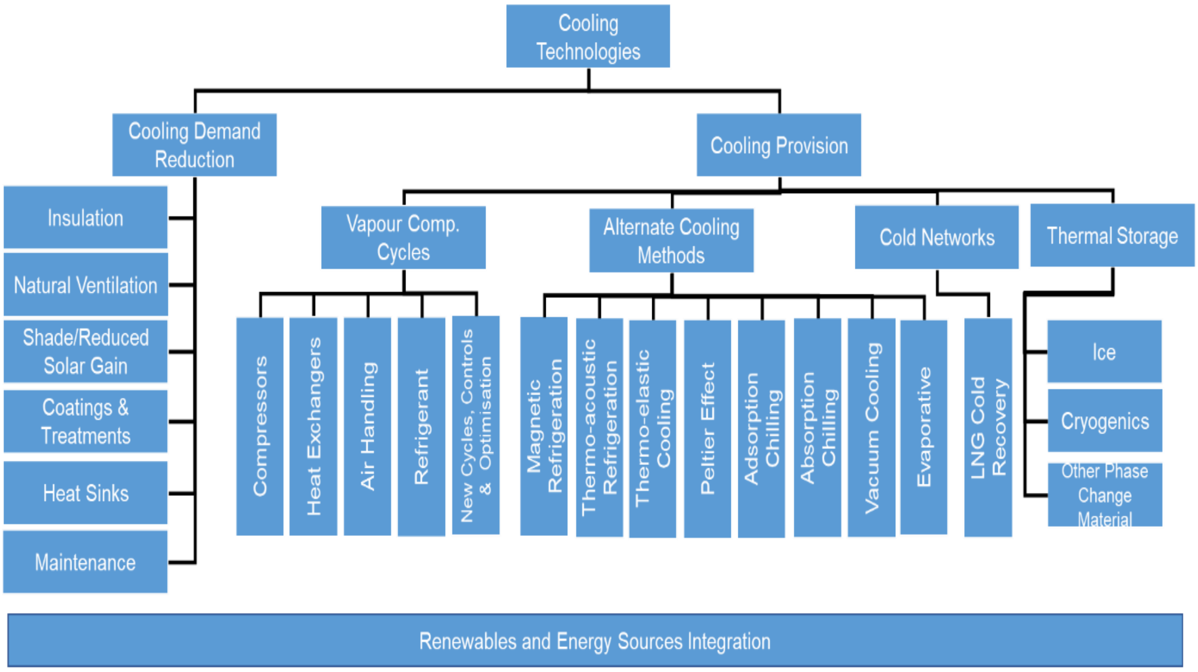


Figure 2 - Cooling Technologies

2.2.1. Cooling Demand Reduction Technologies

Cooling demand reduction technologies are a suite of methods designed to reduce the requirement for active cooling provision and associated energy consumption, emissions, and costs. They include:

- Thermal insulation – which acts as a barrier to reduce heat transfer into a space. It is commonly used in both buildings and refrigerated boxes.

- Natural Ventilation –most common in buildings, operates by allowing air to flow through a building along carefully designed paths, it is possible to maintain a building at a comfortable temperature in many climates year-round using this method.
- Shade and reduced solar gain – by protecting a space from direct sunlight, heat absorbed from solar radiation can be reduced which in turn reduces the need for cooling. This technique is most common in building applications but is also sometimes used in food preservation applications.
- Coatings and Treatments – innovation in the chemicals industry has produced a range of products that can reduce cooling demand. In the building sector, highly reflective coatings that reduce solar radiation absorption have been developed. In the food and drug sector a variety of treatments and coatings have been developed that extend shelf life by trapping moisture, inhibiting oxidation processes or other means.
- Heat Sinks – substantial "free" cold resources are available that can be used to make mechanical heat removal more efficient. Large bodies of water, the ground and even liquefied natural gas (LNG) have all been used at various times for both comfort cooling and refrigeration applications.
- Maintenance – how well cooling equipment is maintained (e.g. cleanliness, refrigerant charge, how intact the insulation is etc.) could have substantial impacts on both its effectiveness and its energy consumption. Performing proper maintenance of cooling equipment can substantially reduce demand.

2.2.2. Alternate Cooling Methods

A variety of alternatives to the VCC have been proposed over the years. To date they have only found niche uses because they cannot compete with the efficiency and cost of the incumbent VCC technology, a 200-years old that is manufactured at largescale. Alternatives include:

- Magnetic Refrigeration which relies on magnetizing and demagnetizing a magnetocaloric substance. The magnetization process causes the temperature of the substance to change which means that heating or cooling effects can be generated. Whilst prototypes have been built of a variety of refrigeration applications, no mass market products exist yet though companies like Cooltech and Camfridge are continuing to develop technology.
- Thermo-acoustic Refrigeration utilizes sound waves to compress and expand gas in an enclosed space. The technology has been used in some aerospace applications where the lack of refrigerant and moving parts has been desirable. Sound energy BV are developing this technology for medium scale applications.
- Thermo-elastic Cooling utilizes a property of certain shape memory alloys that causes them to absorb or reject heat as they are deformed. Much like magnetic systems, this affect can be multiplied through heat removal to generate cooling effects. The technology is being researched for air conditioning applications in academic institutions. Research teams from MIT are working on lab-based systems funder by the US Department of Energy.
- Peltier effect cooling devices work by passing current across the joint between two different conductive substances to develop a temperature difference. This "solid state" or "thermo-electric" cooling process is used in applications where precision or compactness is valued. Peltier effect coolers are commercially available and used in niche applications. Phononic have developed several refrigeration devices which they are marketing to the commercial and laboratory refrigeration segments.
- Absorption, adsorption, and vacuum cooling all work by exploiting the fact that water boils at a much lower temperature when it is under vacuum. By creating a vacuum and boiling water (which absorbs a great deal of heat), these technologies can cool spaces and products. Sorption technologies tend to be used in space cooling applications where waste heat is available whereas vacuum cooling is more commonly used in food processing. Companies like Yazaki Corporation market space cooling solutions.
- Evaporative Cooling further exploits evaporation of water in conditions of low humidity the technique can be used to create small temperature differences by passing air over a moist object (e.g. damp pad or pool of water). Evaporation of the water cools the passing air. The technique is mature for space cooling where climatic conditions and water supplies allow but also used by subsistence farmers in arid climates

2.2.3. Comfort Cooling Networks

Substantial economies of scale are available with cooling technology. In some countries district cooling networks have been established to exploit these (by using larger scale more efficient plant to provide the cooling) and offer building cooling as a service (CaaS). Access to cooling networks also enables exploitation of waste heat through sorption chillers or heat sink resources like LNG regassification and bodies of water more easily or as the integration costs can be spread across a greater number of users. District cooling systems are common in several Middle East locations where new build developments aggregate the cooling needs. Equally Canadian and Scandinavian systems are in operation that make use of waste cold resources like bodies of water. Paris also has a district cooling network that utilizes the Seine.

2.2.4. Thermal Storage

A range of storage devices that enable cold to be moved in space or time. They are all “charged” by liquefying or freezing a substance and then absorb heat (provide cooling) by being melted or evaporated.

- Ice is one of the oldest and most common storage technologies. It is used in block, cube and flake form for food and drug preservation. Ice Energy uses it to reduce AC peak energy demand while Surechill[22] is also innovating with this technology for refrigeration, using variations in water density at low temperatures to maintain cooling with ice as a cold source.
- Cryogenic liquids are liquids with a boiling point below ~-65°C, the most used for cooling are CO2 and nitrogen. Their use is common in industrial refrigeration applications where product quality is a primary consideration. They are an emerging technology in the transport refrigeration field. Companies like Air Liquide and Linde have developed evaporative systems whereas developers like Dearman Engine Company[23] have a system in commercial demonstration that generates cooling and mechanical work from the evaporation and phase change of liquid nitrogen.
- Other Phase Change Materials (PCMs) function much the same as ice but with better energy density. PCMs can be designed/selected to melt at a wide range of temperatures meaning that they are suitable to store cold for use in comfort cooling and refrigeration applications. University of Birmingham is trialing novel air conditioning and extended running chilled rail containers for food in China with commercial partners.[24] Companies like Hubbard Products are developing and deploying products that incorporate PCMs.

---

[22] Sure Chill is a brand new kind of cooling system. Water surrounds a Sure Chill refrigeration compartment. When it has power, the water cools and forms ice above the compartment leaving only water at four degrees cooling the contents. When the power is switched off, the water warms and rises while the ice begins to melt, keeping only four-degree water cooling the contents of the compartment. So it has its own internal and entirely natural energy store that maintains a completely steady temperature.

[23] Dearman.co.uk

[24] https://www.birmingham.ac.uk/news/latest/2018/12/scientists-develop-world-first-cold-storage-roadrail-container.aspx

3. The Cooling Market

Penetrations of space cooling, industrial and commercial cooling, mobile cooling, and domestic refrigeration equipment vary widely across the world. Differences are especially pronounced in space cooling, domestic refrigeration, and mobile cooling equipment categories. Ownership of ACs has reached 90% among households in Japan and US versus compared to just 8% of the 2.8 billion people living in the hottest parts of the world.[25]

It is estimated there are currently 3.6 billion pieces of cooling units. Current projections estimate that this will grow to nearly 9.6 billion units by 2050.

Reports suggest that this projection is likely to be conservative, insofar as an increase of 56% would be needed to reach a cooling for all scenario 14 billion cooling units).[26]

The Green Cooling Initiative (GCI) has produced an estimate of the global cooling market and its evolution to 2050. The estimate is based on market participant figures, international trade records, growth projections and factors like urbanization, population, and GDP growth.

We use this estimate in this analysis. To simplify a data set that contains seven equipment types, we divide it in to four main application categories:

- Space cooling – which relates to temperature maintenance in buildings delivered via air conditioners and chillers.
- Industrial and Commercial – which refers to cooling delivered to industrial, medical and food processing as well as refrigeration delivered in commercial storage, distribution, and retail environments.
- Mobile Cooling Systems – which incorporates both mobile air conditioning and mobile refrigeration applications and
- Domestic Refrigeration – to cover devices installed in people's homes for preservation of foodstuffs.

It should be noted that availability of data regarding market size and cooling demand is challenging. Sales and disposal records are typically incomplete, whilst at the same time providing a detailed bottom up assessment of demand requires knowledge of factors such as building design standards, building stock thermal performance, agricultural and pharmaceutical goods movements, etc.

3.1. The Current Global Cooling Market

Excluding fans, about 3.6bn pieces of cooling units exist globally, with annual sales of 356m cooling units per year. Table 2 summarizes the volumes of cooling equipment in use and sold today.

Equipment Type	Equipment Stock	Annual Sales (vol)	Annual Sales ($)
Space Cooling	922 million	106 million	$ 59 billion
Industrial and Commercial	90 million	7 million	$ 15 billion
Mobile Cooling Systems	979 million	107 million	$ 29 billion
Domestic Refrigeration	1,619 million	136 million	$ 40 billion
Total	3,611 million	356 million	$ 142 billion

Table 2 - Global Cooling Industry Current Status, 2018

Access to cooling equipment varies widely from country to country. Some of this variation can be explained by climatic differences. However, income inequality and development drive different levels of equipment access.

---

[25] https://www.iea.org/newsroom/news/2018/may/air-conditioning-use-emerges-as-one-of-the-key-drivers-of-global-electricity-dema.html

[26] (University of Birmingham, 2018)

A comparison of different data sets is shown in Appendix 3. All confirm the core findings that cooling demand is seeing significant growth over the next 30 years, but deployed capacity will not meet development needs and deliver access to cooling for all.

3.1.1. *A Comparison Across 14 Countries*

Using the GIZ Proklima data set, to illustrate global differences in cooling access, a subset of 14 countries listed in table 4 below have been selected representing different regions.

The countries selected also include the top 5 countries globally by population. These countries collectively represent ~55% of the world's population, 56% of the world's equipment stock and ~61% of its energy consumption for cooling.

To illustrate the levels of cooling access globally, the below table lists annual cooling equipment sales, energy consumption, and population. For data on all countries, please refer to the Global Cooling Initiative report.[27]

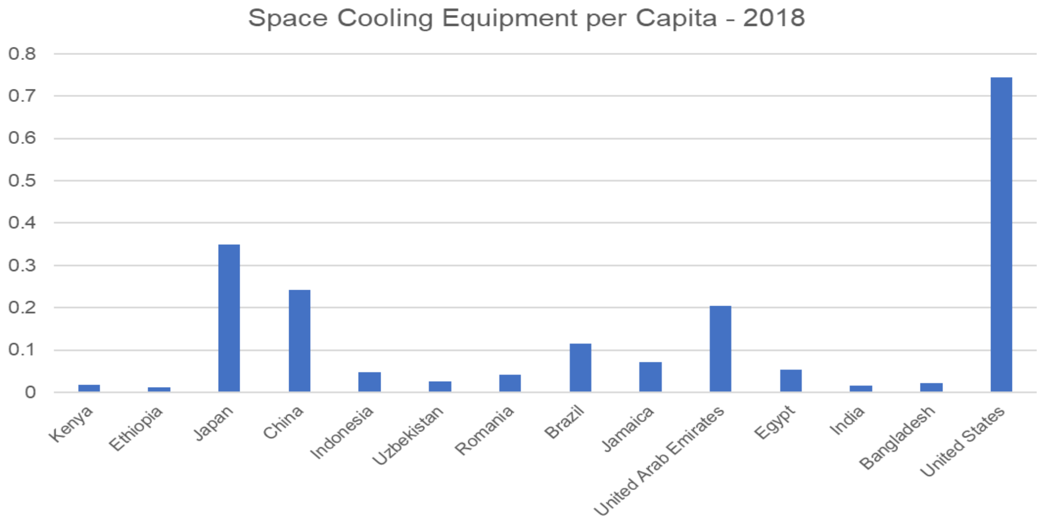
Country	Annual Equipment Sales Value ($m)	Energy Consumption (GWh)	Population
World	142,463	3,938,655	75 b
Kenya	343	11,699	50 m
Ethiopia	593	12,729	106 m
Japan	5,813	155,305	126 m
China	36,067	1,043,190	1.4b
Indonesia	2,623	100,830	264m
Uzbekistan	217	5,701	31m
Romania	737	13,783	21m
Brazil	2,905	108,862	208m
Jamaica	30	1,663	3m
UAE	246	15,065	10m
Egypt	854	24,265	88m
India	8,607	328,320	1.3b
Bangladesh	1,120	32,355	166m
USA	21,510	547,380	332m

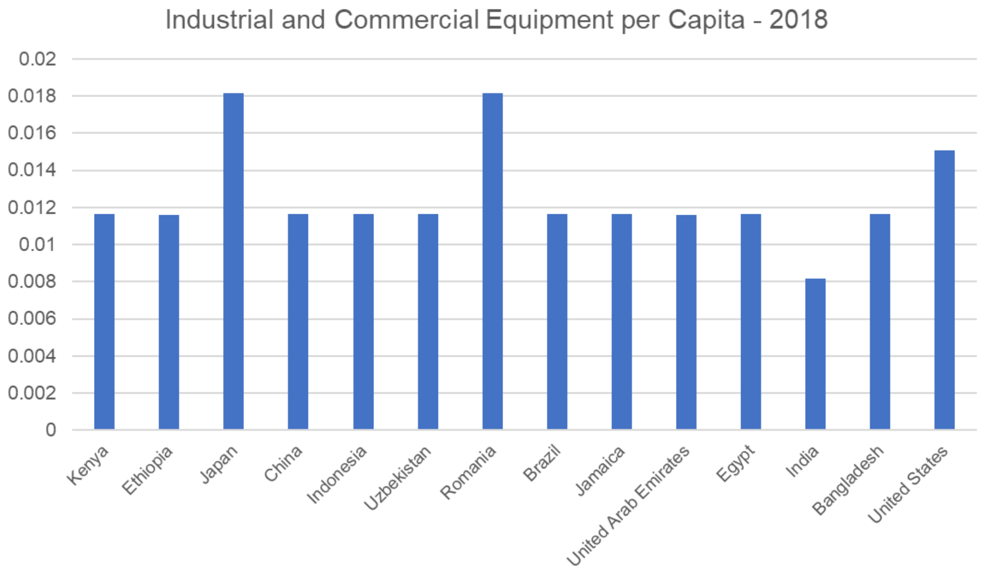
Table 3 – Focus Group Countries, 2018

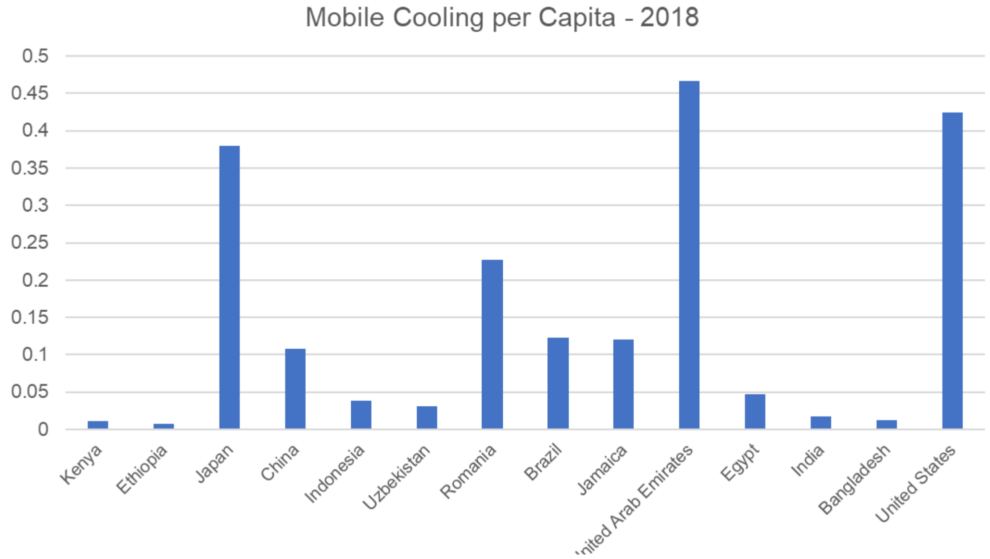
Penetrations of space cooling, industrial and commercial, mobile cooling and domestic refrigeration equipment vary widely. Figure 3 provides comparisons between focus countries. Differences are especially pronounced in space cooling, domestic refrigeration, and mobile cooling equipment categories. For example, India's penetration of space cooling equipment is about 1/50th that of the United States despite it having more than five times as many cooling degree days.

---

[27] https://www.green-cooling-initiative.org/data/user_upload/Downloads/Publications/EN_Green_Cooling_Technologies_-_Market_trends_in_selected_refrigeration_and_air_conditioning_subsectors.pdf


Space Cooling Equipment per Capita - 2018
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Kenya
Ethiopia
Japan
China
Indonesia
Uzbekistan
Romania
Brazil
Jamaica
United Arab Emirates
Egypt
India
Bangladesh
United States


Industrial and Commercial Equipment per Capita - 2018
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
Kenya
Ethiopia
Japan
China
Indonesia
Uzbekistan
Romania
Brazil
Jamaica
United Arab Emirates
Egypt
India
Bangladesh
United States


Mobile Cooling per Capita - 2018
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Kenya
Ethiopia
Japan
China
Indonesia
Uzbekistan
Romania
Brazil
Jamaica
nited Arab Emirates
Egypt
India
Bangladesh
United States

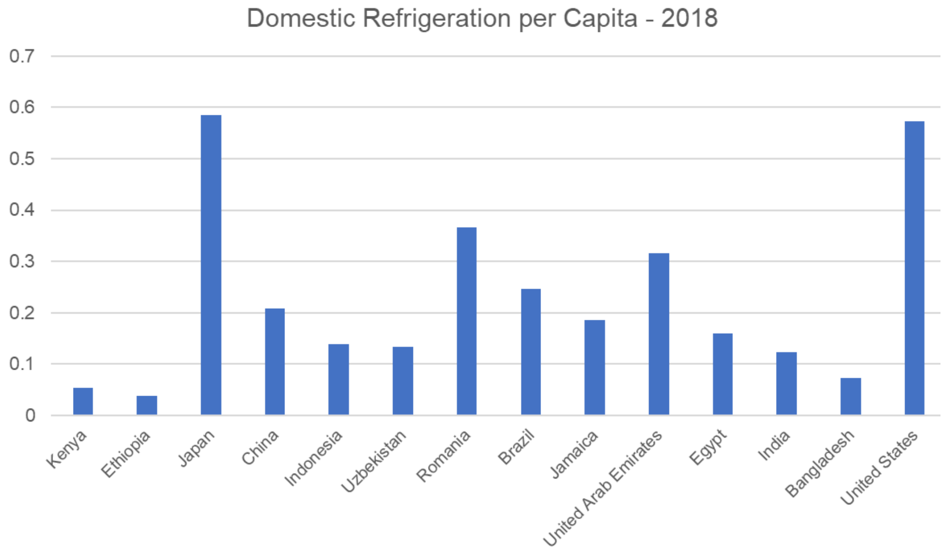


Figure 3 - 2018 Per Capita Equipment Penetrations – Focus Group Countries

3.1.2. A Business as Usual Projection of Cooling Market To 2050

As an indication of how the market for cooling equipment may evolve over the coming decades, GCI has produced projections of cooling equipment growth that account for forecasted growth in GDP, population, urbanization and electrification (for more detail on the projection methodology, see Appendix 4). This projection suggests a substantial increase in both the equipment parc, and annual sales volumes globally summarized in Figure 4.

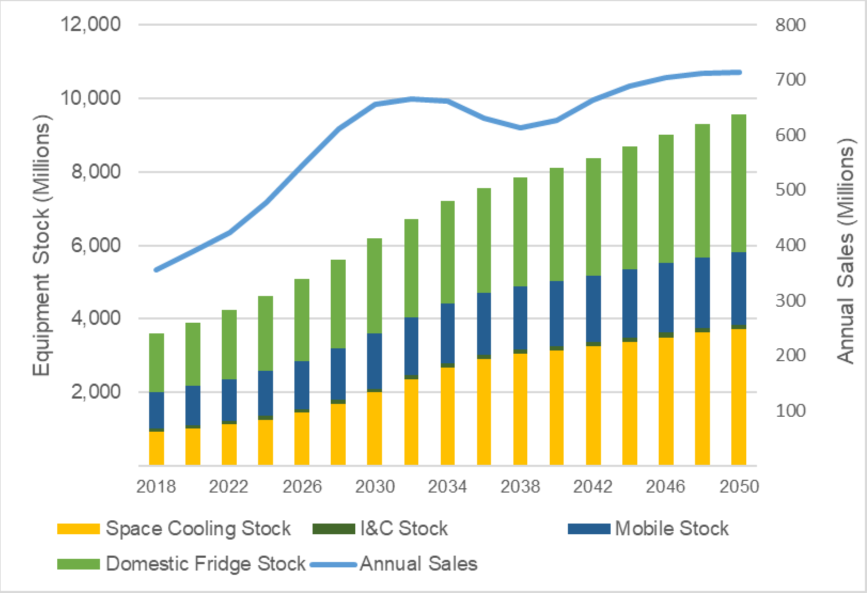


Figure 4 - BAU Cooling Stock Evolution - Global

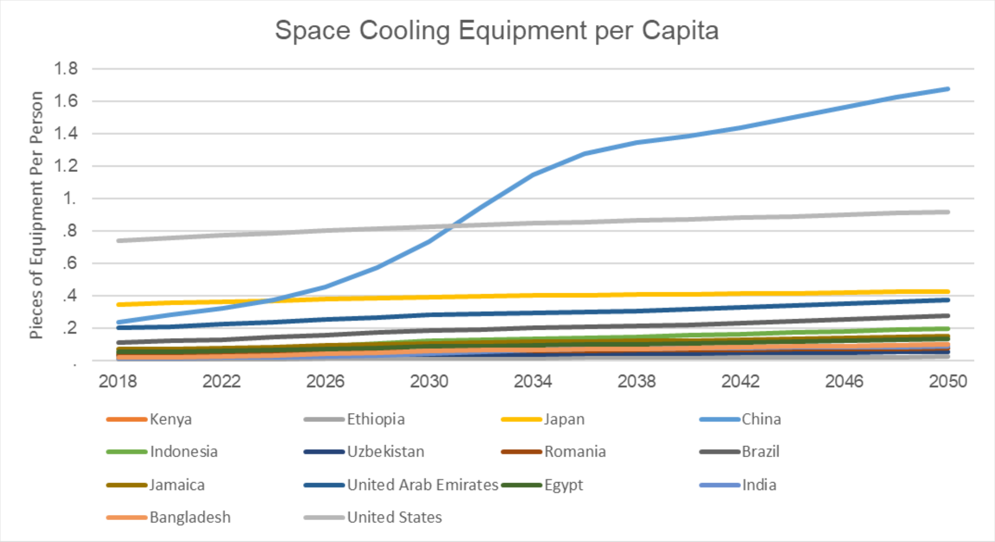
Under this business as usual projection, global equipment stock grows from 3.6 billion units in 2018 to nearly 9.6 billion by 2050, annual sales increases (about double) to 700 million units per year.

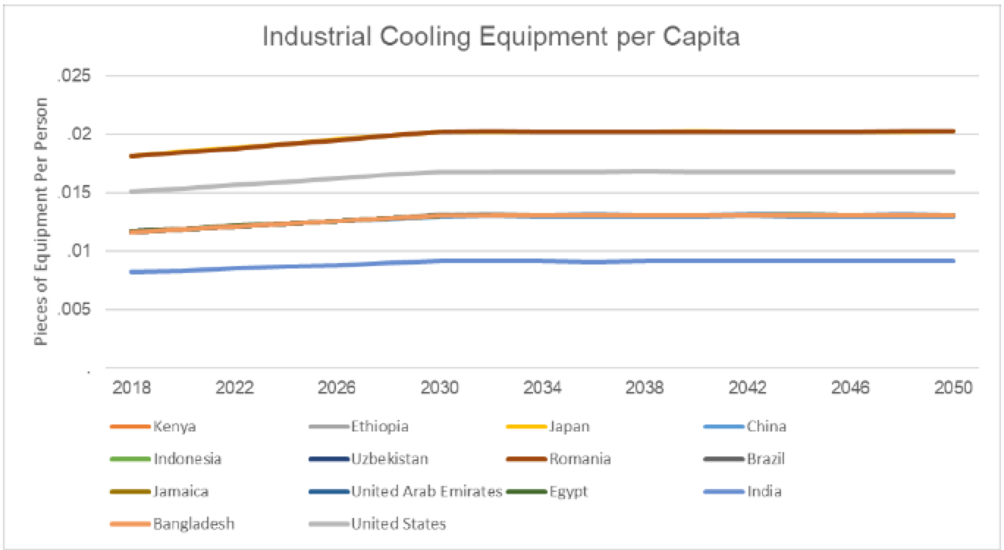
In of the selected 14 countries, substantial increases in cooling equipment stocks occur under the GCI business as usual projection, these are summarized in table 5 below. A breakdown by category for each market is included in the appendices.

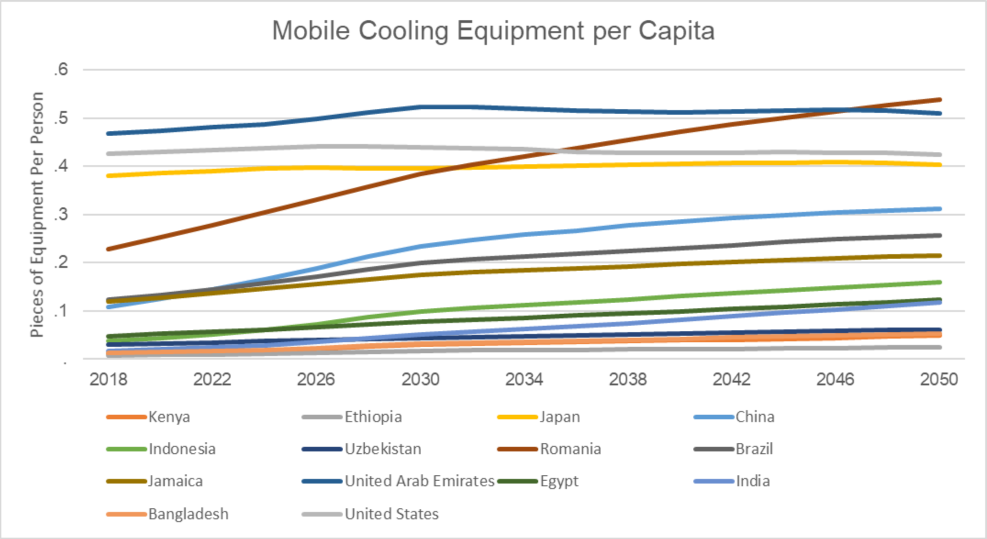
	Equipment Stock		
	2018	**2050**	**Change**
Kenya	4,789,720	40,523,320	746%
Ethiopia	7,238,140	49,173,100	579%
Japan	167,941,300	168,214,400	0%
China	808,133,000	3,424,566,000	324%
Indonesia	62,159,450	242,416,700	290%
Uzbekistan	6,233,107	14,458,930	132%
Romania	13,957,740	20,403,440	46%
Brazil	103,202,140	237,806,980	130%
Jamaica	1,109,199	2,088,743	88%
United Arab Emirates	10,191,990	22,778,501	123%
Egypt	24,213,370	73,636,920	204%
India	216,155,000	906,223,100	319%
Bangladesh	19,671,370	88,810,920	351%
United States	584,962,100	830,926,600	42%
Group Total	2,029,957,626	6,122,027,654	202%

Table 4 - BAU Growth Focus Group Countries

The total stock represented by the focus group of countries increases to around64% of the global total. Despite this very substantial growth, equipment penetrations do not converge globally by 2050. Figures 5 and 6 compare penetrations per capita and by household over the period for the 4 main application types.







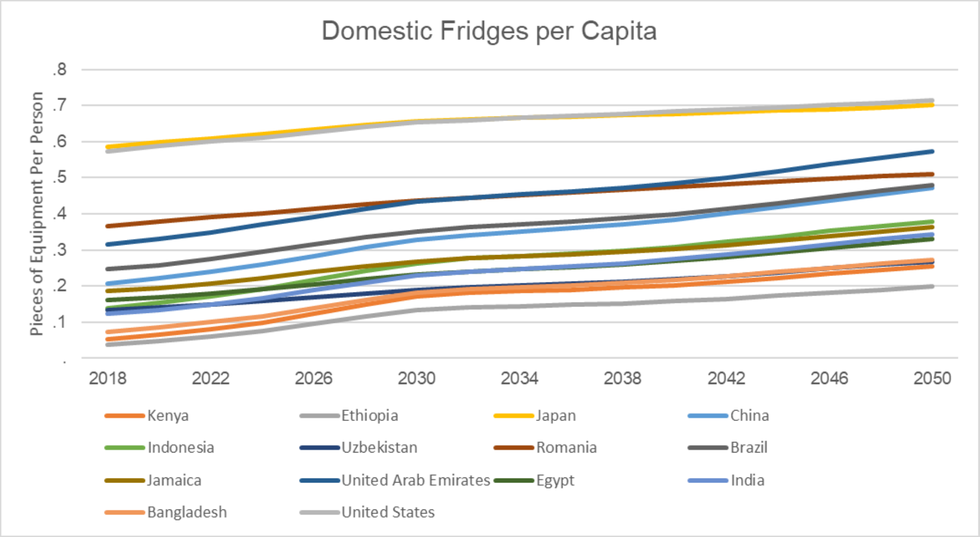
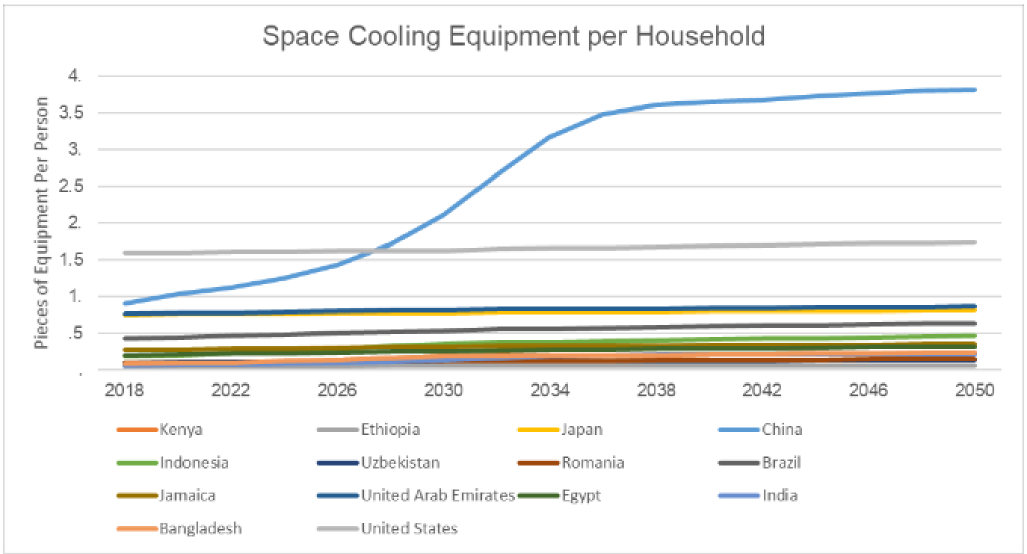
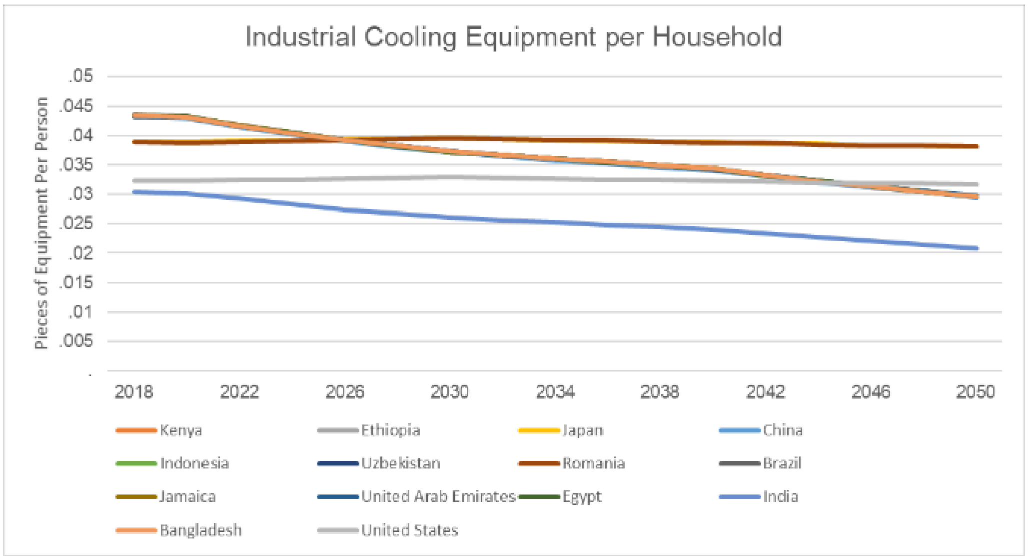
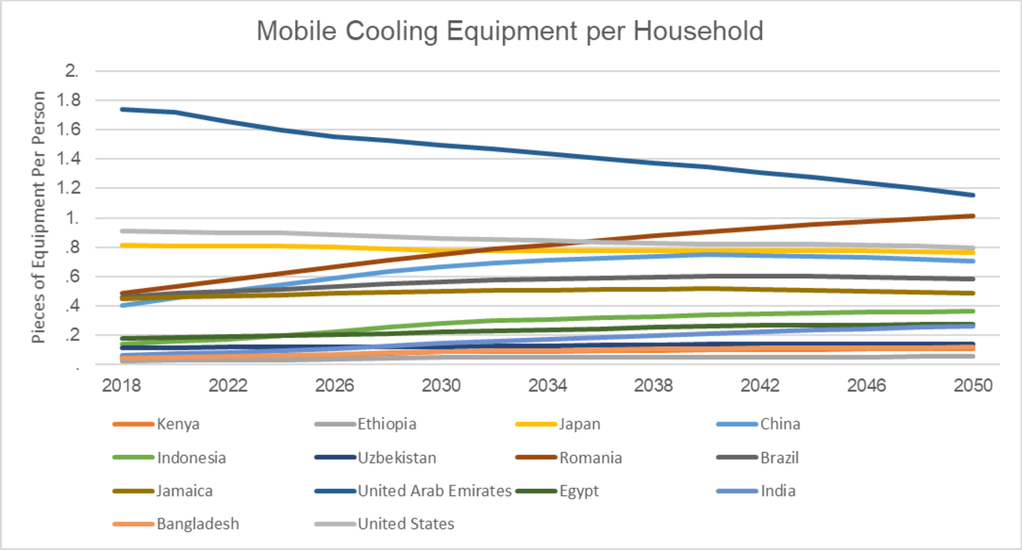


Figure 5 - Per Capita Equipment Penetrations Focus Group Countries


Space Cooling Equipment per Household
Pieces of Equipment Per Person
4.
3.5
3.
2.5
2.
1.5
1.
.5
.
2018
2022
2026
2030
2034
2038
2042
2046
2050
Kenya
Ethiopia
Japan
China
Indonesia
Uzbekistan
Romania
Brazil
Jamaica
United Arab Emirates
Egypt
India
Bangladesh
United States


Industrial Cooling Equipment per Household
Pieces of Equipment Per Person
.05
.045
.04
.035
.03
.025
.02
.015
.01
.005
.
2018
2022
2026
2030
2034
2038
2042
2046
2050
Kenya
Ethiopia
Japan
China
Indonesia
Uzbekistan
Romania
Brazil
Jamaica
United Arab Emirates
Egypt
India
Bangladesh
United States


Mobile Cooling Equipment per Household
Pieces of Equipment Per Person
2.
1.8
1.6
1.4
1.2
1.
.8
.6
.4
.2
.
2018
2022
2026
2030
2034
2038
2042
2046
2050
Kenya
Ethiopia
Japan
China
Indonesia
Uzbekistan
Romania
Brazil
Jamaica
United Arab Emirates
Egypt
India
Bangladesh
United States

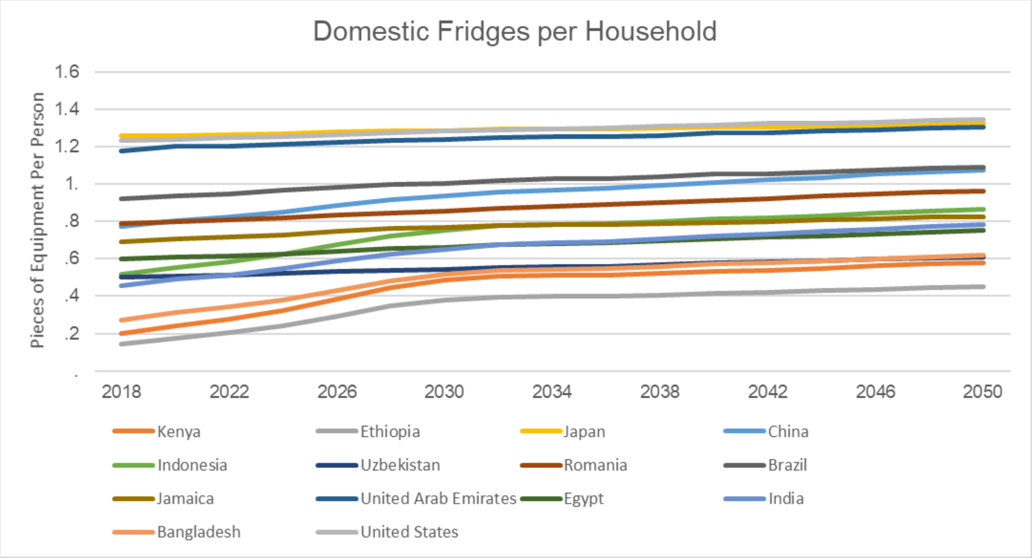
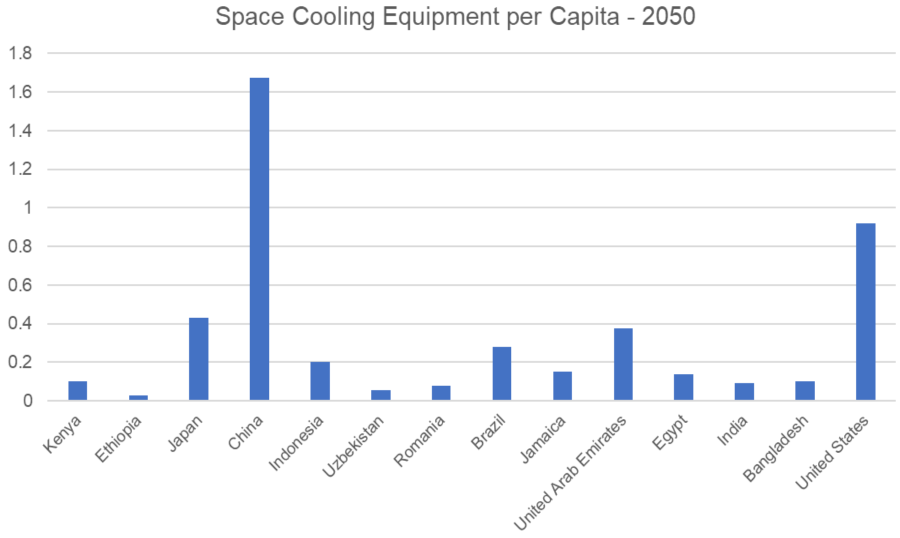
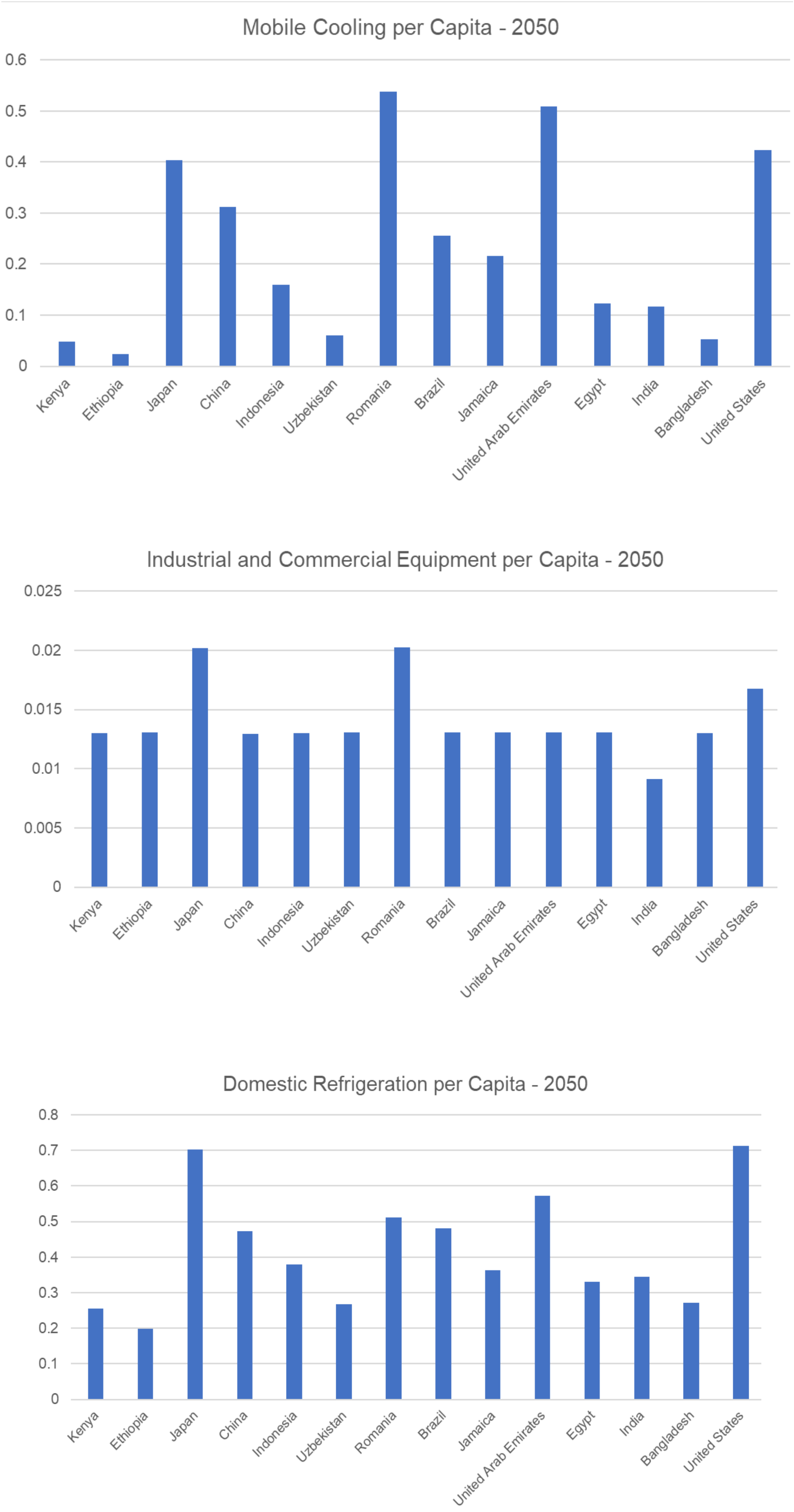


Figure 6 - Household Equipment Penetrations Focus Group Countries

By 2050, few of the global inequalities in cooling equipment are projected to have substantially changed (except for China in the field of space cooling). As can be seen in Figure 7, China's Space Cooling equipment stock expands to a point where it overtakes the United States, this is a function of both the higher number of cooling degree days (CDD) in China (about 27% higher than the USA) and rapid economic growth.

This implies that substantial portions of the world do not have access to cooling equipment to maintain temperatures at safe levels in high ambient temperature environments, and to prevent food and medicine from perishing.




Mobile Cooling per Capita - 2050

Industrial and Commercial Equipment per Capita - 2050

Domestic Refrigeration per Capita - 2050

Figure 7 - 2050 Per Capita penetrations of technologies - Focus Group Countries

3.2. Climate Change and Cooling Demand in 2050

Emissions from cooling (both directly from refrigerant leakage and indirectly from the energy consumed by cooling devices) will have an impact on climate change mitigation goals.**[28]** Equally climate change is already impacting cooling demand; a trend likely to become more pronounced in coming years. Significant heat wave related deaths have been reported in recent years, in particular in densely populated cities in both developed and developing countries.[29, 30]

Several studies explore the various negative impacts of global temperature rise at regional and national levels. As an example, the WBG published a series of reports produced by the Potsdam Institute of Climate Impact Research and Climate Analytics.[31] These reports explored the breadth of impacts that will be felt in different regions of the world. The potential impacts identified included:

1. Highly unusual and unprecedented heat extremes
2. Rainfall regime changes and impacts on water availability
3. Reduced agricultural crop yields
4. Land ecosystem shifts (e.g. drought driven deforestation and permafrost melt)
5. Marine ecosystem changes (especially acidification) substantially reducing fishery catches
6. Sea level rise
7. Glacier melting (causing flooding then loss of water sources for agriculture and power generation)
8. Social impacts (via reduced incomes and increased food scarcity)

Some of these impacts will drive an increasing demand for space cooling, such as heat extremes and prolonged periods of high temperatures (extending from a few days to months in the case of some regions).[32] In some regions the heat extremes look likely to test the limits of human physiological capability meaning that access to space cooling may be a health as much as a comfort issue in the future. A combination of the factors listed above is likely to reduce crop yields and fish catches with knock-on effects for other types of food production like meat and dairy products (which rely on crops for feed). This will happen at the same time as an increase in world population from 7.6 billion to 9.8 billion.[33] Under these circumstances, post-harvest food loss will have more severe consequences under conditions of more restricted food supply. This will create a greater need for complete cold chains that will require substantial expansions in equipment stock.

Climate change will also impact energy availability. Hydropower resources currently supply ~16.4% of the world’s electricity (71% of renewable energy).[34] Loss of this resource will create a significant electricity generation gap that will have implications for global electrical energy availability.

3.3. Universal Access to Cooling By 2050

To develop a picture of what universal access to cooling would look like, we developed a scenario for universal access (UA). Under this scenario, for air conditioning, countries are categorized as high ambient or low ambient based on the number of cooling degree days (CDD) that they experience per year (2000 is taken as a boundary value and 21.1°C as the threshold value, as a comparator Japan experiences ~1365 CDD per year).

Refrigeration equipment per household rates are set to converge with the United States for all countries by 2050. This is assumed to be required to bring food loss ratios down to the ~9% observed in that country. At the same time, space cooling equipment (stationary and mobile) penetrations for high ambient countries also converge and low ambient countries continue on their current trajectories.

The impact of this convergence is substantial on the number of units sold with an overall uplift of 56% with some countries seeing more than 100% uplift in demand.

---

[28] Explored in more detail in Section 3

[29] https://www.ready.gov/heat;

[30] https://www.aljazeera.com/news/2018/05/kills-65-pakistan-karachi-180523080507561.html

[31] Turn Down the Heat: Why a 4’C Warmer World Must be Avoided, 2012, Turn Down the Heat: Climate Extremes, Regional Impacts and the Case for Resilience, 2013 and Turn Down the Heat: Confronting the New Climate Normal, 2014

[32] Turn Down the Heat: Confronting the New Climate Normal, 2014

[33] https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html

[34] https://www.worldenergy.org/data/resources/resource/hydropower/

	Equipment Stock (thousands)			% Change	
	2018	**2050 BAU**	**2050 UA**	**vs 2018**	**vs 2050 BAU**
Kenya	4,790	40,523	167,224	*3391%*	*313%*
Ethiopia	7,238	49,173	322,793	*4360%*	*556%*
Japan	167,941	168,214	169,505	*1%*	*1%*
China	808,133	3,424,566	3,647,842	*351%*	*7%*
Indonesia	62,159	242,417	553,056	*790%*	*128%*
Uzbekistan	6,233	14,459	62,493	*903%*	*332%*
Romania	13,958	20,403	24,010	*72%*	*18%*
Brazil	103,202	237,807	397,733	*285%*	*67%*
Jamaica	1,109	2,089	4,833	*336%*	*131%*
United Arab Emirates	10,192	22,779	29,090	*185%*	*28%*
Egypt	24,213	73,637	209,601	*766%*	*185%*
India	216,155	906,223	2,787,937	*1190%*	*208%*
Bangladesh	19,671	88,811	347,531	*1667%*	*291%*
United States	584,962	830,927	830,927	*42%*	*0%*
Group Total	2,029,958	6,122,028	9,554,574	*371%*	*56%*

Table 5 - Universal Access - Impact on Focus Group Countries

Based on a linear convergence between 2026 and 2050,[35] equipment stocks can be projected at 4-year intervals to show a growth trajectory. Modelling results for the 14 focus group countries are shown in Figure 8 and 9 below.

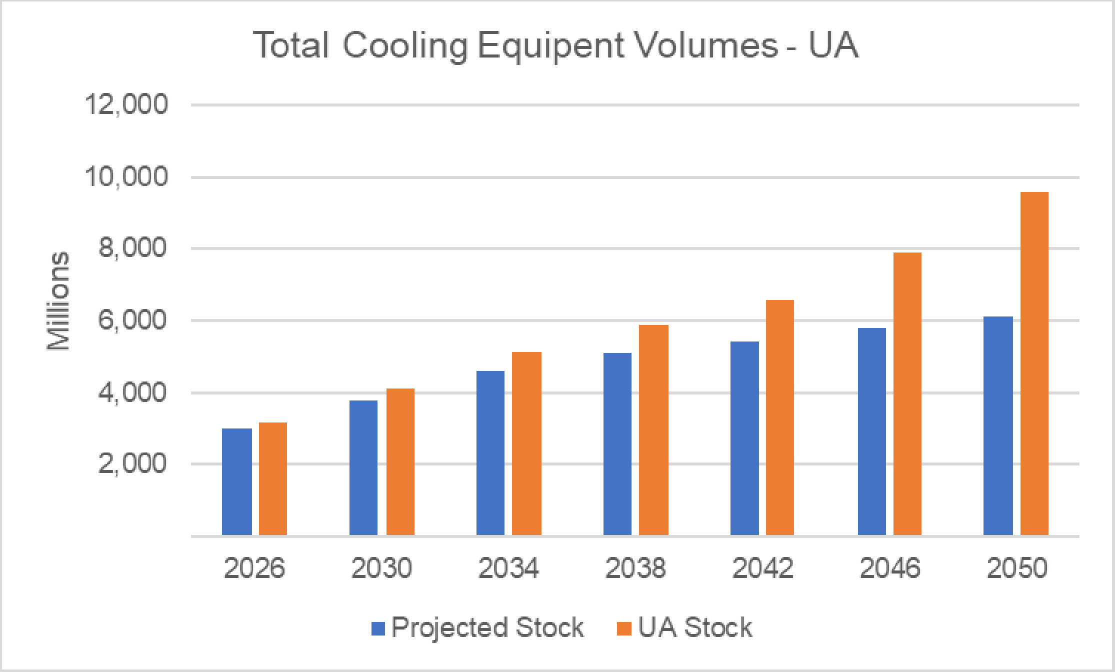


Figure 8 –Total Cooling Equipment Stock Changes - Focus Group Countries

---

[35] Convergence with US values based on minimum of 20% in 2026, 30% in 2030 etc to 100% of US values in 2050

Figure 9 – Equipment Stock Changes Focus Countries

Owing to the mix of countries in the group of 14, adjustments to projected stocks vary widely because of differences in projected needs. India, Ethiopia, Kenya, Uzbekistan, and Bangladesh all experience more than 200% increases in equipment stocks vs business as usual. Results for India are reproduced below as an indication of the difference across sectors of the cold economy.

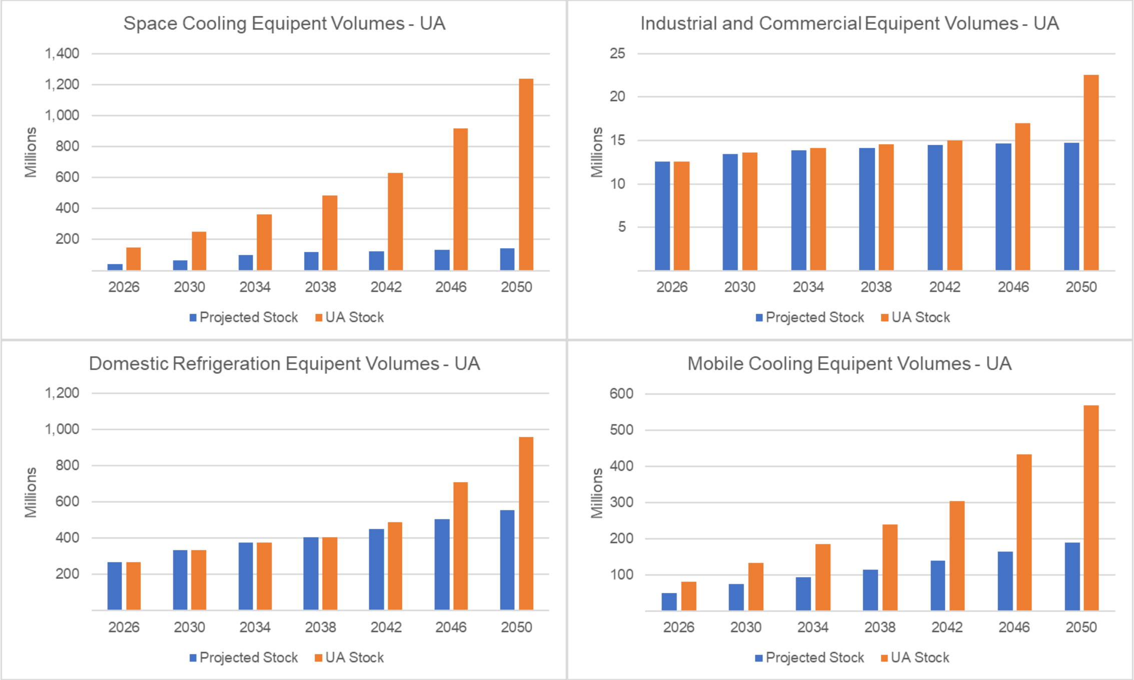


Figure 10 - Equipment Stock Changes by sector India 2026-2050

The current convergence modelling has limitations. It does however evidence that there is a significant gap between current penetration market growth projections and actual cooling needs. It is also likely to be conservative. As we are experiencing faster increases in global temperatures due to climate change. This will result in more locations experiencing more climate degree days which will likely reflect in greater demand for all types of cooling as well as great migration.

University of Birmingham is researching the impact of higher temperature increases (i.e. 4°C or even

4.5°C) on the cooling demand as part of the global adaptation strategies. This is both for comfort cooling, but also the importance of minimizing post-harvest food loss in ensuring total global food supply with climate change resulting in higher temperatures reducing the amount of productive land, water as well as creating catastrophic weather events which destroy crops.

4. The Environmental Impact of Cooling

- Projected growth in cooling will currently have significant environmental impacts:
    - Directly, through increased levels of high global warming potential refrigerant leakage
    - Indirectly, through increased energy consumption
- The total energy consumption associated with cooling equipment today is estimated to be 3,900 TWh – 15% of all electricity produced in 2017.[36]
- In a business as usual scenario this is projected to rise to 9,477 TWh by 2050. Associated CO2e emissions are expected to see 2.18 times increase and reach 8.971 GTCO2e, based on the current grid mix.[37]
- In a universal access to cooling scenario, cooling related energy consumption could be 19,600 TWh and associated emissions would be 18.8GTCO2e based on current grid mix.[38]
- To green this volume of electricity would consume 68% of the IEA 2 Degree Scenario projected 2050 total global renewable energy capacity (solar and wind); and more than 100% of the IEA's Reference Technology Scenario.
- Cooling is also a major contributor to peak energy demand in many countries. Growth in cooling demand will have significant impact on the capacity needed for electrical systems worldwide.

Cooling equipment impacts the environment via direct emissions from refrigerant leakage and indirectly through energy consumption. Both impacts are significant because:

- Refrigerants used in cooling equipment have extremely high global warming potential (GWP). As an example, 404A (an extremely common refrigerant in refrigeration applications) has a GWP of 3922 times that of carbon dioxide. This means that every kg of leakage is equivalent to ~3.9T of CO2e being emitted to the atmosphere.
- Cooling equipment consumes very substantial quantities of energy. This energy either comes from electricity in the case of most stationary systems or from directly burning fossil fuels in the case of mobile systems.

Note: These figures do not include the environmental impact of lack of cooling, primarily on post-harvest food loss. In 2011 food lost on the supply chain accounted for about 1 G ton of CO2 equivalent; more than the total GHG emissions of road transportation in the EU in 2012 (0.9Gtons) and in fact equal to 25% of the total emissions of cooling in 2017.[39]

4.1. Direct and Indirect Emissions Today

Total direct and indirect emissions from cooling today estimated by GCI are 4.1GTCO_2e, about 70% of this comes from indirect emissions caused by the energy consumption of cooling equipment. As a comparator, the IEA estimated energy production related CO_2 emissions globally were about 32.5GTCO_2e in 2017.[40]

Total energy consumption from cooling equipment estimated by GIZ Proklima is about 3,900 TWh today, this is equivalent to about 15% of all electricity produced in 2017.[41]

The current split in emissions and energy sources by the four main application types are shown in Figure 11.

---

[36] Toby Peters calculations based on GIZ Proklima dataset
[37] Ibid.
[38] Ibid.
[39] http://www.foodcoldchain.org/wp-content/uploads/2016/07/Reducing-GHG-Emissions-with-the-Food-Cold-Chain-NOV2015.pdf
[40] Global Energy and CO2 Status Report, IEA 2017
[41] https://www.iea.org/geco/electricity/

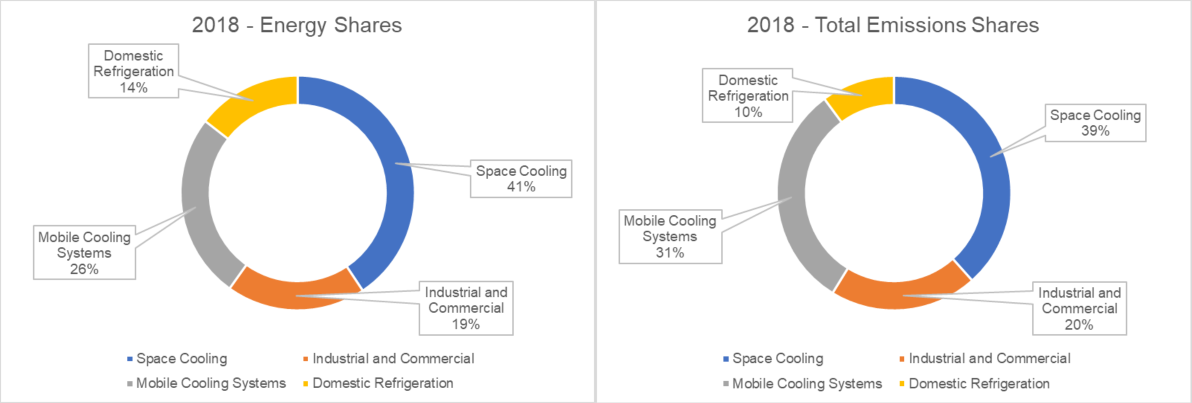


Figure 11 - Current Total Energy and Emissions

4.2. Emissions and Energy under a business as usual scenario

Under the GCI business as usual equipment growth projection scenario, both energy use and emissions from cooling increase substantially to about 9,477 TWh and 8.971 GTCO$_2$e (2.43 and 2.18 times increases), based on current grid mix.[42]

The growth pathway of energy consumption and emissions in the GCI business as usual projection is summarized in Figure 12 below.

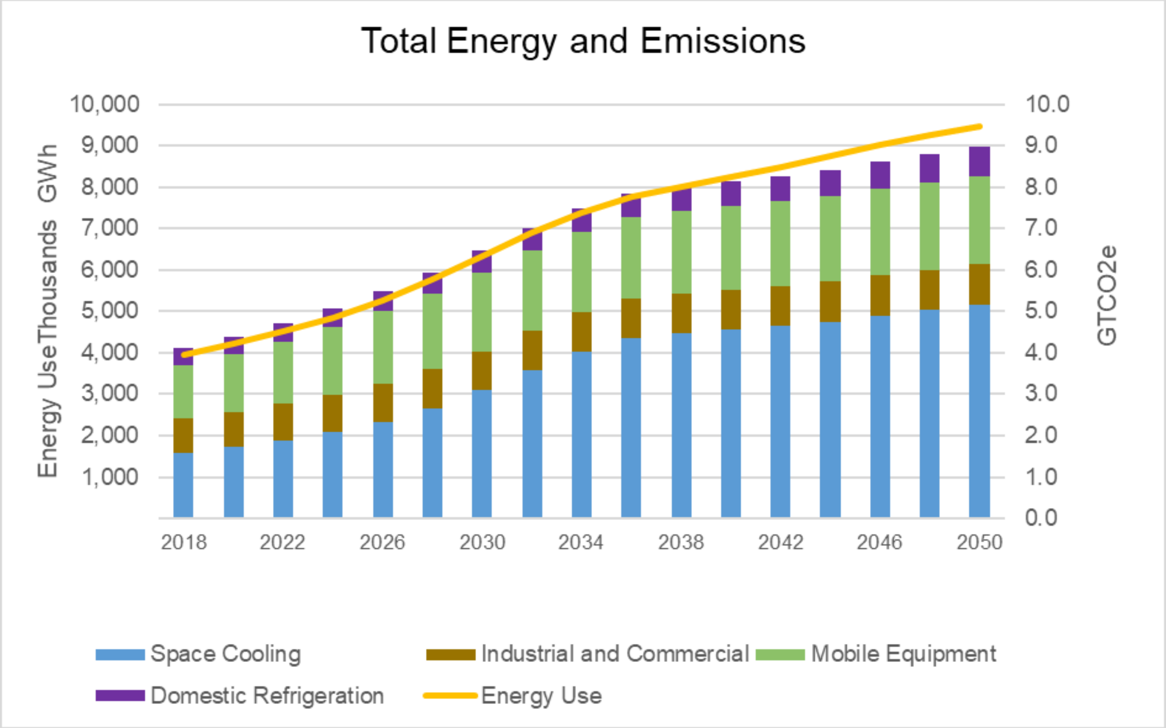


Figure 12 - Global Energy and Emissions Evolution BAU

Even under this scenario where access to cooling is not universal, this represents a substantial challenge to carbon targets and implied energy budgets globally. Sectoral energy and emissions shares are shown in Figure 13 below.

---

[42] A factor not accounted for in these figures is grid decarbonisation. GCI's rationale for this is to separate the issues of refrigeration energy demand and associated emissions and renewables deployment policies. Whilst differing grid carbon intensities between countries are reflected in the data set, they remain constant over time.

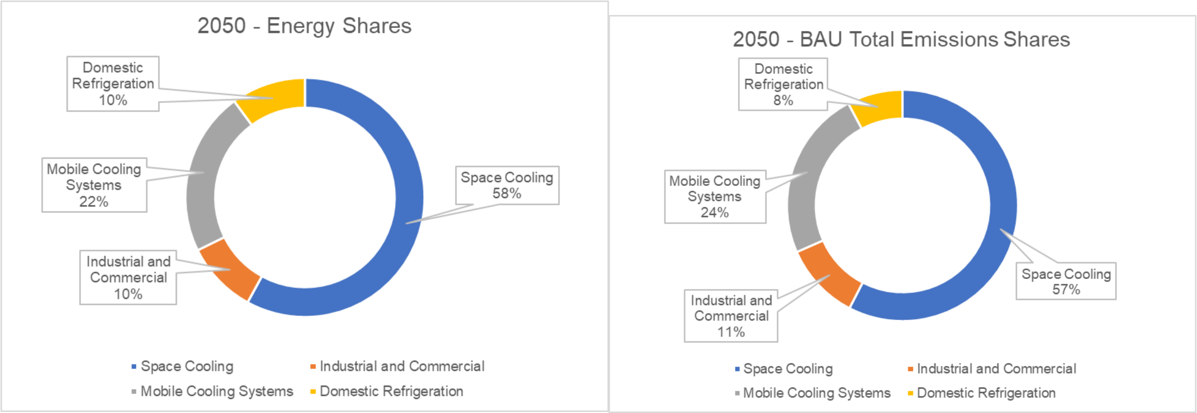


Figure 13 - Business as usual energy and emissions shares

These business as usual figures include significant improvements in device efficiency and reductions in direct emissions. These improvements (averaged across the global equipment parc) are summarized in the tables below and reflect improvements incorporated in already enacted legislation and current technological progress. These gains are insufficient to mitigate the impact of cooling market growth on climate change.[43]

	No. Units			Annual Per Unit Energy Usage (MWh)		
	2018	**2050**	**Change**	**2018**	**2050**	**Change**
Space Cooling	705,968,061	3,072,942,434	335%	1.62	1.36	-16%
Industrial and Commercial	45,860,390	57,834,480	26%	7.95	7.16	-10%
Mobile Cooling Systems	419,629,176	999,250,740	138%	1.37	1.23	-10%
Domestic Refrigeration	858,500,000	1,992,000,000	132%	0.37	0.26	-30%
Total	2,029,957,626	6,122,027,654				

Table 6 - Per Unit Energy Usage Changes BAU

	No. Units			Per Unit Total Annual Emission TCO2e		
	2018	**2050**	**Change**	**2018**	**2050**	**Change**
Space Cooling	705,968,061	3,072,942,434	335%	1.73	1.42	-18%
Industrial and Commercial	45,860,390	57,834,480	26%	10.51	9.47	-10%
Mobile Cooling Systems	419,629,176	999,250,740	138%	1.73	1.29	-25%
Domestic Refrigeration	858,500,000	1,992,000,000	132%	0.33	0.24	-26%
Total	2,029,957,626	6,122,027,654				

Table 7 - Per Unit Total Emissions Changes BAU

---

[43] GCI assumptions about appliance efficiency are not explicitly stated in their public results. However, an indication of improvements assumed can be calculated for both the Business as Usual (BAU) and Mitigation (MIT) scenarios. By dividing total energy (or emissions) figures for an application type by the total number of cooling units assumed to be in operation in a given year an energy consumption per unit or emissions per unit average can be calculated. The GCI dataset does not include any allowance for climate change therefore the amount of cooling that each appliance needs to deliver per year can be assumed to be relatively constant. Therefore, changes in energy consumption (or emissions) are the result of efficiency improvements as opposed to usage requirements.

	No. Units			Per Unit Direct Annual Emission TCO2e		
	2018	2050	Change	2018	2050	Change
Space Cooling	705,968,061	3,072,942,434	335%	0.40	0.17	-59%
Industrial and Commercial	45,860,390	57,834,480	26%	3.74	3.36	-10%
Mobile Cooling Systems	419,629,176	999,250,740	138%	0.63	0.30	-52%
Domestic Refrigeration	858,500,000	1,992,000,000	132%	0.01	0.01	-37%
Total	2,029,957,626	6,122,027,654				

Table 8 - Per Unit Direct Emissions Changes

4.3. Emissions and energy under a universal access scenario

Under the theoretical universal access (UA) scenario, emissions and energy consumption growth are substantial across the group of 14 focus countries. Emissions from the group increase to more than 14.8GT of CO2e (a 64% increase over the 2050 global total from the business as usual projection) and energy consumption grows to 13,200 TWh (a 338% increase from today's global total). Emissions and energy consumption evolution for the focus group of countries is shown in Figure 14 for a linear convergence growth pathway vs the business as usual projection. Again, these include a degree of improvement in terms of reductions in energy consumption and reductions in direct emissions through refrigerant substitution and measures to reduce leakage.

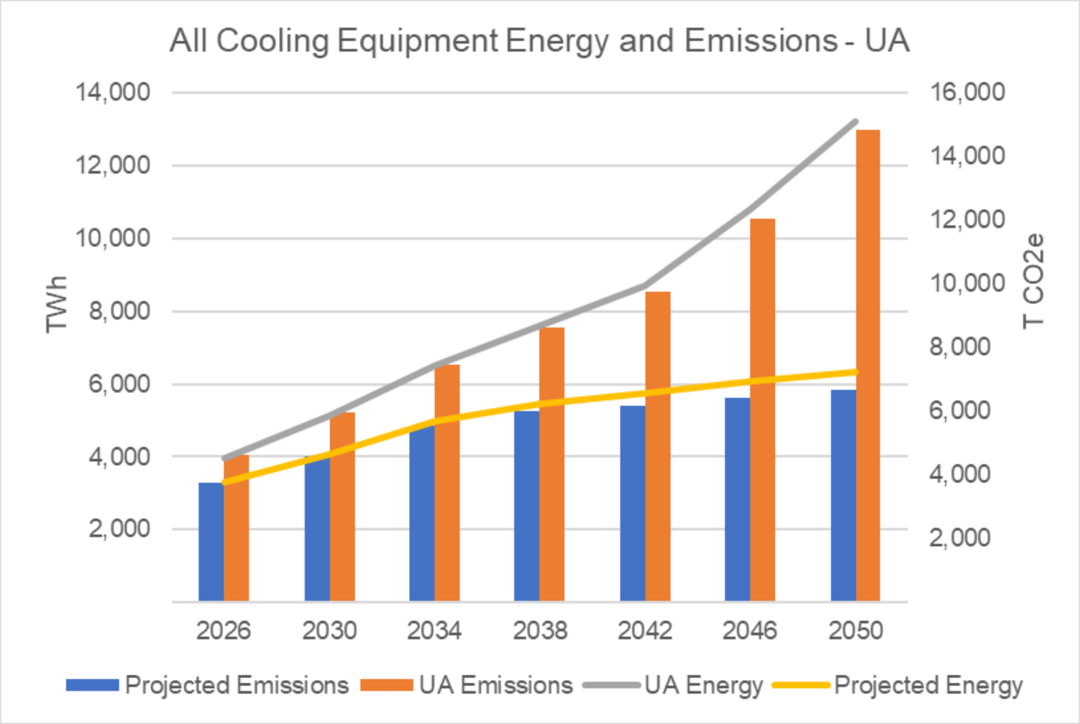


Figure 14 - Focus Group Emissions and Energy Consumption

As with the equipment penetrations, changes to emissions and energy consumption are even more pronounced in countries with low penetrations of cooling equipment today. Figure 15 charts emissions evolution across the 4 main cooling sectors for India as an example.

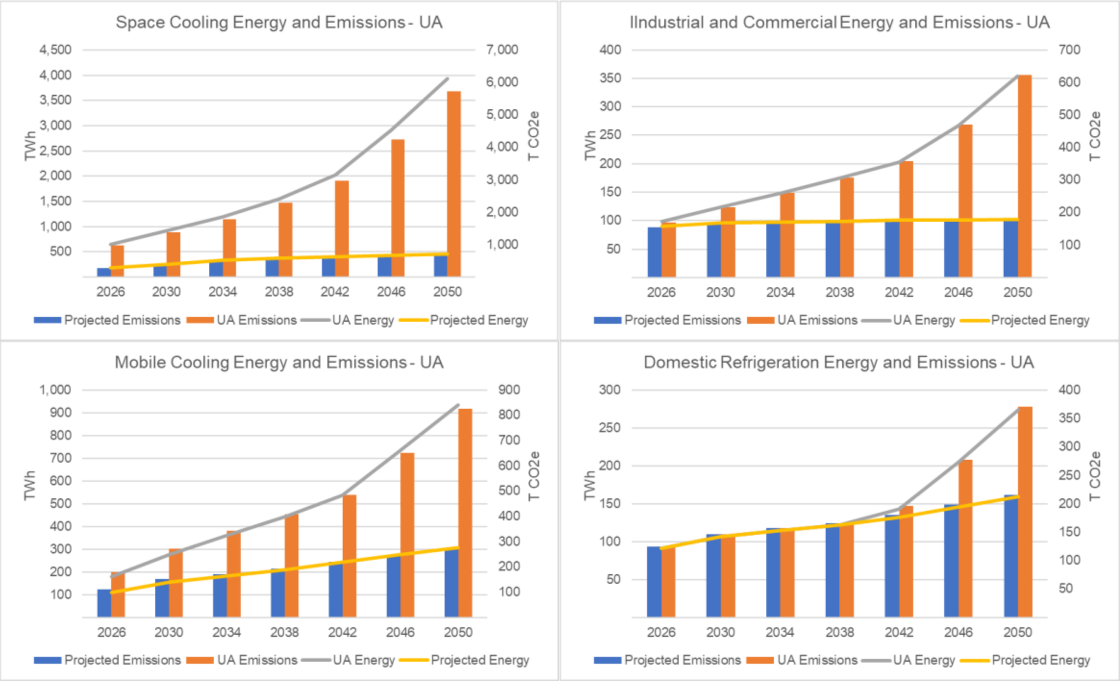


Figure 15 - Energy and Emissions Evolution India

4.4. Energy Implications of Cooling for All

A report published by the University of Birmingham explored the implications of a global convergence in equipment penetrations. The report utilized broadly the same convergence basis described above but applied it globally.[44] Additionally, the report disaggregated a global allowance for cooling energy consumption and carbon usage from the IEA's Energy Technology Perspectives 2017 publication. By looking at space cooling (a separate line item in their energy projections) and a proportion of transport and appliance energy consumption (which was assumed to be held constant at around 3.3% of total transport energy demand and 22.5% of appliance energy use within buildings) it was possible to derive an implied energy budget for the sector.

Under the IEA 2DS scenario (where global temperatures have a greater than 50% chance of only rising 2°C), the resulting energy allowance is 5,000 TWh/year in 2030 and 6,300 TWh/year in 2050. A similar proportional method can be used to assess the implied carbon budget which amounts to ~1.4 GtCO2e from the sector by 2050 if the 2DS scenario is to be achieved.

In our convergence calculations above, the 14 focus group countries alone consume 13,200 TWh/year of energy by 2050. This is just over twice the implied energy budget for the entire world. The 14 focus group countries under the UA scenario produced combined emissions of 14.8GTCO2e (direct emissions amount to ~.93GTCO2e).

Applying the same convergence globally, energy consumption from the cooling sector could reach 19,600TWh with emissions of 18.8GTCO$_2$e a value that massively exceeds the cooling budgets implied by the IEA's projections.

It is important therefore to note that relying on renewable energy-based generation without significant energy consumption reduction measures from the cooling sector would mean the sector consumes much of the world's projected renewable capacity for 2050. In the 2DS, the IEA models total global wind generation (both on and off-shore) capacity at 8,179 TWh by 2050 – less than the 9,100 TWh by which the cooling sector surpasses its energy budget in C4A AT (the accelerated tech progress scenario). Adding the 5,500 TWh of total solar PV generation projected to be available by 2050 in IEA 2DS to the wind capacity, the total capacity available increases to 13,729 TWh – which is still 50% less than the potential energy consumption of Universal Cooling, regardless of other demands including electrification of transport.

---

[44] The only difference in methodology is between household unitary air conditioner penetrations. The Birmingham report capped these at 1 per household whereas this report aligns them with US penetrations which reach 1.73 units per household by 2050

4.5. Cooling and Peak Energy Demand

In countries that experience high ambient temperatures space cooling in particular causes problems for electricity networks around peaks.

Total electrical energy consumption varies through the course of a day. This is driven by changes in behavior of the users of electricity. In most countries, electrical energy consumption is lower at nighttime than during the day because people do not tend to use electricity to power appliances or machinery whilst they are asleep. Day time electricity consumption also exhibits “shape” too. Peaks usually occur when people wake up in the morning and in the evening when they return home from work. Electricity generation, transmission and distribution systems must be built to cope with peak rather than average demand as the amount of electricity going into an electrical system must always equal the amount being taken out. As a result, the size of peak demand determines how much capacity to deliver electricity an electrical system has. The capacity of an electrical system has very substantial implications for its cost.

A further issue is that peak electricity demands are generally met by the most expensive to run plants on the system (that are typically less efficient and more polluting). This is because higher efficiency (or low-cost fuel) plants are generally asked to generate electricity before lower efficiency ones because their marginal cost of generating electricity is lower. Thus, the highest peaks in demand are met by more to operate generation plants that are operated relatively infrequently to meet the highest peaks. On many systems, these are old hydrocarbon powered generators whose capital investment has been repaid as the low frequency of generation cannot justify investment in a new plant. Because of this dynamic the grid carbon intensity of electrical systems (amount of CO2 emitted per kWh of electricity generated) tends to increase as demand on the system goes up.

Air conditioning is a major contributor to peak demand in many countries. A recent report from the IEA explored the role of space cooling in peak energy demand.[45] As examples, in Mexico and India about 10% of the peak comes from space cooling, in Indonesia, Korea and China it is nearer to 15% and in the United States more than 25% of peak demand comes from this source. These figures disguise considerable regional and temporal variations. The report references peak consumption contributions during heat waves as high as 70% in the United States and 50% in some parts of China.

If cooling continues to contribute in this way to peaks in demand (or even expands its contribution) it will directly drive increases in the amount of renewable electricity generating capacity that has to be installed on the system to service peak demand. The IEA study (2018) found that without action by 2050, AC could be contributing over 20% to peak demand countrywide in several places around the word. As an example, it is projected that by 2050, 40% of peak demand in India could be caused by air conditioners. This would require a further 800GW of generation capacity to be built (compared to 349GW in service today).[46]

4.6. Cooling and linkages to International Agreements on Climate

4.6.1. United Nations Framework Convention on Climate Change (UNFCCC)

The UNFCCC was signed in 1992 to coordinate international efforts to combat climate change by limiting emissions of CO2 into the atmosphere. Within this framework, the Kyoto protocol was adopted in 1997 to set limits for emissions of Carbon Dioxide, Nitrous Dioxide, Hydrofluorocarbons (HFCs), Perfluorocarbons and Sulphur hexafluoride. In 2015 at COP21 in Paris, an agreement was made to attempt to limit global warming to 1.5 to 2 °C and established a framework for nationally determined contributions (NDC) to the required global reduction in CO2e emissions.

Global scientific consensus is that deep reductions in CO_2e emissions are required globally to achieve this. As an example, the last Intergovernmental Panel on Climate Change (IPCC) report, states that a reduction of global emissions by ~45% from 2010 levels by 2030 and to net zero by 2050 is required if warming is to be limited to 1.5°C.[47] This year, however, CO2e emissions level has increased.

Clearly the cooling sector that under BAU will increase its emissions by 120% between now and 2050 and by 348% in a universal access scenario represents a challenge to decarbonization efforts when it already accounts for ~12% of global emissions.[48] This suggests that action on cooling is required to

---

[45] The Future of Cooling: Opportunities for Energy Efficient Air Conditioning, IEA 2018

[46] https://powermin.nic.in/en/content/power-sector-glance-all-india

[47] https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/

[48] ETP2017 Scenario Overview – Total direct CO2 emissions 34,254 MtCO2 vs 4,100 MtCO2 estimated by GCI

avoid it undermining other decarbonization efforts.

Additionally, a key component in the decarbonization challenge is decarbonizing the energy and transport sector. About 40% of direct CO2 emissions arise from the power generation sector and a further 22% from transport.[49] Decarbonizing these sectors will require electrification of substantial parts of the transport network alongside massive deployment of renewables, expensive carbon capture and storage and network re-enforcement/energy storage deployment effort. This is highly likely to increase electricity costs and reduce energy availability. Increasing the amount of energy allocated to cooling by 143% or 427% seems infeasible in this context.

At the moment, directed action on cooling via this mechanism is limited. Only 83 of 197 NDCs even mention refrigeration and cooling. India and Rwanda have recently launched draft National Cooling Action Plans NCAPS) and 27 other countries are drafting NCAPs; but these are very heavily focused on air-conditioning from a climate perspective. This suggests that there needs to be a significant uplift in government action in this area.

4.6.2. Montreal Protocol (including the Kigali Amendment)

The Montreal Protocol on Substances that Deplete the Ozone layer came into force in 1989 and aims to phase out production of substances that deplete the ozone layer such as Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Halons, Carbon Tetrachloride and Methyl Chloroform. The cooling sector has been a major user of these substances both for blowing insulation foams and as a refrigerant.

Hydrofluorocarbons (HFCs) were selected as an alternative to CFCs and HCFCs, however many of the HFCs have an extremely high global warming potential (GWP). The Kigali amendment to the Montreal Protocol was intended to address this by providing a route to phase down usage of HFCs to about 15% of baseline levels between 2037 to 2047 depending on which group signatories to the Montreal Protocol countries were in.[50] For the most aggressive phase down countries, baseline consumption was established in 2011-2013. However, for the 147 countries listed in Article 5 of the treaty, baselines will not be established until 2020-22 or even 2024-26. Growth in cooling equipment deployment volumes without very substantial changes in the refrigerants and blowing agents used will result in phasedown targets being missed. Additionally, growth in HFC consumption associated with a growth in refrigeration equipment consumption within Article 5 countries before their baseline years could substantially reduce the effectiveness of the treaty.

In addition to the commitments to reduce production and emission of HFCs, HCFCs and CFCs the Montreal Protocol established a multilateral fund that has approved funding of $3.6 billion since 1991 for a variety of projects incorporating industrial conversion, technical assistance, training and capacity building to assist with refrigerant switching.[51]

4.7. Other Actors

Several other organizations are actively working to address the cooling challenge around the world, these may differ in scale from the larger multilateral fund and MDBs which have funded EE appliance replacement programs.

4.7.1. The Global Cooling Prize

Rocky Mountain Institute (RMI) is a US based nonprofit organization that aims to catalyze decarbonization efforts by identifying opportunities for market-based solutions that reduce energy consumption or enhance the effectiveness of renewables deployment. They work in collaboration philanthropists and the US government across their programs.

Their most significant activity in the field of cooling is the Global Cooling Prize. The prize is offering up to $3m in prize money for a residential cooling solution for a typical tropical or subtropical home that:

- Has at least 5x less climate impact (80% via reduced energy consumption and 20% via lower GWP refrigerant).
- Costs no more than twice the incumbent solution at scale.

---

[49] ETP2017 Scenario Overview (2014 baseline)

[50] Groupings are determined by a combination of ambient temperature, income and politics

[51] http://www.multilateralfund.org/default.aspx

- Meets further requirements in terms of having feasible peak power consumption, water use and maintenance needs.[52]

The competition primarily relates to the smaller end of the unitary air conditioner segment. Were it to succeed in its goals and achieve the target reduction, substantial emissions and energy savings could be achieved. If one were to assume that the part of the Unitary Air Conditioner market addressed by the innovation was as high as 50%, we estimate that 20-22% of energy consumption and 25-27% of emissions from the entire cooling sector could be avoided depending on the scenario assessed for the 14 focus countries.

Theoretical results of the impact of the Global Cooling Prize for the focus group countries are summarized in Appendix 5. The competition launched in November 2018 and will be open for one year with demonstration in 2020.

4.7.2. Kigali Cooling Efficiency Program (K-CEP)

K-CEP is a $52m program supported by a group of philanthropic foundations that aims to increase the efficiency of cooling in developing countries and assist with HFC phase down. Its work is split across four windows:

- Strengthening for Efficiency – by supporting training for policy makers alongside information resources and funding to add energy efficiency into projects.
- Policies, Standards and Programs – by working with policy makers to accelerate adoption of energy efficiency standards for cooling equipment through advisory and information sharing practices.
- Finance – by providing grants for cooling related initiatives but also by catalyzing private sector investment in the cooling sector (e.g. for efficient equipment financing).
- Access to Cooling – by advocating internationally for cooling to be included in international development plans so that sustainable approaches that deliver universal access (to those that need it) can be delivered.

4.7.3. Green Cooling Initiative (GCI)

GCI is an initiative funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and implemented by GIZ Proklima. It provides advice to policy makers and industry in relation to reducing emissions from cooling provision technical assistance activities, analytical work, and demonstration projects. A Nationally Appropriate Mitigation Action (NAMA) toolkit was developed under this initiative, to support policy makers to incorporate cooling in their NAMAs.

---

[52] Global Cooling Prize – Prize Overview – Rocky Mountain Institute

5. Intervention Options

Achieving a goal of affordable access to cooling for all whilst meeting the targets of the Paris Climate Agreement will require action on both direct (refrigerant) and indirect (energy generation) emissions. The focus to date has been primarily on the climate impact of refrigerants.

Direct emissions from cooling and refrigeration are primarily a result of the high global warming potential of refrigerants. Emissions reductions can be achieved through:

- Reducing the number of pieces of refrigeration and cooling equipment
- Reducing refrigerant leakage in refrigeration equipment manufacture installation, use and disposal
- Substituting current refrigerants with low or zero (natural) GWP alternatives

These however account for only 20% of the total GWP impact of cooling (UNEP TEAP, 2017a). Indirect emissions from refrigeration and cooling equipment account for 80% and are predominantly caused by the generation of energy they consume. To reduce indirect emissions action is required across a range of factors:

- Demand mitigation - across all cooling applications via technical solutions in cooling equipment and wider building and urban design, and behavior change in equipment use and maintenance
- Efficiency improvements - at a component level as well as overall system optimization and control
- District cooling versus individual appliances
- Maintenance to ensure optimal operating efficiency
- Renewables and electricity network integration – particularly developing cooling appliances that enable demand management to limit peak load impact on electricity networks.
- Harnessing free and waste resources

None of the approaches identified (demand mitigation, efficiency, refrigerants, renewables, or new technologies) will be sufficient if implemented in isolation to deliver access to cooling for all and simultaneously achieve the targets of the Paris Climate Agreement. What is required is a holistic system driven approach to:

- Identify cooling service demands in a need driven manner.
- Assess the local social, economic, and wider energy landscape of the region under review.
- Better consideration of the HVAC cooling loads within mobility; this will become increasingly important given both the projected growth in vehicles and the planned electrification of the transport network
- Highlight behavior change and demand mitigation strategies likely to be effective whilst maintaining required service levels.
- Explore opportunities to harness free cooling and synergies between processes, waste resources and cooling needs that can further reduce the required cooling requirement.
- Match technology characteristics to local conditions and residual cooling demand in a way that minimizes cost and carbon whilst maintaining the required service levels.

This should be reflected in a Merit Order of Intervention based on a range of values including cost of mitigation or adaptation impact, likely starting with demand mitigation.

The rapid growth in cooling energy demand and associated emissions are a major threat to global climate targets. To date the focus has been on mitigating the climate impact of the "here now" growth of air conditioning primarily driven by the increasingly affluent lower middle class in developing countries who are on the brink of purchasing the most affordable—and therefore often least efficient—air conditioners. If we account for the SDG goals, the potential for growth in energy demand and emissions rises by 2050 to values that are more than five times those experienced today, with impacts across cold chain, mobile cooling as well as room air conditioning.[53] The purpose of this paper is to consider how do we deliver Access to Cooling for All without over-heating the planet?" given that we cannot green this volume of electricity. This also needs to consider the economic challenge of universal access to cooling.

GCI data set on which these projections are based also includes a further scenario, 'mitigation'. It assumes what it considers to be an optimistic set of assumptions around technology progress and

---

[53] A Cool World – Defining the Energy Conundrum of Cooling for All, 2018 University of Birmingham states that global cooling energy demand is 3,900 TWh p.a in 2018 with the potential to grow to 19,600 TWh by 2050

implementation globally.

The per unit emissions and energy improvements under this scenario are summarized vs the business as usual case in the tables below.

Energy Improvements	BAU	MIT
Space Cooling	-16%	-35%
Industrial and Commercial	-10%	-29%
Mobile Cooling Systems	-10%	-26%
Domestic Refrigeration	-30%	-41%

Table 9 - Energy Efficiency Improvements GCI BAU and MIT scenarios vs. today

Total Emissions Improvements	BAU	MIT
Space Cooling	-18%	-44%
Industrial and Commercial	-10%	-45%
Mobile Cooling Systems	-25%	-40%
Domestic Refrigeration	-26%	-39%

Table 10 – Total Emissions Improvements GCI BAU and MIT scenarios vs. today

Direct Emissions Improvements	BAU	MIT
Space Cooling	-59%	-59%
Industrial and Commercial	-10%	-10%
Mobile Cooling Systems	-52%	-52%
Domestic Refrigeration	-37%	-37%

Table 11 - Direct Emissions Improvements GCI BAU and MIT scenarios vs. today

The energy reductions in every sector are insufficient to keep energy consumption growth within target in the face of baseline projected demand growth or universal access. None of the emissions reductions projections will result in a net reduction in emissions from the sector between now and 2050 nor keep up within the 2°C scenario or be deliverable using current renewable generation capacity. Also, CGI suggests many efficiency improvements could result in significant equipment cost increases (as much as 100%), whereas there is a requirement to significantly reduce the cost of cooling as well as energy usage.

In this section some guidelines for intervention are proposed along with a qualitative assessment of the role that various measures might play in achieving them.

5.1. Defining targets for intervention

Detailed definitions of targets should be made based on the cooling needs and sector specific conditions that will be explored in sectoral companion papers. However, an overall aspirational target has been defined at the initiation of this study whose implications can be explored.

The World Bank Group (WBG) aims to initiate an approach to a global roadmap to achieve sustainable cooling for all by 2050 whilst transforming the industry towards a goal of zero emissions from cooling.

This will be challenging to achieve. The implications of achieving universal access by aligning equipment penetrations have been reviewed earlier. We will look at options to affect the amount of cooling equipment required in Sections 6.2.

Achieving the goal of zero emissions will require action on direct and indirect emissions. The implications of this are outlined below at a high level and then explored in more detail later in the report.

5.1.1. Direct Emissions from Cooling

While a variety of direct emissions occur in the production of refrigeration and cooling equipment and extraction of the raw materials from which it is made, the most significant direct emissions come from refrigerants. These direct emissions occur via leakage of refrigerant during refrigerant container handling or refrigeration equipment manufacturing, operation, and disposal. Three routes exist for achieving emissions reductions that will have to be used in combination:

Reducing the number of cooling units

Reducing the number of pieces of refrigeration and cooling equipment that contain refrigerant charges will reduce overall refrigerant demand as well as potential for leakage during manufacturing, operation, and disposal.

Reducing leakage

Leakage of refrigerant from cooling equipment is currently substantial. The table below has been derived from IPCC Guidelines for emission inventory assumptions in relation to leakage for the four sectors considered.[54] The four major sectors cover a range of equipment types and so a couple of representative options have been chosen in each category for illustrative purposes.

Equipment Type	Charge Capacity (kg)	Installation Emission Factor (%	Operating Emissions (% of capacity/yr)	Implied Loss over 5 years from Operation	Refrigerant Remaining at Disposal (% of	Recovery Efficiency (% of	Implied Loss During Disposal	Total Implied Refrigerant Loss Over a 5-year life	Total Implied Refrigerant Loss Over a 10-year
Space Cooling (Residential)	.5-100	0.2%	5.0%	25.0%	80%	80%	16%	41.2%	66.2%
Space Cooling (Large Systems)	10-2000	0.2%	2.0%	10.0%	100%	95%	5%	15.2%	25.2%
Industrial and Commercial (Small Systems)	0.2-6	0.5%	1.0%	5.0%	80%	70%	24%	29.5%	34.5%
Industrial and Commercial (Large Systems)	10-10,000	0.5%	7.0%	35.0%	100%	90%	10%	45.5%	80.5%
Mobile Cooling (AC)	.5-1.5	0.2%	10.0%	50.0%	50%	50%	25%	75.2%	125.2%
Mobile Cooling (Refrigeration)	3-8	0.2%	15.0%	75.0%	50%	70%	15%	90.2%	165.2%
Domestic Refrigeration	.05-0.5	0.2%	0.1%	0.5%	80%	70%	24%	24.7%	25.2%

Table 12 - Refrigerant Leakage Rates

Measures that reduce or eliminate refrigerant leakage will be a key part of tackling direct emissions from the refrigeration and cooling sector especially in relation to mobile and larger systems.

Substituting Refrigerants

The global warming potential (GWP) of many common refrigerants is extremely high. It is typically measured in terms of tons of carbon dioxide equivalent, this measure is a means of comparing the environmental impact of leakage. A GWP of 1,000 would mean that releasing 1 ton of refrigerant to the atmosphere would be equivalent to emitting 1,000 tons of CO_2 in terms of its warming effect.

As examples of high GWP refrigerants:

- R404a commonly used today in refrigeration equipment has a GWP of 3,922
- R410a commonly used in air conditioning applications has a GWP of 2,088.
- Current near-term replacement refrigerants like R407a (proposed for refrigeration) has a GWP of 2,107 whereas R32 (proposed for air conditioning) has a GWP of 675.[55, 56]

Lower GWP refrigerants are available, as an example Carbon Dioxide (GWP 1) is being deployed in many European countries. However, this technology requires higher operating pressures to achieve the same cooling effect. This has resulted in increased energy consumption in many cases and new requirements to install and maintain systems. Other common synthetic or hydrocarbon derived options

---

[54] Methodological Tool: Calculation of baseline, project and leakage emissions from the use of refrigerants, Clean Development Mechanism, United Nations, 2017

[55] Refrigerants Environmental Data. Ozone Depletion and Global Warming Potential - Linde Group

[56] https://www.danfoss.com/en-gb/about-danfoss/our-businesses/cooling/refrigerants-and-energy-efficiency/refrigerants-for-lowering-the-gwp/r32/

have the drawback of flammability; the implication of this is again a requirement for different skills in the technician base responsible for installing and maintaining systems.

Substantial reductions in direct emissions from refrigeration and cooling equipment will most likely require substitution (low GWP refrigerants for high) alongside reducing leakage and minimizing the number of units in use. This will have implications for energy consumption management and skills needs for the sector.

5.1.2. Indirect Emissions from Cooling

The most significant source of indirect emissions from refrigeration and cooling equipment is that caused by generation of the energy that they consume. For most cooling equipment this is either electricity or heat and mechanical energy generated by the burning of hydrocarbons.

Electricity Related Emissions

Most of the stationary cooling equipment is powered by electricity, exceptions to this would include absorption chillers (often driven by heat from a co-located industrial or power generation process). Indirect emissions from this type of equipment are therefore dependent on:

1. The number of cooling units in operation
2. The frequency with which they are used (i.e. how much cooling do they do; can this be reduced through waste resources?))
3. The efficiency of those systems (typically defined as coefficient of performance)
4. The carbon intensity of generating the electricity used by the system (typically expressed as gCO2e/kWh)
5. Using non-electric cooling to harness thermal energy resources
6. The maintenance regime they are subject to (discussed under skills)

Factors 1 and 2 indicate a requirement for demand mitigation measures that reduce the need to install and operate cooling equipment. 3. Indicates a requirement for technology improvement. Whilst directly impacting indirect emissions, 4. is beyond the scope of a cooling strategy, lower carbon intensity electricity generation is typically smaller scale, more distributed and intermittent than high carbon generation sources. 5. We believe is key given the size of the challenge although the interaction between thermal low carbon energy resources and cooling equipment energy demand is likely to have implications for both technology and policy measures.

Fossil fuel driven systems

In stationary space cooling and industrial applications natural gas is a common fuel. The gas is burnt to generate heat which is converted to cooling via sorption cooling processes. This method of cooling is common in larger applications.

In mobile cooling applications, refrigeration and air conditioning are currently an ancillary load on the main engine (most often burning a petroleum product derived fuel) or have their own dedicated small internal combustion engine (burning similar fuels). These cooling loads can be significant in the context of overall vehicle energy consumption. Additional fuel consumption arising from air conditioning in cars ranges from 3%-18% depending on ambient temperatures, driving speed and humidity etc.[57] whereas estimates for fuel consumption associated with transport refrigeration range from ~8% to more than 20% of total vehicle energy consumption depending on ambient temperatures, duty cycle and set point.[58]

In a transport context, a two-way relationship exists: On the one hand, low or zero carbon alternatives in the transport sector must be able to meet these needs as the requirement for comfort cooling and refrigeration in transport contexts is unlikely to disappear; on the other the amount of energy on the vehicle available for supporting these loads will decrease as lower energy density alternatives to hydrocarbons like hydrogen and electricity storage are adopted to decarbonize transport. This is likely to drive a technological requirement for enhanced efficiency and potentially new storage media.

In summary, achieving decarbonization of the refrigeration and cooling sector is likely to require a combination of measures encompassing:

---

[57] Fuel Consumption and CO2 pollutant emissions of mobile air conditioning at a fleet level – new data and model comparison, Environmental Science and Technology, Welenmann, Alvarez and Keller 2010

[58] Food Transport Refrigeration, Tassou, De-Lille and Lewis

- Demand mitigation – by reducing the overall need for active cooling to reduce the number of cooling appliances required and their environmental impact.
- Efficiency improvements – at component, appliance, and system level to reduce the energy need (and associated indirect emissions) from supplying a given level of cooling.
- By harnessing free and waste thermal energy resources to replace electricity demand.
- Renewables and electricity and thermal network integration – to ensure that remaining energy demands from cooling appliances "fit" with the optimum capabilities and breadth of zero carbon resources including thermal.
- Refrigerants – to tackle direct emissions via reducing refrigerant charges, leakage and substituting for lower GWP refrigerants.
- New Technologies - new ways of providing cooling enabling substitution of hydrocarbon energy sources as well as electrically driven.

Within this the consideration of emissions reduction needs to take account of both direct and indirect emissions. Measures called Total Equivalent Warming Impact (TEWI) and Life Cycle Climate Performance have been designed for this purpose.

TEWI incorporates:

- Emissions of refrigerant released during the lifetime of the equipment
- Emissions of CO2 from production of electricity (or mechanical energy) to power the equipment

LCCP incorporates:

- Emissions of refrigerant released during the lifetime of the equipment
- Emissions of CO2 from production of electricity (or mechanical energy) to power the equipment
- Emissions associated with embedded energy (i.e. energy required for manufacturing the equipment); and
- Emissions of refrigerant released during the production of the equipment.

5.2. Demand mitigation

The first step to reduce the energy and emissions impact of cooling is to mitigate demand. This is not about denying people access to the services provided by cooling (e.g. comfortable living temperatures, data/ connectivity, and food preservation) but by finding ways to provide these services with less.

Looking at the four main sectors considered in this report, multiple options exist (these are not exhaustive but examples):

Space Cooling

Cooling habitable spaces is among the largest consumers of energy. Demand for this type of cooling is forecast to grow exponentially under a variety of scenarios. Limiting cooling demand from buildings can be achieved in multiple ways that can be used in combination.

Building and urban environment design

A variety of approaches that make use of shade and reflective surfaces have been shown to be capable of substantially reducing the demand for air conditioning during high ambient temperature conditions by reducing the amount of solar radiation absorbed by the building. Cooling demand can be further reduced by applying techniques like natural ventilation to enable the movement of air within the building without drawing substantial quantities of energy.

Social and Cultural Changes

Cultural norms about required temperatures can be adjusted to reduce demand for cooling whilst still maintaining a livable environment. As an example, the annual Coolbiz campaign in Japan is designed to reduce air conditioning demand. The campaign encourages workers to adjust their dress (e.g. to short sleeve shirts without ties from a suit) and to alter thermostat temperatures to 28°C as opposed to a lower air conditioning set point. Changing perceptions about what the temperature needs to be and adopting other measures to achieve thermal comfort is a low-cost route to saving substantial quantities of energy.

A study in India as part of the India Cooling Action Plan investigated the correlation between energy use and thermostat setting in an Indian context.[59] The study found that 8 to 10% savings in energy consumption were possible per degree Celsius set point increase for inverter (variable speed) room air conditioners, savings were lower for fixed speed models.

These factors should be included and assessed in the studies for each cooling sector.

Industrial and Commercial Systems

Though energy consumption by industrial and commercial refrigeration equipment is relatively modest owing to the small number of units in use, demand mitigation options exist here too.

Insulation performance

The performance of insulation in refrigerated appliances directly impacts their energy consumption because of the amount of heat that needs to be removed by the refrigeration cycle. Enhancing the effectiveness of insulation for chilled warehouses, cold stores and display cabinets could substantially decrease their energy requirements. It would also have the effect of building more inertia into their energy demands (a better insulated container can last for longer without requiring active cooling), which would be useful for electricity network integration. A specific example linked to behavior is also present with display cabinets in the retail sector, frequently these have no doors because retailers believe that they reduce sales. Adding doors to display cabinets can reduce energy consumption by 20-50%.[60]

Behavior and maintenance

The way in which industrial and commercial refrigeration equipment is used and maintained can have significant implications for its energy consumption too. A combination of cleaning (2-10%), refrigerant (up to 15%) and controls checks (up to 15%) could also provide substantial gains.[61] It should be noted though that most projections for refrigeration and cooling demand assume that equipment is reasonably maintained, so whether these gains represent a return to trend or net gains needs to be considered carefully.

Store Temperatures

Adjusting the instore temperature can be an effective way of reducing refrigeration demand during winter in lower ambient temperature countries as many types of retail display case in reject heat into the shops in which they are located. This can be achieved by expanding the range of acceptable temperatures within the store by a few degrees. Reports estimate that the saving from this approach could be ~10% of energy consumption during winter.[62]

These factors should be included and assessed in the studies for each cooling sector.

5.3. Mobile Cooling Systems

Mobile Cooling Systems are currently significant consumers of fossil fuels. Potential strategies for reducing demand are slightly different between comfort cooling and refrigeration applications.

5.3.1. Comfort Cooling

The emergence of electric vehicles has led to increased focus on heating ventilation and cooling (HVAC) loads as they significantly impact vehicle range. Techniques that have been tested and shown to reduce total cooling requirement (and extend vehicle range) include:

- Vehicle coatings and glazing materials to reduce solar gain in the cabin – studies have indicated that even simple measures like painting cars white as opposed to black can save nearly 2% of total fuel consumed in warm climates.[63]
- Localized cooling of occupants (reducing the total amount of cooling duty required by avoiding cooling air through the entire car) has been achieved through direct contact cooling techniques

---

[59] Summary presentation - Saving Energy for Air-Conditioning through Behaviour Change: The Case of India Cooling Action Plan, Alliance for Energy Efficient Economy 2019

[60] Refrigeration Road Map, Carbon Trust, 2012

[61] Refrigeration Road Map, Carbon Trust, 2012

[62] Refrigeration Road Map, Carbon Trust, 2012

[63] Cool Colored Cars to Reduce Air-Conditioning Energy Use and Reduce CO2 Emission, Lawrence Berkley National Laboratory, 2011

and highly directed fans. Research by NREL has achieved savings that could yield 7-15% longer range in electric vehicles from this approach.[64]
- Parked car ventilation (through strategic location of vents) reduces the need for significant temperature pull downs of vehicles that have been parked for an extended period. About 1% of air conditioning related fuel consumption may be saved by this approach.[65]

These options should be explored and assessed in the studies for each cooling sector.

5.3.2. Transport Refrigeration

Energy demand in this application can be affected by a combination of system design and operational practices. These should be included and assessed in the sector-specific studies.

- Design Considerations – relate to how the refrigeration unit is integrated into the wider trailer or shipping container product and encompass:
    - "Right sizing" the refrigeration unit to reduce on and off cycling and ensure that the refrigeration unit operates at an efficient point
    - Use of reflective surfaces to minimize solar gain on the trailer or container
    - Use of insulation to minimize heat gain from other sources
- Operational Considerations – relate to how the unit is operated and maintained, considerations would include factors:
    - Turning off the unit when doors are open – as this causes icing that can lead to energy intensive defrost events.
    - Ensuring the unit is properly charged with refrigerant and that evaporator and condenser heat exchangers are clean and free from obstructions.

5.3.3. Domestic Refrigeration

Considerable progress has been made in enhancing the overall efficiency of domestic refrigerators via enhancements in cooling system and overall appliance performance. In terms of reducing demand for cooling input, enhancing the performance of the insulation of the refrigerator can mitigate 60% of heat leakage that comes in through the walls and door.[66]

5.4. Efficiency improvements

Enhancing the efficiency with which cooling is produced is a key element of reducing its environmental impact.

The vapor compression cycle (VCC) is in use in all these sectors as the dominant means of providing cooling effect. The technical approach to enhancing the efficiency of the vapor compression cycle will need to focus on both component efficiencies and overall system optimization and control.

Key components that could be the focus for efficiency improvements include:

- Compressors
- Heat exchangers
- Fans
- Thermal expansion valves
- System configurations
- Controls

Examples of potential innovations that can be explored within the specific application categories are identified in the table below.

---

[64] https://www.nrel.gov/docs/fy14osti/62363.pdf

[65] US Light Duty Vehicle Air Conditioning Fuel Use and the Impact of Four Solar/Thermal Control Technologies, NREL, SAE 2017

[66] Climate-friendly and energy-efficient refrigerators, UN Environment, United for Efficiency, 2017

System Element	Potential Innovations	Potential Impact
Compressor	Reduced mechanical parasitic loads via bearing and electric drive innovation	Increase in overall system efficiency via reduced losses
	Enhanced sealing or reduced pressure drop	Increase overall system efficiency via reduction in work wasted overcoming pressure drop or compressing refrigerant unnecessarily.
	Variable speed and displacement compression technologies	Enhanced part load efficiencies
Heat Exchangers	Enhanced heat exchanger effectiveness via increased heat transfer area (for a given volume) or coatings	Improved heat exchanger performance and overall efficiency gain
	Light-weighting techniques	Enables larger heat exchangers (with bigger surface areas and high efficiency) to be used for a given packaging constraint.
	Hydrophobic or ice crystal formation impeding coatings	Reduce heat exchanger icing and energy intensive defrost events in refrigeration applications and avoid condensation build up (with associated energy penalty) air conditioning applications.
Fans	Enhanced efficiency electric motors	Reduced energy requirement
	Integration with variable speed drive technologies	Improved part load efficiency
	Optimization of air flow	Reduced pressure drops through heat exchangers or cooled compartments reducing fan loads and corresponding energy requirements.
Thermal Expansion Valves	Improved thermal expansion valve (TXV) control techniques	Enhanced part load efficiency.
	Expander Technologies (large systems only)	Recover energy from refrigerant expansion process for use in electrical or mechanical processes.
System Configurations	Cascade cycles to reduce temperature differences covered by individual VCCs.	Enhanced co-efficient of performance (overall system efficiency) often at the expense of system complexity.
	Separate dehumidification steps (e.g. via membranes or coatings)	Avoiding cooling substantial quantities of water in the air will reduce energy requirements and enhance overall system efficiency.
	Integration with heat sinks (e.g. ground, bodies of water and LNG)	Enhanced system efficiency by making use of “waste” cold resources.
	Integration with thermal energy stores	Enhanced system efficiency (depending on ambient temperatures)
Controls	Refrigerant flow and pressure optimization to match load conditions	Enhanced efficiency at wider range of operating conditions

Table 13 - Vapor Compression Cycle Efficiency Enhancements

In the recent Rocky Mountain Institute’s report (2019), it is highlighted that substantial efficiency gains can be achieved through enhancing the vapor compression cycle, while only 14% of maximum theoretical efficiency has been achieved so far . Achieving the ~80% reduction in energy consumption implied by the Global Cooling Prize’s assessment criteria could substantially reduce global cooling energy demand and associated emissions.

5.5. Refrigerants

Changes to refrigerant composition and handling practices are relevant to all cooling sectors as current GWPs of common refrigerants are extremely high and leakage rates significant over the lifecycle of products.

The two most significant measures that can be undertaken are substitution and leakage reduction.

5.5.1. *Substitution of high GWP refrigerants for low GWP refrigerants*

Few of the alternative lower GWP refrigerants are drop-ins. Consequently, changing to lower GWP refrigerants will require in many cases significant component and system design alterations to enable adoption without substantial efficiency or durability penalties. Changes to refrigerants should be considered in combination with system efficiency related interventions.

Substitution of refrigerants is likely to create a skills requirement also because of the higher operating pressures or flammability risks posed by low GWP alternatives currently available. As a result, refrigerant substitution will need to be considered in combination with skills and maintenance issues (explored further in section 7).

5.5.2. *Leakage Reduction*

Leakage reduces the efficiency of appliances and so increases energy demand. Leakage reduction involves installation and maintenance practices (covered in section 7), but also relates to component and system designs.

Because the charge volumes are relatively large and leakage rates high. Several academic studies have focused on identifying the sources of leaks within large commercial refrigeration systems of the type used within supermarkets. The majority of leaks occur within joints made during installation or from leaking seals or glands within the system,[67] suggesting problems with making effective joints and seals within these systems. Some of the studies have recommended design changes to rectify this. This suggests that changes to installation techniques to rely less on brazed joints (which are in some respects dictated by product design) or switching to integrated cabinets may be necessary to radically reduce leaks.

Mobile units exhibit a different leakage challenge. Whilst transport refrigeration units are typically charged with refrigerant during installation with significant brazing of joints (leading to similar problems to those observed with commercial systems), mobile air conditioning equipment is typically charged and commissioned at the factory. The high leakage rates observed in both types of equipment suggest that substitution (of refrigerants or vapor compression technology) or radically reduced refrigerant charges may be the best options for decarbonizing this sector.

Leakage reduction measures should be investigated on a sector specific basis**.**

5.6. Renewables and electricity network integration

Outside of the refrigeration and cooling sector the energy industry is undergoing very substantial change. Thermal, electrical and transport energy systems are changing in unprecedented ways as decarbonization efforts gather pace. At the same time, these systems are becoming ever more integrated, meaning that they will impact each other in a variety of ways that are difficult to predict. Particularly, intermittent renewables are presenting challenges in terms of how to manage electric loads.

Currently, most cooling appliances are relatively “dumb” electrical loads reliant on electricity being available in large quantities whenever they require it. This will need to change so that appliance users can manage their operating costs by accessing electricity during times that it is abundant and avoiding peaks in pricing caused by demand spikes or supply troughs. There is also an expectation amongst electricity network operators that in future flexible electricity demand will play a major role in balancing the system. Cooling is frequently cited as a major demand side response resource in discussions about future system operability because of the significant amounts of inertia potentially involved in systems (provided by insulated boxes or building fabric). It will be necessary to respond to both pulls to decarbonize the sector.

Mobile cooling systems also have the potential to impact on system operation. Electrification of transport

---

[67] An Investigation of Refrigerant Leakage in Commercial Refrigeration, International Journal of Refrigeration, C. Francis, G. Maidment and G Davies, 2016

is gathering pace. As the penetrations of electric vehicles increase, attention will turn to managing demand for charging infrastructure and network capacity. Given the significance of HVAC and cooling loads in overall vehicle energy consumption and the corresponding impact on range, decisions taken about cooling in transport applications will have consequences for charging profiles of electric vehicles and consequently on the wider electricity network.

Electricity network impacts and renewables integration (including through thermal storage) should be considered in all sector specific studies.

5.7. New technologies

New technologies can have a role to play within decarbonization of the sector, though their benefits compared to incumbents need to be assessed carefully.

Areas that could be useful to consider within sector specific studies include:

- Complementary Vapor Compression Technologies – to unlock efficiency improvements
- Alternatives to Vapor Compression – to eliminate refrigerants where leakage cannot be sufficiently reduced or where a compelling efficiency advantage exists
- Energy storage options – to enhance electricity network integration efforts
- Waste Resources – to make use of sources of “waste cold” to reduce overall energy requirements
- System design tools and approaches – to better match technology/products with cooling service needs
- Manufacturing Strategies – to reduce the skills requirement associated with equipment installations and maintenance.

5.7.1. Complementary Vapor Compression Technologies

Numerous innovations are in development that can affect the operation of individual vapor compression cycle components (e.g. new geometry compressors, intelligent electric motors, heat exchanger coatings etc.). These will be a key element in increasing individual component efficiencies. Control technologies and cycle design (e.g. component and refrigerant selection) are also important options for increasing efficiency, enabling adoption of low GWP refrigerants, or eliminating leaks.

5.7.2. Alternatives to Vapor Compression

A variety of alternatives to vapor compression have been proposed historically (e.g. magnetic refrigeration, Peltier effect, acoustic etc.). Typically, these have had relatively niche applications because of poor efficiencies and high production costs. These alternatives should though be considered in the sector focused studies alongside newer techniques like thermo-elastic cooling using shape memory alloys, as efficiencies and materials science are constantly advancing. These alternatives may also be the only route to eliminating refrigerant leakage in some applications.

5.7.3. Energy Storage Options

Several storage options exist that are relevant to cooling that should be considered on an application specific basis:

- Electro-chemical storage systems like batteries and capacitors are easily integrated with wider electrical systems and benefit from vary significant volumes of research and development.
- Mechanical storage systems like fly-wheels may be appropriate in exceptionally large systems where inrush currents created by compressors may cause problems for local networks as they can deliver relatively high powers over short periods for low costs.
- Thermal Energy Storage systems like phase change materials (ice or PCMs) or other thermal batteries may be appropriate for low cost longer duration storage. This technology also benefits from several equipment thermal integration opportunities that could enhance efficiency.

Integration between cooling devices and energy storage systems and cooling sector specific energy storage device innovation should be considered as part of the wider technology agenda. These technologies are likely to be important to cooling’s ability to fit within the future energy system and harness thermal resources.

5.7.4. Free and Waste Resources

Several "waste" cooling resources exist that can act as heat sinks to improve the efficiency of cooling provision or even in some cases eliminate the need to provide active cooling. Cold resources can be human or man-made ranging from using cold water in lakes or cellars to harvesting very high-grade waste cold from Liquefied Natural Gas (LNG) import terminals. Waste heat resources can also be used to provide cooling via various absorption processes. A variety of waste resources and applications are summarized in the table below.

Heat/Cold Resource	Example Sources	Cooling Tech	Cooling Applications	Alternative Uses?
100-130°C	Process waste heat, turbine or engine exhaust gases	Absorption Chilling	Process cooling AC – mainly stationary	Organic Rankine Cycle Power Generation
70-100°C	Food frying water condensate, solar thermal (vacuum tubes) and engine jacket water	Absorption and Adsorption Chilling		Process heat make up
10-12°C	The earth, water bodies like the sea	Ground Source heat pumps (cascade vapor compression cycles), underground storage	Multiple stationary applications in comfort cooling and refrigeration	N/A
4-10°C	Deep lake water	District cooling networks	Space cooling	N/A
0-4°C	Snow	Inter-seasonal snow storage	Space cooling	N/A
-164°C	LNG regasification	District cooling networks + Cryogenics	Air separation, process chilling and freezing + space cooling. Cryogenics can offer transport refrigeration too.	Direct cryogenic power cycles

Table 14 - Summary of Waste Thermal Resources and Potential Uses

5.7.5. System Design Tools and Approaches

Popular systems design approaches focus on individual appliances and integrated installations (e.g. a store refrigeration system or at the larger end of the scale a district space cooling project). Considerable efficiency gains can be achieved by assessing space cooling and refrigeration needs at a regional or national level and exploring how economies of scale, waste resource opportunities and synergies between processes can be best unlocked. There is an innovation opportunity around tools that can assess integrated cooling and refrigeration requirements, assessing waste resources and demand mitigation measures, evaluating technology and operational options, and using the outputs to support an integrated system design. The feasibility of this approach, the practicality of applying it within the individual focus sectors and potential benefits should be explored in more detail in the sector specific studies. This sort of toolset would also facilitate development of quantitatively driven technology roadmaps.

5.7.6. Manufacturing Strategies

Current manufacturing (and application integration) strategies applied in some sectors substantially increase the amount of bespoke work undertaken by technicians during installations of equipment. Refrigerant handling and brazing activities are particularly skills intensive and often a point of failure within systems at a variety of scales.

Current and future technology opportunities should be explored to review the extent to which skill requirements for installing systems can be reduced to address the skills gap (and the emissions associated with poor quality installations and maintenance). It is also possible that other technology innovations under consideration may require manufacturing innovation to achieve cost competitiveness with incumbent technologies.

5.8. Systems approach

None of the approaches identified (demand mitigation, efficiency, refrigerants, renewables, or new technologies) will be sufficient if implemented in isolation to achieve zero carbon impact from refrigeration during a 2050 timescale. What is required is a holistic system driven approach to:

1. Identify cooling service needs in a data and fact driven manner.
2. Assess the local social, economic, and wider energy landscape of the region under review.
3. Highlight demand mitigation strategies likely to be effective whilst maintaining required service levels.
4. Explore opportunities for synergies between processes, waste resources and cooling needs that can further reduce the required cooling requirement.
5. Match technology characteristics to local conditions and residual cooling demand in a way that minimizes cost and carbon whilst maintaining the required service levels.

A toolset suitable for undertaking this activity does not currently exist. There is a requirement to develop one and test its efficacy, which Heriot-Watt University is planning to explore. In the meantime, we recommend that the sector studies follow this approach at a qualitative level to try to ensure that at least the most obvious opportunities are captured in the road-mapping activity. Within each application set, a “merit order” exists for meeting cooling needs. The merit ranking is based on energy requirements, emissions, and cost factors; this is discussed in more detail in section 9 of the report.

6. Skills and Maintenance

Poor skills are a factor in poor maintenance of refrigeration and cooling equipment, poorly maintained equipment tends to cool less effectively, leak more refrigerant and use more energy. Utilizing badly maintained systems at large scale can increase direct and indirect emissions across the sector by 10-30%

It is estimated that that the Cooling for All scenario will need an increase of trained refrigeration technicians from an estimated 975,000 today to 3.8M in 2050.[68] It is worth noting that 80% of RAC equipment is projected to be deployed in the developing markets by 2030.[69]

The availability of skilled technicians and its impact on installations and maintenance practices is a global issue. Equally, there are also skills deficits in users of refrigeration equipment (e.g. selecting an appropriate set point for an air conditioner or applying refrigeration at the appropriate time and temperature within a cold chain).

6.1. Overview of current skills and maintenance and future demands

Today there are gaps in the availability of skills required to maintain and install refrigeration and cooling equipment.

Currently, the EU has ~160,000 technicians registered with national governments as part of its efforts to control direct emissions.[70] According to GCI figures they currently look after ~592 million cooling units,[71] this is the equivalent of ~3,700 cooling units per engineer.[72]

By 2050, GCI projects that the EU will have about 724 million cooling units, if they are as efficient as today, this would require ~35,000 more technicians to maintain these units. Extrapolating these engineer- to- equipment ratios to a variety of scenarios modelled in this and other papers, implied technicians' requirements are summarized in the table below.

	2018		2050	
Scenario	**Equipment Stock**	**Technicians**	**Equipment Stock**	**Technicians**
Europe - GCI	592 million	160 k	724 million	196 k
World - GCI	3,611 million	975 k	9,562 million	2,583 k
14 Focus Countries - GCI Subset	2,030 million	548 k	6,122 million	1,654 k
14 Focus Countries - UA Scenario	2,030 million	548 k	9,555 million	2,581 k
World - C4A Scenario[73]	3,611 million	975 k	14,065 million	3,800 k

Table 15 - Implied Quantities of F-gas Engineers

It is unlikely that global qualified refrigeration technicians' penetrations in developing markets are as high as in Europe since the market is relatively special in the degree to which it is regulated. So, the training gaps suggested of ~1.6 million technicians globally for the non-convergence scenarios could be ignoring a substantial amount of "catching up" required to properly install and maintain current equipment. This training need relates to handling of "f-gasses" (essentially all synthetic refrigerants), a necessary skill to install and maintain refrigeration equipment.

The emergence and increasing penetration of low GWP refrigerants would likely result in the need for trainings to be replaced by different ones focusing on handling toxic Ammonia, high pressure CO_2 systems, or other potentially flammable alternatives. Within the European Union, training is available in many member states, but a survey undertaken by the European Commission in 2016 reported very low rates of staff being trained in handling of alternate refrigerants – between 0% and 2.3% depending on

---

[68] This figure is based on data for the EU which needs to be modified, awaiting new data points .

[69] Vardanian, Mike. 2016. "BSRIA Industry Presentation." Referenced to Coordinating finance for sustainable refrigeration and air conditioning, GIZ 2018

[70] Retail Refrigeration, Making the Transition to Clean Cold, University of Birmingham, 2017

[71] GCI estimate the European Union refrigeration and cooling equipment parc to be 592,238,725 cooling units

[72] We are currently seeking review of current shortfall in number of maintenance engineers as this will impact projections.

[73] A Cool World – Defining the Energy Conundrum of Cooling for All, University of Birmingham, 2018

the type of refrigerant. There is therefore likely to be a substantial requirement for retraining the current technicians to switch to lower GWP refrigerants safely.

6.2. Case Study: India's Cooling Skills Program

In September 2018, India's Ministry of Environment, Forest & Climate Change published a draft Cooling Action Plan. The first document of its type published by a country that covers the entire cooling sector.

The Action Plan has 5 key goals:

1. Recognition of "cooling and related areas" as a thrust area of research under national science and technology program to support development of technological solutions and encourage innovation challenges.
2. Reduction of cooling demand across sectors by 20% to 25 % by year 2037-38
3. Reduction of refrigerant demand by 25% to 30% by year 2037-38
4. Reduction of cooling energy requirements by 25% to 40% by year 2037-38
5. Training and certification of 100,000 servicing sector technicians by year 2022-23, synergizing with Skill India Mission

This represents a holistic approach combining technology innovation, demand mitigation, refrigerants, efficiency and training and skills touching on many of the elements of the systems-based approach mentioned in Section 6.

Training a further 100,000 servicing sector technicians by 2022-23 is a very substantial commitment. In the discussion of skills needs, the Plan summarizes a survey conducted in 2017 of service technicians that found relatively low levels of compliance with good practice.[74] Of the five "good practices" (recovery of refrigerant, flushing without refrigerant, brazing/flaring, calibrated charging and leak testing), only leak testing was practiced by the nearly all (90%) technicians across air conditioning sectors, calibrated charging was followed by ~60% of surveyed technicians and less than half flushed without refrigerant or recovered refrigerant from systems. This is likely to have significant efficiency and emissions implications for the equipment being serviced.

The skills gap in India is recognized and substantial scale efforts have been applied for about the last 20 years or so to addressing it. A collaboration between Swiss and Indian governments, enabled the training of about 20,000 technicians in good service practices under the ECOFRIG and HIDECOR projects. In these projects, skills and capacity were transferred to Indian training institutions to improve training quality (this training was predominantly in relation to CFC phase out).

This was then followed by HCFC handling focused training under the HCFC Phase-Out Management Plan a national program to train ~28,000 engineers across two stages, this was financed by the Multilateral Fund. A new initiative to train 100,000 more technicians is planned as a collaboration between the Ministry of Environment, Forest and Climate Change and the Ministry of Skill Development and Entrepreneurship.

Beyond merely increasing the volume of "trained" individuals, the Plan makes some specific recommendations for skills development that can be summarized as:

- Collecting (better) data about the number of technicians operating in India so that the challenge can be better understood.
- Ensuring that certifications offered are sufficiently practical to be useful to technicians operating in commercial situations by getting industry input and focusing on best practice rather than being overly theoretical.
- Enhancing the training infrastructure in terms of training instructors, providing test equipment etc.
- Mandatory certification of technicians (though carefully phased in to avoid damaging livelihoods and the industry by forcing uncertified people out).
- Promoting awareness of certification requirements among customers.
- Developing a social security scheme dedicated to certified service technicians to incentivize certification and compliance.

Leaning from India's cooling skills plan (described in adjacent case study) indicates that training programs at country scale need to be:

---

[74] India Cooling Action Plan Draft, Ministry of Environment, Forest & Climate Change, Government of India 2018

- Large enough to make an impact, which will require training capacity development rather than direct training in many cases.
- Tailored to local conditions so that training is delivered that people will actually apply whilst also addressing a clear need.
- Combined with some kind of compliance incentive. Whilst ultimately, this can be achieved by regulation, in the short-term positive incentives may be required.

The types of training required are also likely to be sector specific, so this area should be investigated further in the sector studies.

6.3. Impact of maintenance, including on energy and emission projections

A generic example of the importance of even basic practices like cleaning was supplied in a previous study by WAVE Refrigeration.[75] Refrigeration and cooling systems are heat removal devices. The amount of heat that they can remove from a system is defined as:

$$Q = M.\ x\ Cp\ x\ \Delta T.$$

Where

Q = Heat removed

M. = Mass flow of medium

Cp = Specific heat of medium used

ΔT = Temperature differential

If air flow across a heat exchanger is restricted by dirt or deformation by say 35%, to remove the same amount of heat the refrigeration cycle needs to create a 35% larger temperature difference to maintain the same cooling effect. To achieve this temperature difference, generally 15-20% more energy is required. Depending on the system, this may not be possible so the net result could be a loss of cooling capability too. Equally, factors like refrigerant charge, pressure and temperature set points can all substantially affect energy consumption by as much as 30% in combination.[76]

Installation and maintenance practices can also impact on refrigerant leakage, poor refrigerant handling techniques or joints can emit refrigerants. The projections produced earlier in the report, do not explicitly assume poorly maintained systems are widely in use. Utilizing badly maintained systems at large scale could increase direct and indirect emissions across the sector by 10-30%.[77]

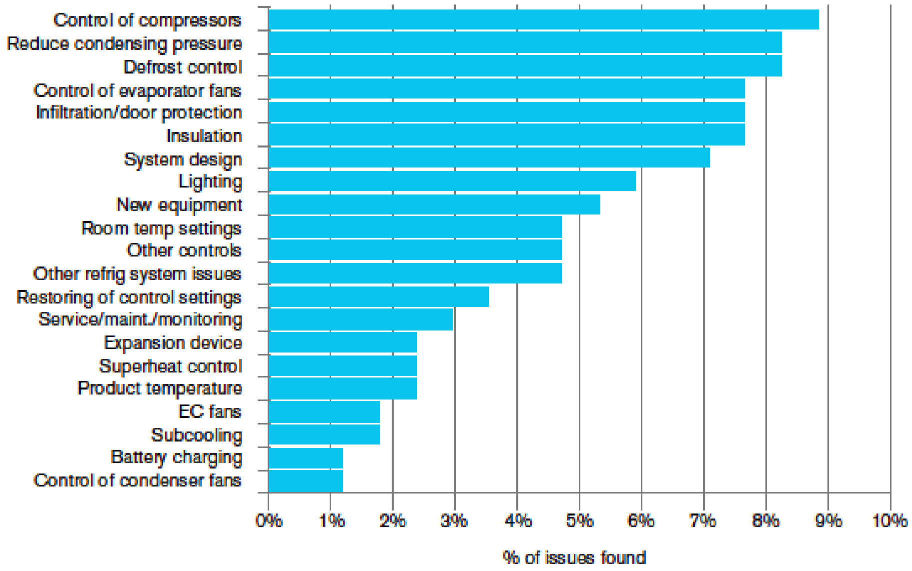


Figure 16: Potential to improve the efficiency of cold stores, Source: LSBU

---

[75] https://wave-refrigeration.com/wp-content/uploads/White-Paper-2019.pdf

[76] Refrigeration Road Map, Carbon Trust, 2012

[77] London South Bank University

7. Commercial and Policy Options

Market failures currently limit access to cooling and do not incentivize emissions reduction. Several business model innovations and policy interventions have been identified to address these failures.

In many countries, there are several market failures that limit access to cooling, these include:

- Insufficient financial resources to mitigate demand or purchase and install cooling equipment
- Lack of access to electricity
- Lack of integration of non-electric resources

There are also additional barriers to deploying energy efficient cooling.

Business model innovations could contribute to tackling investment and energy access challenges, for example:

- Aggregate individual demands to create “time of use” trading groups
- Multiple stakeholders whose production volumes are small could pool resources to access cooling infrastructure i.e. farmers at time of harvest
- Cooling as a Service, where clients are charged per unit of produce cooled

Policy interventions implemented in parallel could expand access and overcome barriers to uptake, these include:

- Renewable thermal incentives, not just electricity generation
- Policy Maker Capacity Building e.g. through awareness raising, best practice needs assessment and policy intervention tools
- Information and Communication with relevant stakeholders to build understanding of the importance of cooling to societal and development goals
- Education and Skills Development to ensure effective installation, maintenance and use of cooling equipment
- Financing Provision e.g. coordinating provision of finance or mass procurement to overcome initial investment challenges to purchasing cooling equipment
- Incentives, e.g. preferential import tariffs, reduce interest rate loans or direct subsidies

These however must be focused on *clean* cooling resources not simply access to cooling.

Emissions reduction

Market failures that are currently barriers to emissions reduction in the cooling sector include:

- Lack of awareness amongst users of cooling equipment of its emissions impact, energy consumption and true running cost
- Lack of skills - insufficient numbers of properly trained engineers, leading to low equipment take up and poor maintenance
- Dominance of the first costs in purchasing decisions (domestic and commercial) and lack of stakeholder cohesion/split incentives regarding purchase and maintenance and operating costs in commercial settings
- National interest vs. Minimum Efficiency Performance Standards
- Ensuring a focus on MEPS for appliances should not preclude system solutions to better harness free and waste resources
- Market structure where significant power is held by a small number of organizations, limiting innovation
- Lack of data, limiting understanding of scale of challenge and efficacy of proposed measures
- Lack of research funding
- Lack of integrated system tools and demonstrators

Business model innovations that could contribute to emissions reduction include

- Purchase or leasing combined maintenance contracts with efficiency incentives
- District cooling systems
- Cooling as a service

A wide variety of policy interventions are identified, including:

- Renewable Thermal Incentives (free cooling, harnessing waste, and natural resources)

- Training capacity development and provision
- Provision of funding and development of financial instruments, including loans, enhanced capital allowances, co-opetition funds, coordination of access to capital for Cooling as a Service providers, R&D funding
- Regulation and building codes or other standards to force purchasing and behavioral changes

As stated above, we need to ensure that a focus on MEPS on electrically driven appliances does not preclude the longer-term integration of free and waste thermal resources essential to meet 2030 and 2050 goals. Currently, the market looks unlikely to independently resolve the twin challenges of expanding access to cooling of all types whilst reducing energy consumption and emissions.

In summary the scenarios explored in this report are:

- *A business as usual scenario*
    - Driven by a growth in equipment parc from 3.6 billion cooling units to 9.5 billion pieces, global annual demand for energy to power cooling equipment expands to 9,500 TWh (vs. 3,900 TWh in 2018 and an implied IEA budget of 6,300TWh).
    - CO2 emissions are 4.1GTCO2e vs a target of 1.4GTCO2e. The group of 14 countries alone would account for 6,122 TWh of energy consumption in this scenario.
    - Despite this growth, substantial inequalities in access would remain, for example even by 2050 not every household has a domestic refrigerator.

- *An accelerated access scenario*
    - Through converging global equipment penetrations, the global equipment parc would grow to more than 14 billion devices by 2050.
    - Global energy consumption would increase to more than 19,600 TWh (vs the implied IEA energy budget of 6,300 TWh).
    - Emissions implied by this level of deployment are 14.8GTCO2e (vs a 1.4 GTCO2e target). The group of 14 countries alone would account for more than 13,200 TWh of this energy demand.

Only the accelerated access scenario considers equality of access and neither scenario produces energy consumption or emissions outcomes that are acceptable within a climate change context, so interventions are likely to be necessary.

7.1. Access related market failures

7.1.1. Market failures that limit access to cooling

Currently, the market delivers less access to cooling than would be optimal from an economic and human development perspective. This is especially true in relation to cold chain access.

The lack of cold chains in certain countries is a multi-faceted issue:

- Cold chain investment costs – some communities simply lack the financial resources required to purchase and install cold chain equipment. This problem is particularly acute for small-scale farmers. The result is that the financial and environmental benefits of increased cooling provision, e.g. more produce making it to market, are lost.
- Lack of access to energy – except for solar fridges designed primarily for vaccine cooling, many cooling solutions currently available need to be connected to the electricity grid. Clasp has launched an off-grid cold storage competition (see appendix
- Lack of skills – making best use of pre-cooling, transport refrigeration and cold store equipment requires complex knowledge of set point temperatures and how to manage respiration of certain products. This skillset needs to be built up where a community previously has had only limited access to cooling.
- Cultural perceptions in relation to cooling – in some cultures there is a perception that refrigerating food somehow compromises its freshness.

Policy and business model innovations can contribute to improving cooling access.

7.1.2. Business model innovation opportunities

Business model innovation could contribute to tackling investment and energy access challenges. The approach could reduce investment costs in a couple of ways:

- A shared ownership/access model can be supported by renting mobile pre-cooling and cold storage system for harvests. Multiple stakeholders whose production volumes are small could pool resources to access cooling infrastructure. The Indian company ecoZen has developed a solar powered shipping container pre-cooler to enable this approach for example.
- A Cooling as a Service (CaaS) model would charge clients a fee per unit of produce cooled. This overcomes the challenge of securing sufficient investment whilst at the same time creating strong incentives to enhance energy efficiency on the part of the service provider (as energy is a major input cost). The Nigerian company Cold Hubs is pursuing a model based around charging per “crate” of produce pre-cooled.
- Energy access issues could also potentially be addressed through business model innovation. In mature markets, cooling equipment is typically supplied separately to the energy required to operate it. By bundling renewable energy generation, appropriate storage and cooling equipment off grid cooling devices could be offered for sale. This would almost certainly require some kind of finance offering as the investment costs are likely to be higher for this approach than a simple equipment purchase (as lifetime energy costs are being turned into a single capital investment).
- We should also consider the opportunity to use smart technology (and energy storage embedded in the appliance) to aggregate individual technologies to access “time of use” energy service markets (see Ice Bear model).

7.1.3. Policy interventions that could be required

In parallel, several policy interventions may be required to expand access and overcome barriers to uptake:

- Policy Maker Capacity Building –Best practices and tools regarding needs assessment and policy interventions should be shared with policy makers alongside basic awareness development.
- Information and Communication – communication with relevant stakeholders to build awareness of the potential benefits of cooling and overcome and misconceptions is a key part of building the environment for a successful policy intervention.
- Education and Skills Development –It is necessary to train people in most effective use of cooling equipment as well as its installation and maintenance.
- Financing Provision – policy makers can facilitate provision of finance or bulk procurement activities (to achieve better pricing).
- Incentives – policy makers could provide incentives to increase the uptake of cooling equipment, such as preferential import tariffs, reduced interest rate loans or even direct subsidies.

The optimal combination will depend on the socio-cultural and economic conditions present in the country and sector under review. The planned sector studies should investigate this in more detail.

7.2. Emissions related market failures

7.2.1. Market failures that are barriers to reducing emissions

Achieving a feasible emissions reduction pathway within equality of access, is challenging. The market will need a combination of interventions and clear signals if it is to deliver the required change. Barriers that have been previously identified include:

- Lack of awareness – few users of cooling equipment are fully aware of its emissions impact, energy consumption and thus true running costs. Equally, there is sometimes a lack of awareness about the products available on the market meaning that in some instances, consumers are unaware that they could purchase much more efficient equipment.
- Lack of Skills – in several countries there are an insufficient number of properly trained engineers to maintain cooling equipment in efficient working order. This problem is compounded when new emissions reducing technologies require an expansion in skills. Severe skills shortages can limit take up or result in equipment performing poorly.
- Dominance of capital cost in purchasing decisions – in both commercial and domestic settings capital cost considerations dominate purchase decision-making. This is a problem because

more efficient equipment often has a higher purchase price (even if the total cost of ownership (TCO) is lower once the lower running costs are considered).

- Lack of stakeholder cohesion/Split incentives – in some commercial organizations, different departments are responsible for purchasing equipment, operating it, and paying for the energy it uses. As a result, the incentives given to employees who make purchasing decisions may be quite different from those one would expect if TCO was to be optimized.
- National Interest vs. MEPs – Minimum efficiency performance standards (MEPs) are a proven and successful means of improving the efficiency of all types of product. However, if technological capabilities of domestic equipment manufacturers differ from those of globally dominant players then policy makers may be reluctant to impose MEPs of the highest possible standard.
- Market Structure – nearly all segments of the cooling sector are dominated by a small number of players, this gives them incredibly significant market power. Few if any innovations can make it to market without the "buy-in" of at least one or two of these players.
- Lack of Data – a lack of good quality data about equipment stocks, equipment sales and refrigerant inventories can contribute to a lack of understanding of the scale of the challenge as well as the efficacy of any measures proposed.
- Lack of Research Funding – historically, cooling has received relatively limited R&D investment. Even large players with a reputation for innovation have R&D budgets that are about half the proportion spent by automotive players.[78]
- Lack of integrated system tools and demonstrators – though integrated systems thinking shows great promise, currently there are only limited tools to plan systems and no large-scale demonstrations have been completed that demonstrate its efficacy and validate those tools. Until this work is done, any emissions savings that could be available from the approach will not be achieved.

7.2.2. Business model innovation opportunities

Some of these barriers are susceptible to changes in business models. Examples would include:

- Purchase or Leasing Combined Maintenance Contracts with Efficiency Incentives: Exceptionally large cooling systems are already sold with maintenance contracts that may have reliability targets. Some purchasers have begun to write these contracts with Key Performance Indicators (KPIs) around efficiency. This has the impact of incentivizing the maintenance provider to undertake maintenance practices likely to maintain device efficiency.
- District Cooling Systems: District cooling systems provide cooling to an entire community from a network of centralized cooling devices. Customers typically pay a standing demand capacity charge and then a per unit of cooling delivered fee. By aggregating cooling loads across many smaller customers, opportunities are created to deploy larger more efficient equipment. At the same time, the funding requirements for more efficient equipment are centralized and can be supported by the cooling supply contracts of multiple customers. District cooling projects also necessitate development of a cooling distribution network (e.g. pipes with water in) that could enable access to waste cooling resources like lake water in a way that would be impossible without access to the network. This approach could be used to overcome awareness and capital cost barriers.
- Cooling as a Service: By offering a service (e.g. comfort cooling, crates of vegetables cooled etc.) the service provider has maximum freedom about how they choose to meet the cooling need. As a result, this could be highly synergistic with selecting efficient plant to minimize the total cost of providing the cooling service over the equipment's life. It may also be a way of achieving an integrated systems approach, as in some cases providing the true service required could be compatible with demand mitigation. This could address capital cost and awareness barriers.

Within specific sectors, there may be scope for other types of business model innovation around servitization or bundling to improve the economics of reduced energy consumption and emissions, this should be investigated further in the sector studies.

---

[78] Comparison of Daikin and Ford global R&D budgets as a % of revenue (Daikin 2.6% and Ford 5.5%)

7.2.3. *Policy interventions that could be required*

Many potential policy measures exist that could be effective at overcoming the barriers to achieving emissions and energy consumption reductions. The table below summarizes barriers and potential policy responses.

Barrier	Possible Policy Responses
Lack of awareness	• Information campaigns • Device labelling (e.g. comparative efficiency ratings, running costs)
Lack of skills	• Training capacity development • Training provision • Introduction of mandatory certifications (and register of certified parties)
Dominance of capital cost in purchasing decisions	• Device labelling to make device economics clearer to purchasers (e.g. comparative efficiency ratings, running costs) • Bulk procurement initiatives to reduce equipment costs • Utility efficient appliance programs to bundle energy and purchase costs • Loans to overcome high capital costs • Enhanced capital allowances to reduce tax liabilities or accelerate depreciation and improve the business case • Regulation (e.g. MEPs, F-gas levies, building codes or other standards) to force purchasing behavior
Split Incentives	• Support and build awareness of servitization approach • Coordinate access to capital for CaaS providers • Regulation (e.g. MEPs, F-gas levies, building codes or other standards) to force purchasing behavior
National Interest vs. MEPs	• Technology transfer programs • Equipment loans to local manufacturers so that they can achieve MEPs (e.g. leveraging multi-lateral or other climate finance mechanisms)
Market Structure	• Engage industry representatives in formulation of policy • Co-opetition funds to enable dominant players to communicate their development needs coherently to research and SME players as well as share risk in developing new technology. • Set performance targets aggressive enough to require step change innovation (and communicate them consistently well in advance)
Lack of Data	• Work with industry and users to build equipment (and refrigerant) inventories • Develop new product registration databases with details like make model number and purchase year so that likely performance can be estimated.
Lack of Research Funding	• Target cooling through specific innovation funding calls • Co-ordinate industry co-opetition fund • Set performance targets aggressive enough to require step change innovation (and communicate them consistently well in advance)
Lack of Integrated System Tools and Demonstrators	• Finance a series of living labs to prove the concept and develop an open source toolset

Table 16 - Barriers and Policy Responses

Optimum policy response will be country specific and depend on the sector targeted. This should be investigated in more detail in the sector studies.

8. An Integrated Set of Interventions

How we manage our growing demand for cooling will have enormous implications for our society, economy, energy demands and climate change. In order to achieve *clean-cooling* that is affordable, financially sustainable and accessible to all we need a new needs-driven, integrated system-level approach that incorporates 'thinking thermally' into our energy strategies, including: mitigating demand; understanding the size and location of the thermal, waste and wrong-time energy resources; understanding novel energy vectors, thermal stores, clean cooling technologies and new business models; and integrating these resources optimally with various cooling loads.

We need a set of interventions that mitigates demand today and ensures more fundamental system changes. Key actions have been identified to achieve this:

- Needs assessment for development and emissions reduction, including development of service or outcome-based demand models.
- Joined-up Merit Order understanding of interventions based on energy requirements, emissions, and cost factors (system / TCO) to provide an ascending order of cost of impact. Deploying solutions in this way can should minimize infrastructure requirement, cost of new electricity.
- Using data analytic and modeling capabilities to map and predict temporarily varying social, economic, health, etc. cooling demands of the community and explore technology and operational changes with the goal of meeting those needs whilst reducing emissions and costs.
- Acceleration of behavior change and demand-side management, including building an improved understanding of user needs, an inventory of available technologies and cost-benefit assessments of different technologies and their associated emissions
- Technology acceleration, a framework that includes research, investment, product development and demonstration and deployment of innovative technologies
- Demonstration - representative market embedded multi-service Community Cooling Hubs and Clean Cold Chain Living Lab and Innovation Centers to test, validate and demonstrate innovative and integrated solutions (technology and business model) for sustainable clean cold chains as well as community cooling solutions, in real world based controlled environments.
- A cross-sector skills roadmap that identifies and addresses the training and skills needs for product development, installation and maintenance, and improved usage practices
- Business model innovation, including business model definition and funding for business model simulation, innovation development, demonstration and scale-up.
- Policy – an integrated policy intervention framework relevant to OECD, Upper Middle Income, Lower Middle Income and Least Developed Countries. This will include segment specific policy recommendations and will include as a minimum policy-maker capacity building, education and skills development, funding and financial instruments, regulation, and engagement of industry.
- Financing – both for accelerated technology development and deployment and cooling infrastructure harnessing currently under-utilized thermal and waste resources
- Customer and policymaker information dissemination – leveraging current efforts, design, and dissemination of a program of information that:
    - raises awareness among customers and policy makers of cooling issues and possible actions
    - stimulates development and adoption of nationally determined contributions (NDCs) and nationally appropriate mitigation actions (NAMAs) for cooling related emissions
    - makes available total cost of operation information models that are intelligible to domestic and commercial consumers

Energy systems are experiencing fundamental structural change driven by targets to cut emissions and the associated transition to renewables from fossil fuels. Within this, thermal, transport and electrical energy systems are becoming interconnected as electrification is seen as the cornerstone of transport and thermal decarbonization.

There is an urgent need for innovation and flexibility in how an integrated energy infrastructure is provided. By understanding the detail of communities' operational, market and regulatory needs and pressures, we can leverage technology bundles to offer new combinations of products and services that provide efficiency, flexibility, resilience, and cost-effective decarbonization.

This, along with other reports, have demonstrated we are on the cusp of a major new phenomenon in our demand for energy – cooling. How we manage it will have enormous implications for our society, economy, energy demands and climate change. Already in many markets, 50% of electricity consumption in the summer months is for cooling while peak electricity in hot countries is driven by AC usage. We are however projected to see 19 new cooling appliances deployed every second up to 2050.

Our energy demand for cooling is projected to nearly triple by 2050 based on GDP growth; if we deliver "cooling for all" – essential to meet the UN's Sustainable Development Goals - it could double again. While the climate impact of cooling has focused on refrigerants, more than 80% of the global impact of refrigeration and air conditioning systems is associated with the indirect emissions of electricity generation to drive the cooling appliances (UNEP TEAP, 2017a).

'Clean cooling' is about taking the necessary steps to deliver comprehensive access to cooling efficiently and sustainably *within our CO2, natural resource, and clean air targets*. Clean cooling necessarily must be affordable, financially sustainable, and accessible to all to deliver key societal, economic and health goals.

A clean cooling roadmap should aspire to 0 direct and indirect emissions. The IEA 2DS scenario can serve as a target to achieve a compliant pathway for cooling. To achieve this, we must meet our total cooling demands – built environment and transport - consuming just 6,300TWh of electricity. As a start point to this, we propose that sectoral emissions maintain their current shares of energy and emissions usage. Based on the University of Birmingham's Cooling Conundrum paper, this would result in the following energy and emissions allocations by 2050.

	Current Energy Split	Energy Budget (TWhs)	Current Emissions Split	Emissions Budget (mTCO2e)
World - 2DS - IEA		6,300		1,400
Space Cooling	41%	2,561	38%	538
Mobile Cooling	26%	1,610	31%	435
Industrial and Commercial	19%	1,214	20%	285
Domestic Refrigeration	15%	914	10%	142

Figure 17 - Cooling Conundrum Implied Annual Energy and Emissions Allowances 2050

The appropriateness of this split along with whether these budgets can be achieved should be explored further in specific papers under this work program.

We have calculated that if cooling is to be sustainable and with access to all, we need at least a 70% reduction in primary energy usage. Current stretch efficiency pathways from GCI suggest we can achieve at best half this target. GCI also suggest there will be a significant cost premium.

Mainstream analysis to date has focused on the near-term issues of space cooling energy demand and the clear demand trajectories exhibited by growing middle classes. It has not considered the equality of access in the context of a changing climate cold chain energy demand and emissions impacts. At the same time, the cold chain impact on human development could be exceptionally large.

8.1. "Thinking Thermally"

A core challenge is that when people talk about energy, they often mean electricity, and when they talk about energy storage, they mean batteries. Cooling demands may need to be served by energy carriers other than electricity and batteries. To this end we need a new needs-driven, integrated system-level approach to think thermally, including:

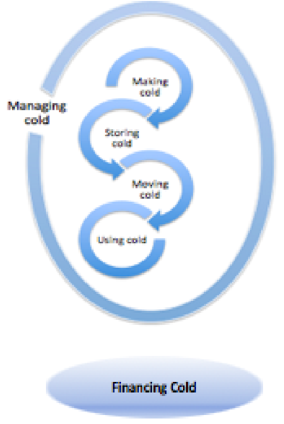
- mapping cooling demands
- mitigating demand and
- seeking synergies or opportunities to pool demand understanding the portfolio of resources, the optimum merit order of intervention
- the business models and policy interventions to optimally integrate those resources.

This will provide the routes for achieving the cheapest system cost, greatest energy system resilience, and lowest carbon emissions sustainable energy systems.

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

Storing cold
Thermal energy storage to warehouse

Moving cold
New energy vectors and material to shift cold



Using cold
Reduce cold loads
Increase efficiency and reduce GWP of conventional technologies
New technologies to harness new stores and vectors

Managing cold
Monitoring, controls and management

Financing Cold
How do we charge and pay for cold

8.1.1. A set of interventions

Clean cooling is key to development and countering the negative impacts of cooling on climate change. The challenge of providing *clean* cooling *for all* is urgent and requires immediate action both (i) to mitigate demand today and (ii) make more fundamental system changes.

Bridging the critical gap in the clean cold innovation landscape requires:

- Bringing the key intervention delivery partners into a joined-up strategy
- Needs assessment – Development and emissions.
- Creating a merit order of interventions
- Bringing together technology and system innovations into a cross-sector systems approach; to harness all renewable and waste resources.
- Accelerating behavioral change and demand-side management
- Creating the necessary results-driven economic and impact models.
- Creating the right policy and financing environments.
  - Engage commercial and private sector
  - Make clean cooling accessible
- Capacity building in-country
  - Ensure in-country manufacturing and supply chains where appropriate.
  - Develop the skills and workforce to design, install and maintain the volume of appliances.
- Demonstrating impact to accelerate take-up.
- Tracking progress
- Managing unintended consequences

8.1.2. Ladder of Opportunities

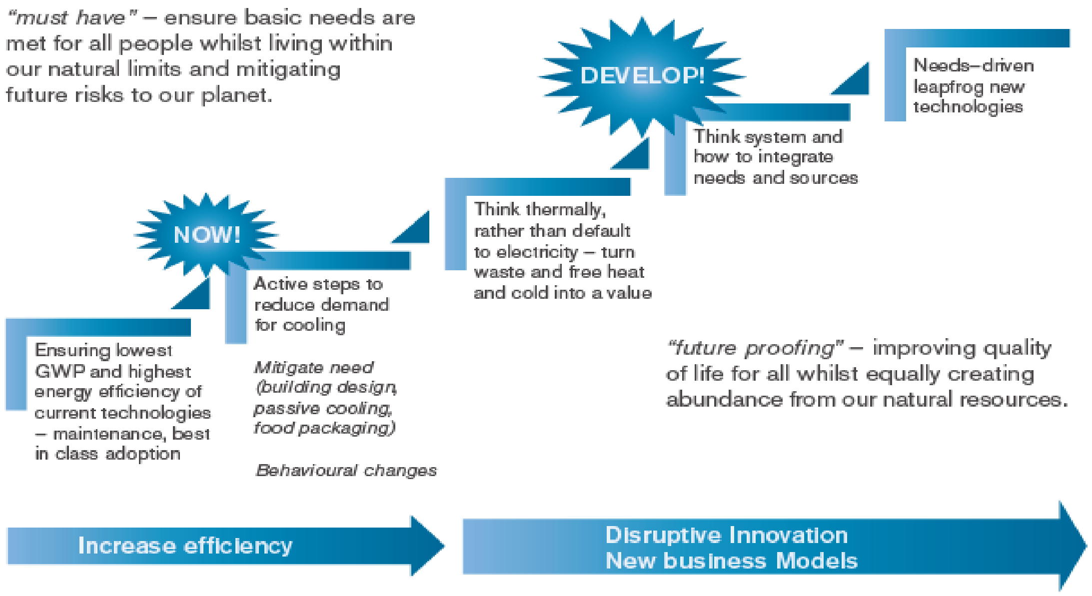
Given the increase in energy demand and the need for cooling access, clean cooling is about radically reshaping cooling provision. Technology, operations, financing, and consumer behavior must be addressed using a holistic approach with a system perspective. By exploring opportunities to pool demand and achieve economies of scale or synergies at the same time as fully understanding the portfolio of resources available, we are able to re-map processes and technology to achieve great efficiencies. This will also enable the new business models to make cooling affordable and accessible to all.

However, we cannot wait for system redesign, clean cooling starts with what we can do today to reduce demand and deliver incremental efficiency improvements. Though these interventions are important, they will not deliver the required reductions in energy usage, emissions, and pollution, nor will they adequately increase resource productivity. We therefore need both short-term interventions to reduce energy demand now and embed the most energy efficient technologies as well as system redesign.

Today	reduce climate impact of cooling
Medium Term	ensure basic needs are met for all people while meeting climate and natural resource constraints
Long Term	a society that is prepared for future changing climates

With a series of projects focused on accelerated deployment of energy efficient air-conditioners, the focus of this work is on the system design.

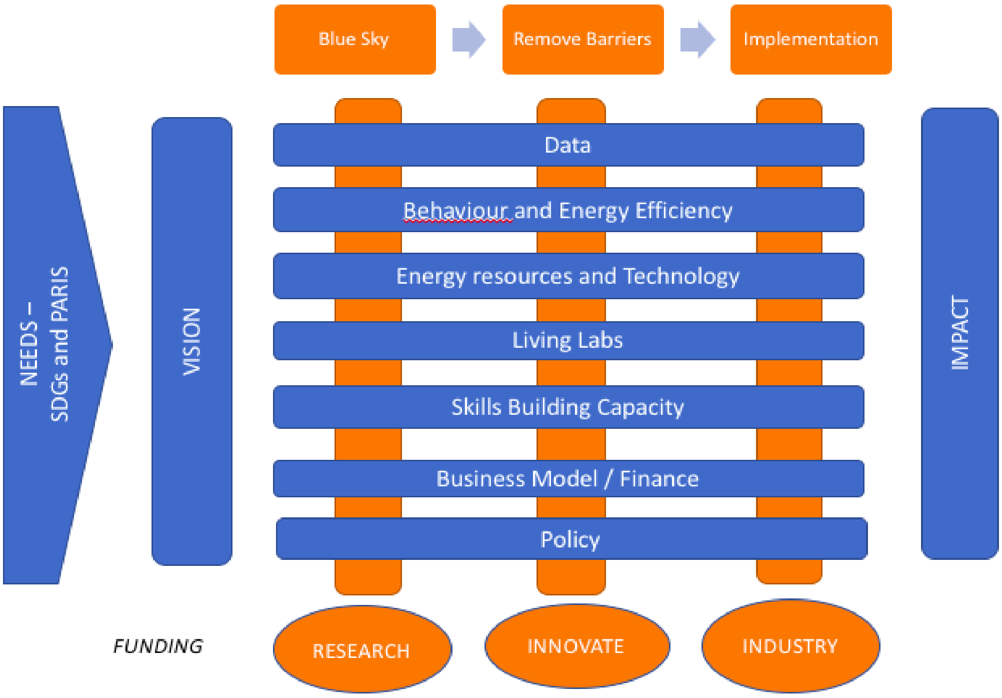
THE LADDER OF OPPORTUNITIES



We specifically need to see more focus on both (1) how to mitigate demand and (2) how to bring forward more quickly disruptive, novel technologies and harnessing the portfolio of thermal energy sources. Currently industry investment focuses on incrementally improving current technology at the expense of expanding the capabilities of other potentially more efficient cooling technologies and cooling energy systems.

8.2. Key Actions

We need to ensure a collaborative approach to deliver the portfolio of skills required – technology, economics, business models, skills development, policy, behavioral change, system modelling, etc. Key actions have been identified to advance clean-cooling and are outlined below.



8.2.1. *Needs assessment – for development and emissions reduction*

There is not a comprehensive cross sectoral understanding of the size of current and future cooling demand (cooling for all) at local, national, or international scale. Equally the implications of this demand for energy systems/new build generation requirements and the environment (climate change and pollution) or workforce are poorly understood.

Furthermore, studies focus on equipment-based projections of cooling demand, which pre-supposes a solution to specific cooling needs and risks ignoring the possibility of electricity demand mitigation by redesign of systems and use of waste or currently untapped resources.

This acts as a barrier to achieving a cohesive and integrated system strategy to mitigate or meet cooling needs in the most economically and environmentally sustainable and resilient way, while managing natural capital and greenhouse gases and sustaining economy growth.

We need demand models which are service, or outcome based as far as possible taking national or regional circumstances into account, including available energy sources. This would then enable optimum and “fit for market” choices between demand mitigation, harnessing untapped thermal resources and traditional cooling provision technologies and renewable electricity. We propose the development of a toolset that enables assessment of:

- Individual and national food security driven stationary and mobile refrigeration demand.
- Agricultural and fisheries income driven stationary and mobile refrigeration demand.
- Vaccination and medicine coverage-based stationary and mobile refrigeration demand.
- Health cooling demand.
- Industrial cooling demand.
- A comfort cooling related air conditioning demand – domestic and commercial.
- Domestic refrigeration and food management.

Development and validation of an open-source standardized demand-mapping methodology for evaluating the cooling requirements of a defined community against 2030 and 2050 timelines is outside of the scope currently proposed under this work program. Therefore, we would recommend the following approach for the planned work:

- Review of available equipment penetration projections (not exclusively GCI).
- Assessment of implied demand

- Testing against other data sets (e.g. volumes of vehicle deployment, urbanization rates and agricultural output forecasts).
- Qualitative exploration of equipment and cooling output requirement mitigation measures.

This is intended to provide an advance over historic equipment projections for the market segments but does not replace the need for a separate needs-assessment toolset.

8.2.2. *Whole system design and modelling*

System-led approaches can:

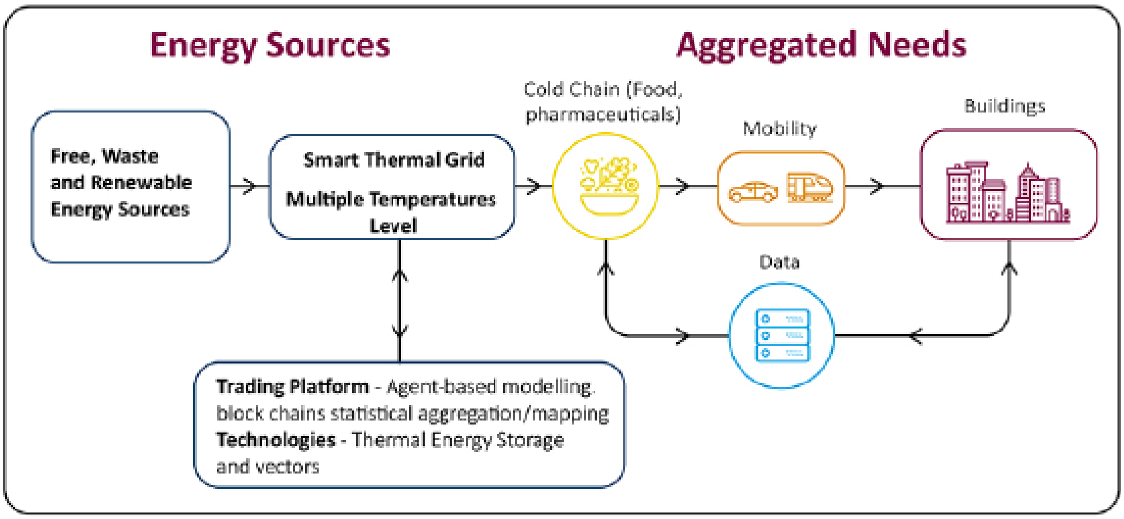
- Leverage untapped synergies between thermal sources and sinks
- Deliver added value from system optimization
- Allow new economic values to be captured, and
- Ensure resilience and optimized energy management across transport and built environment in the transition to renewables using bundles of technologies.

In the transition to non-hydro-carbon energy resources, cold networks and cold chains will likely need to integrate energy storage to cost-effectively smooth intermittent renewable generation and unreliable grid supply as well as support zero- emission transport. Specifically, we need to there is no cohesive and integrated methodology to support food producer communities to design ‘fit for market’ and fit ‘for finance’ end to end cold chain needs in the most economically and environmentally sustainable and resilient way.

"Whole systems" can be difficult to understand and contain many interdependencies which create feedback and feed forward mechanisms resulting in an emergent rather than deterministic system. Whole systems are too big and difficult to study in the real world, but powerful computer simulations can be used to identify the factors which have the biggest impact, providing the focus for the more traditional real-world sub-system living labs.

We need to develop systems models to map and predict the temporally varying demands of the community. Models should systematically explore the ways in which demand management, system efficiencies and bundles of existing (and future) technologies could be combined to support key user requirements. This should provide a technology-agnostic selection and optimization function across multiple scenarios to help decision-making relating to community thermal energy. This would provide the tools to

- create system efficiencies and system resilience.
- quantify the opportunities for and economic benefit of thermal storage.
- identify and map symbiotic opportunities to harness renewable, industrial, and geothermal energy and the technological, physical, policy or business model barriers.
- identify where to focus investment to reduce the gap between the thermodynamic recoverable and economically recoverable amount of cold



8.2.3. *Acceleration of behavior change and demand-side management*

As we migrate from fossil fuels to renewables, we need to radically reshape the cooling landscape, combining technology, operations, financing, and consumer behavior in a system perspective.

Research has demonstrated the influence that contextual issues such as individuals and organizational attitudes and behaviors, as well as cultural and market conditions and business models can have on the adoption of low carbon technologies and energy efficient practices. While this provides a logically sound baseline from which to understand the scenario without intervention, the first interventions must be focused on testing the assumed need for cooling, and the opportunities for alternative social interventions to reduce unnecessary demand within the local cultural context.

Low carbon cooling must start with what we can do today to reduce demand by influencing customer behavior. We need to identify non-technical barriers, incentives/enablers to behavioral *and* technological change to low carbon cooling solutions which can then inform the development of strategies designed both to remove or overcome the blockages and encourage and diffuse helpful practices.

We should engage domestic, industrial, and commercial users of cooling to better understand their needs and drivers for their behavior to inform future policy and business model development and design to better manage and reduce demand.

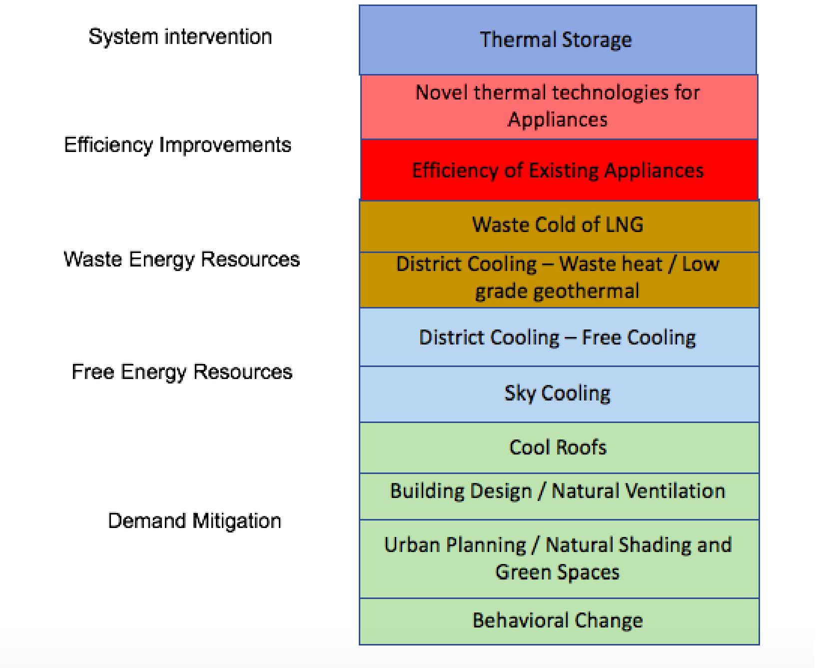
Key outputs should include

- cost-impact analysis of when and where demand-side management (behavioral change as well as technology) would be most valuable at the energy system level to lower carbon intensity in several different countries and markets.
- identify non-technical barriers, incentives/enablers to behavioral *and* technological change to low carbon cooling solutions which can then inform the development of strategies designed both to remove or overcome the blockages and encourage and diffuse helpful practices.
- examine the role that alternative business strategies and models must play in delivering behavioral change alongside increasing energy efficient technology market uptake.
- define policies that could build awareness for, stimulate, and properly reward low carbon cooling, both in (i) reducing our demand for cooling and (ii) adopting more efficient or radical technologies.

A merit ranking should be created based on energy and emissions requirements and cost factors (system / TCO). It is likely to be sector specific for detailed technology comparisons, however at a high level it can be summarized in order of merit (highest to lowest):

- Demand mitigation via behavior or operating practice change – for example altering temperature set points
- Demand mitigation via system or application design – for example natural ventilation within buildings (these could also allow substitution for lower energy alternatives (e.g. swapping AC for fans)
- Making use of free cooling resources that are hyper local – sky cooling
- Making use of more remote free cooling resources via district cooling type network infrastructure – for example city level cooling systems that make use of bodies of water or LNG import terminals.
- Making use of other free cooling resources via conversion technologies – for example sorption cooling technologies capable of converting waste heat resources into cooling.
- Efficiency improvements in electrically-driven cooling equipment – for example via enhanced CoP or seasonal energy efficiency rating (SEER)
- Energy consumption demand flexibility – for example via deploying thermal or electrochemical energy storage to enable better integration with renewable energy resources.

For example, purposes only



An inventory of available technologies, their characteristics, energy sources, likely impact and system interactions needs to be developed. This will need to be quantitative so that adoption impacts can be assessed. Examples of required technology characteristics are described in the table below, however the exact characteristics required should be the subject of discussion within the kick-off meeting for the detailed and sector specific work under this work program. Equipment performance assumptions should be clearly stated, referenced and peer reviewed.

Characteristic	Description	Why Required
Technology Purchase Cost Premium vs. incumbent	Sales price at different volumes	For cost benefit calculations and to inform policy/financing requirements
Installation and maintenance costs vs. incumbent	Installation and maintenance requirements and costs for installation today and potential within 5 and 10 years.	For cost benefit calculations and to inform policy/financing and training requirements
Consumables costs	Any non-energy running costs (e.g. filters, catalysts etc)	For cost benefit calculation and to inform policy/finance requirements
Equipment Lifetime	Years between major service and replacement events	For lifecycle/lifetime cost calculations
System Integration Requirements/Balance of Plant	Any additional application specific equipment or modifications to adopt technology	To ensure all costs are captured in cost benefit calculations
Technology Efficiency Improvement vs. incumbent	Current CoP or SEER measured + potential for improvement within 5 and 10 years	For emissions, energy and cost saving calculations.
Technology direct emissions improvement vs. incumbent	Current refrigerant utilized and measured leakage rates + potential for improvement within 5 and 10 years	For emissions saving calculations

Technology embedded emissions	Emissions from manufacture (likely to require a simplified template)	For emissions saving calculations
Product Readiness	An indication of technical, manufacturing, commercial and operational maturity to assess likely development costs and time to market	For time to market and likely investment costs

Table 17 - Example Data Requirements

After this, implementation costs for different technologies and the probable scale of the emissions reductions they can offer can be calculated. This can be used to develop carbon abatement cost curves for different technologies to aid with decision making. This step is also an opportunity to model the most obvious conflicts or synergies between technologies.

8.2.4. Technology Acceleration

A framework to accelerate technology innovation and deployment is required. Within this, need validated mechanisms for measuring efficacy and impact of innovations (e.g. technology, business model or practice) from a financial, environmental, and societal perspective. The recommendations below provide suggestions for establishing leadership, pump priming innovation and providing routes to market. It is necessary to develop thought leadership in the space and then provide a coordinated intervention across the technology maturity journey.

- Collaborative Fundamental Research and Early Stage Technology Development
- Collaborative Venture based Investment Fund – Late Stage Technology Development
- Living Labs – Product Development and Demonstration
- Accelerate deployment of innovative tech in low income communities by financing deployments of new tech – product Deployment

This stream of activity needs to be intricately linked to ongoing requirements definition activities and business model innovation, policy needs, etc. to ensure that technology innovation is aligned to requirements and fits with commercial frameworks. It should also help us understand the new cross-industry skills and manufacturing opportunities.

See Appendix 6 for high level technology roadmaps for space cooling, mobile cooling, industrial and commercial cooling, and domestic refrigeration.

Examples of areas for research acceleration: thermally-based (geothermal, solar and waste heat) alternative cooling technologies, sky cooling and nocturnal radiation, harnessing the waste cold of liquid natural gas (LNG), novel thermal energy stores research and development, radical cooling innovation (thermal-elastic refrigeration, thermo-chemical energy storage), new thermodynamic cycles and processes, systems integration, control and optimization, green logistics (including lightweight cooling devices for vehicle applications).

8.2.5. Demonstration – Living Labs

We propose a series a series of representative market embedded multi-service Community Cooling Hubs and Clean Cold Chain Living Lab and Innovation Centers to test, validate and demonstrate innovative and integrated solutions (technology and business model) for sustainable clean cold chains as well as community cooling solutions. These will test and demonstrate bundles of technologies and the potential for climate change mitigation, funding models, business models and approaches to governance. These labs will identify the positive and negative consequences of deploying any new interventions.

They will also be physically permanent entities with appropriately skilled and trained staff complements, equipped with essential technologies and test bed facilities (packing, cooling and/or temporary cold storage, leasing reefer vehicles and other equipment and tools for improved postharvest handling), to also provide training and advisory services through demonstrations. This would also include Business Incubation Hubs delivered through participation of business schools with expertise in supporting rural enterprises.

8.2.6. Skills Building Capacity

Training and capacity building are a critical element of enabling the other work streams. Defining training interventions that are aligned with defined requirements and innovation structures is critical to success of the program. Skills requirements are likely to be sector specific and heavily influenced by the choices contained within technology roadmaps, however it seems likely a number of common requirements are going to emerge across product development, installation and maintenance and training end users.

Product developers will need to have an understanding of the systems approach that works from a needs inventory down the merit order of demand mitigation, waste resource, efficiency and flexible energy consumption in order to supply products that fit within the ecosystem.

Depending on the maturity of the toolset available to them, the skills requirement could be simply use of the toolset. Alternatively, if there is no validated toolset available to them, it may be necessary for them to develop a capability to holistically model cooling demand, technology choices and energy systems.

It is also likely that product development teams will need the skills to be able to embrace emerging technologies such as the internet of things (which could be important for coordinating systems of cooling devices), energy storage devices and new refrigeration technologies.

Good service and installation practices will be important regardless of the scenario. They are essential to achieving design point device efficiencies and reducing/eliminating fugitive refrigerant emissions.

Beyond this, it seems likely that emerging refrigeration and connectivity technologies will create new skills requirements.

Finally, the substitution of current high GWP refrigerants for lower GWP alternatives will in many cases create additional skills need due to potential hazards arising from the refrigerants under consideration (e.g. higher operating pressures, flammability, or toxicity).

Equipment usage practices could be enhanced through training. Good practices like maintaining sensible set points and equipment cleanliness are likely to be relevant to all refrigeration technologies in all sectors.

8.2.7. Business Model Innovation

There is significant potential for innovation in business models through which cooling is accessed. Cooling as a Service (CaaS) is one promising route as well as the potential for thermal trading platforms. However, alternatives like shared asset ownership, credit or hire purchase type models that are merged with Energy Service Company (ESCO) type arrangements, benefit sharing or government interventions financed by directed taxation should be explored with regards to the types of hardware (or service) being financed and the preferences of potential customers and vendors. We should also consider the opportunity to use smart technology (and energy storage embedded in the appliance) to aggregate individual technologies to access “time of use” energy service markets (see Ice Bear model).

Activities within this strand would take several forms:

- Business model definition and simulation/evaluation (a variety of economic and behavioral modelling techniques could be used to achieve this).
- Business model innovation development funding
- Business model demonstration funding
- Business model scale up funding

8.2.8. Policy

Multiple policy interventions are likely to be required to create the right environment for clean-cooling, globally and in-country. A detailed set of possible interventions is set out in section 8.1.3 and 8.2.3 of this report and should provide the basis of analysis.

Policy interventions should encompass:

- Policy maker capacity building
- Active support for integrating thermal waste, free and renewable energy

- Development and adoption of NDCs/NAMAs that explicitly incorporate cooling and (i) reduce demand and (ii) accelerate deployment of energy efficient technologies
- Education and skills development
- Provision of funding and development of financial instruments,
- Regulation

8.2.9. Customer & Policy Maker Information Dissemination

Among cooling equipment customers and policy makers, there is a lack of awareness in relation to the issues of cooling access and cooling related energy consumption as well as the required actions to address both challenges. A program of information dissemination needs to be designed and disseminated with the following objectives:

- Raise awareness among customers and policy makers in relation to the issues and possible suite of actions.
- Make available a set of TCO information and models that are intelligible and available to domestic and commercial consumers.

Engagement with key stakeholders across the customer and policy maker landscape will be key to informing the types of information and dissemination that would be most likely to drive change.

8.2.10. Overview of all stakeholder actions

	Fundamental Research	Early Stage Technology Development	Late Stage Technology Development	Product & Service Development / Demonstration	Product Manufacturing	Product & Service Deployment	Maintenance & Servicing	Disposal
NGOs	Market information capture and input to product priorities	Help maintain focus on development that will deliver what users need in the context of the target markets.	Help maintain focus on development that will deliver what users need in the context of the target markets.	Help facilitate product demonstrations in high impact applications where market failure exists.		Education/ dissemination / awareness raising of benefits of cooling and product deployment. Product endorsement.	Market appropriate training schemes for use, operation and maintenance of systems	Verify responsible disposal.
Policy Makers	Incentivise the use of thermal resources for RAC Set forward looking minimum standards for equipment and buildings and create an enabling regulatory environment to drive product development. Catalytic funding for research and development activity.		Fund demonstration and proving activity.		Certification.	Create an enabling regulatory environment and fiscal incentives for deployment. Dissemination of success stories.	Verification and validation.	Mandate responsible disposal.
Infrastructure Investors				Work with product developers on business models to support best in class deployment and operating practices, as well as deployment in new markets.		Expanding access to electricity and other energy resources in target markets.		
Venture Capital		Provide funding for technology development and foster links/ associations with OEMs for product development, business partnership or 'exit' sale.						
Impact Investors		Fund high impact technology development and pre-commercial pilots – provide Catalytic Capital, especially in high (environmental or social) impact application areas – coordinate with VCs/OEM initiatives		Fund demonstrators for high impact applications (environmental or social) and locations.		Support deployments in high impact applications (environmental or social) and locations.		

	Fundamental Research	Early Stage Technology Development	Late Stage Technology Development	Product & Service Development / Demonstration	Product Manufacturing	Product & Service Deployment	Maintenance & Servicing	Disposal
Customers	Proactive communication by all customers, including trade and consumer groups, of a 10 year forward view of product and service requirements to OEMs and Tier 1s. Demand more sustainable products and services to achieve substantial impact reductions – creating market pull.	Input into product and technology requirements to maintain focus on development that will deliver what users need in the context of the target markets.		Host and facilitate demonstrations and trials		Early adopters – Order placement to create demand pull; dissemination / awareness raising of benefits of cooling and product deployment. Product endorsement.	Proactively use maintenance as an impact/cost optimisation tool.	Demand responsible disposal of product
OEMs/ Tier1s		Collaboration with academics, innovator SMEs and internal R&D to deliver new products & services for efficiency improvement and access and accommodate skills shortages. Collaborate in joint finance ventures and offer exits for viable new technologies		Ensure new products meet efficiency and access challenges and also have embedded sensoring and data capture	Support development of in-country manufacture and assembly; adopt IoT and Industry 4.0 and 'factory in a box' approaches.	Support innovation in business models, approaches to finance and product deployment.	Use enhanced data capture and analytics to drive performance management. Support service networks and responsible disposal including use.	
SMEs		Alignment on innovation priority areas => innovation meets OEM standards						
Academia	Create evidence base for impact and interventions. Early stage and fundamental research into low cost and off-grid cooling			Support development of new business models and manage integrated demonstration projects	Design, test and trial novel and innovative manufacturing and assembly processes.	Measurement of impact of refrigeration and space cooling access, study and document best practice and Return on Investment (ROI) achieved. Education/ dissemination / awareness raising of benefits of cooling and product deployment		Research and recommend best in class sustainable disposal methods.

Nb. *Within roles, it is essential to remember the value of Professional Institutions and member-based organisations in developing and delivering messages and key actions, especially skills development.*

9. Unintended Consequences

Introducing more affordable and readily available means of cooling in food supply chains will introduce major shifts to dynamic socio-technical systems as well as the wider environment and eco-systems. These could result in several unintended and sometimes negative, as well as positive, effects. It is important to try to identify and plan for these in advance.

For example, a cold chain will help reduce food loss, in itself a major source of CO2 emissions, and thereby potentially reduce the need for deforestation by ensuring an increased proportion of production reaches the market from existing land resources utilized for agriculture. It could equally allow farmers in developing economies to transition from staple to high value (but temperature sensitive) horticulture. The shift could though have implications for water resources from a move to potentially more water demanding produce. A strong and well implemented water framework will be needed to limit the extent of a shift to much more water demanding agriculture. Equally, the provision of food supply chain cooling allows farmers to transition into larger scale, more diverse agri-businesses. More processing at the farm could lead to increased local CO2e emissions, environmental pollution, and packaging demand – with implications for waste streams and resource use.

The availability of air conditioning once factored into architectural practice radically alters how buildings are designed and a loss of traditional vernaculars that deal with the local environmental conditions. Other means of cooling through shading, natural ventilation is often abandoned and building materials change, e.g. more glass can be used without concerns about solar gain. As a result, urban landscapes change dramatically, e.g. traditional architectural aesthetics are lost, and green spaces are less crucial and may be less valued.

We also need to consider the rebound effect – one behavioral consideration is the need to take into account unmet or “latent demand” for thermal comfort, such that improvements in energy efficiency from better equipment that may result in greater use of air conditioning and consequently less-than-expected reductions in electricity requirements. A program in Mexico between 2009 and 2012 encouraged replacement of inefficient refrigerators and air conditioners more than 10 years old through rebates and consumer financing. While the program successfully replaced 167,000 ACs, a rebound effect led to increased energy consumption and higher energy bills for people, as the lower hourly operating costs encouraged increased operating hours, reflecting unmet demand for comfort. Unintended consequences of programs like these will need to be anticipated and accurately assessed and mitigated for when considering costs and benefits.

Some areas to consider regarding the development of cold chains are as follows:

Greater availability of cold storage will allow farmers to store crops after harvest and to transport more perishable crops to new markets without great losses. This can improve their income from the crops they currently produce, but it is likely to induce changes in the crops that farmers want to grow. Cold storage will make some crops viable that were not before (e.g. soft fruits) and if these are marketable at higher prices, they will be attractive to farmers. There are likely implications for water resources of changes in crops and potential shifts to more water demanding produce. Many states in India for example are already water stressed and have over-developed groundwater resources. Increased water use for agriculture will deplete aquifers and may concentrate pollutants, and/or introduce salt incursions. A strong and well implemented water framework would be needed in any regional context, to control the extent and impacts of a potential shift to much more water- demanding agriculture.

Changes in crops will also have implications for soil fertility and the use of fertilizers and pesticides. These can have further environmental impacts including biodiversity effects and pollution of groundwater.

Better and cleaner means of mobile refrigeration can in the short term reduce emissions of CO2 and other pollutants, but in the longer term will also open up possibilities for reaching more distant markets which is likely to increase demand for refrigerated transport in terms of journey lengths (food miles). Reaching more distant markets can stand to increase farmer’s incomes but overall, this could lead to an increase in transport related emissions rather than a reduction, especially if ambitions for reaching international markets are realized by sea or air. On the other hand, there is likely to be some substitution, so produce grown in India may be able to serve markets that currently rely on imports from further afield. Nevertheless, there needs to be consideration of keeping food chains short in terms of distance and developing and serving more local / regional markets in preference to existing, more distant ones.

Increased energy demand through cold storage and logistics chains is a concern, as is increased energy demand from farmers through increased access to equipment (once incomes are raised), increased water pumping (see above), and increased processing. Better cooling will allow farmers and villages to add value to produce by processing food in various ways which will increase bulk (through packaging), water content and weight, with implications for water and transport. Processing usually also has associated water demands e.g. for cleaning equipment, moving things through a production line, etc.

More processing as discussed above will increase packaging demand – with implications for waste streams and resource use. Packaging needs to be kept minimal and leapfrog straight to easily degradable materials.

Refrigeration in the home can change cooking styles and patterns – especially the case if coupled with more processed food that cold chains have enabled. Fridges and microwaves become more common in kitchens and traditional cooking appliances and methods are less used. Over time this affects kitchen architecture and the design of new buildings. It is also likely to affect diet, in both positive and negative ways.

Domestic refrigeration along with the increase of home-delivery which we are already seeing in the cities of India and China can also reduce the frequency of shopping which can affect local marketplaces. Traditional market stalls selling fresh produce daily may struggle.

The effects on gender equality and gender roles are hard to predict, but technologies tend to get incorporated into existing social systems and hierarchies although they do sometimes have the potential to disrupt them. In male dominated societies, without careful planning and some intervention it is to be anticipated that the benefits of new technologies will flow to men, e.g. men will have more access to them, women’s use will be circumscribed; or the benefits accruing to women (e.g. income) will be claimed by men in the household.

Assumptions about alleviating women’s work should not be made too simplistically. To take an example household from research in Bangladesh, introducing a fridge to the household did not result in less work for the wife, because the husband did not like to eat reheated food and wanted every meal to be cooked from fresh. It did however alleviate the husband’s work, as shopping in the public marketplace was his job, as his wife was expected to stay around the house. He was able to store fresh produce in the fridge and not go shopping as often if he did not wish to.

In other areas however energy services have helped women’s development e.g. home lighting has allowed women to do income generating work in the evenings. Cooling and cold chains may give women new opportunities and allow them to start new enterprises such as food processing. How new services and opportunities affect, and are affected by, gender dynamics will vary according to the local context and should not be taken for granted or assumed to be easily predictable.

Social hierarchies

As with gender, new technologies and new opportunities may be kept for the benefit of the more powerful in communities whilst those at the lower end of hierarchies may struggle to find gains. The ability to invest can also be important in this regard. In India, caste is likely to be an issue in terms of who is admitted into groups, who is given information, who is lent money, etc. Other minority groups that need to be considered include scheduled tribes, and minority religious communities.

Appendix 1 – A history of cooling

Cooling - lowering and maintaining the temperature below that of the ambient surroundings - evolved out of our need to preserve food as well as create comfortable environments in which to live and dates back thousands of years. The basic concept behind air conditioning is said to have been applied in ancient Egypt, where reeds were hung in windows and were moistened with trickling water. The evaporation of water cooled the air blowing through the window. People have been using cooling as a method for food preservation by making use of elements provided by nature, such as snow, ice and cold streams and stored food in caves and underground areas long before the invention of refrigeration.[79] A cuneiform tablet dating from 1780BC records the construction of an ice house in the northern Mesopotamian town of Terqa.

James I of England commissioned the construction of the first modern icehouse in Greenwich Park in 1619. Medieval versions, known as ice pits, have not survived but it is likely that what set them apart from the new 17th century design was that the latter's walls were brick-lined and their cylindrical shape, engineered for temperature regulation and strength.

The ice trade was a 19th-century and early-20th-century industry, centering on the east coast of the United States and Norway involving the large-scale harvesting, transport and sale of natural ice, Ice was cut from the surface of ponds and streams, then stored in ice houses, before being sent on by ship, barge or railroad to its final destination around the world. Networks of ice wagons were typically used to distribute the product to the final domestic and smaller commercial customers. The ice trade revolutionized the U.S. meat, vegetable and fruit industries, enabled significant growth in the fishing industry, and encouraged the introduction of a range of new drinks and foods.

The concept of artificial or mechanical refrigeration was first demonstrated by William Cullen at the University of Glasgow in 1748. Recorded in his published paper, "Of the Cold produced by Evaporating Fluids, and of some other Means of producing Cold", Cullen used a pump to create a small vacuum over a container of diethyl ether. When the diethyl ether began to boil, it absorbed the heat from the container's surroundings, causing it to cool.

Oliver Evans, an American inventor, designed but did not build a refrigeration machine that used vapor instead of liquid in 1805. In 1820, Faraday used liquefied ammonia for cooling. Jacob Perkins, who worked with Evans, received a patent for a vapor-compression cycle using liquid ammonia in 1835 entitled "Apparatus and means for producing ice, and in cooling fluids." For that, he is sometimes called the "father of the refrigerator."

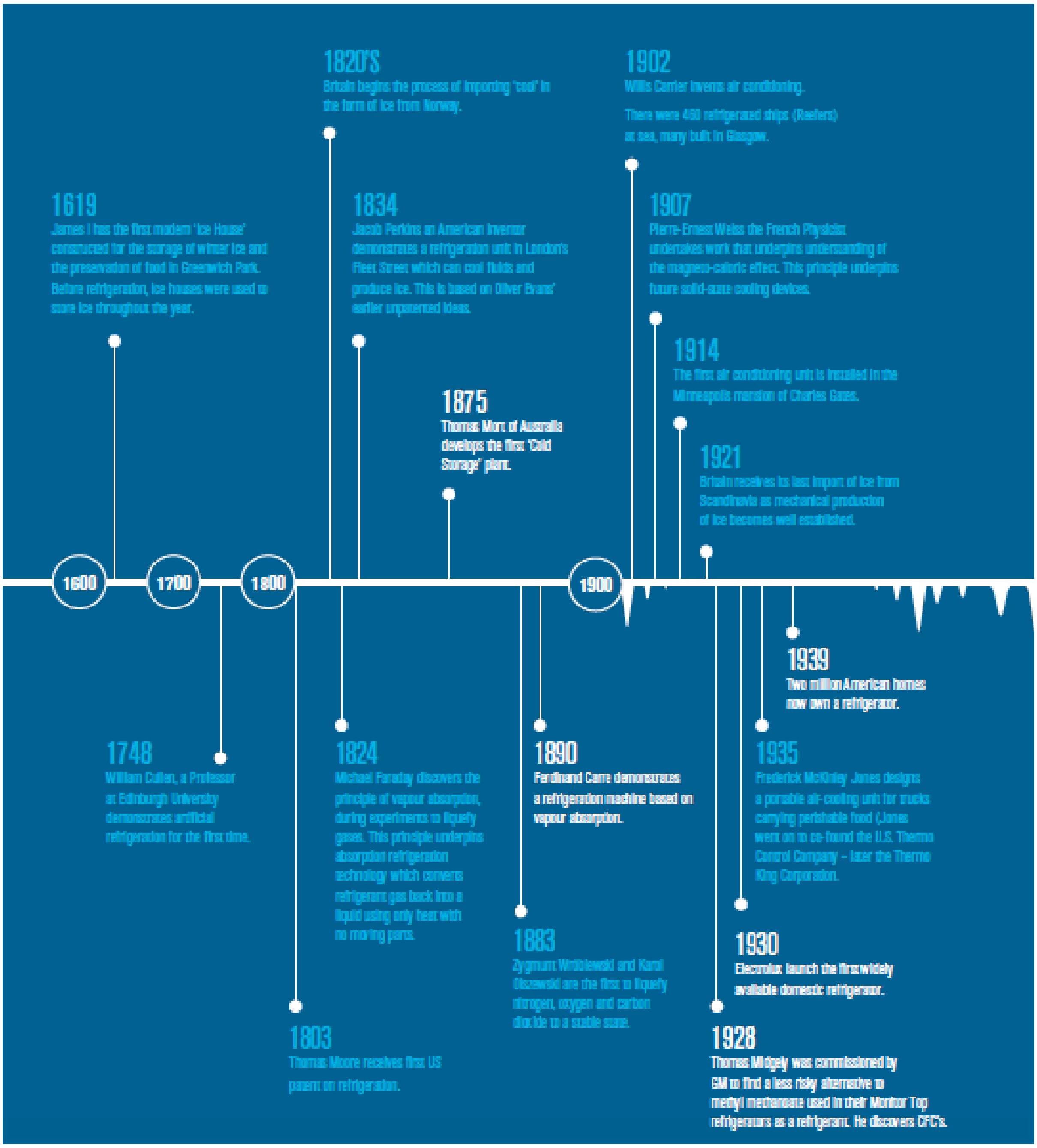
It was at the beginning of the 20th century that artificial comfort cooling in the form of air conditioning began to play a role. In 1902 Willis Haviland Carrier invented the first modern air conditioner, which was installed at the Sackett & Wilhelms printing plant in Brooklyn, cooling the air in the plant while at the same time resolving humidity issues. By 1946, more than 30,000 room air-conditioners were sold a year. In less than seven years this had increased 33 times to more than 1 million per year.

As to the impact, in 1950, 28% of the population of the US lived in its sunbelt, this increased to 40% by 2000 because of access to air-conditioning. The combined population of the Gulf cities went from less than 500,000 before 1950 to 20 million now with tens of millions of visitors. Today in the GCC, air conditioning alone accounts for more than half of the total electricity used; without intervention by 2030 Saudi Arabia will be burning more oil for air conditioning than it will export.

As Rowan Moore described in his article "An inversion of Nature: How air-conditioning created the modern city", in many parts of the "developed" world, it is normal to spend whole days, even weeks in controlled temperature environments; moving from an air-conditioned apartment to an air-conditioned garage and then in your air-conditioned car to malls and workplaces which are all, also, air-conditioned. The mall has become a principal gathering place where large numbers can comfortably pass their time while buildings which appear separate from the outside are internally connected, a hotel turning into a mall into a food.

---

[79] https://www.livescience.com/57797-refrigerator-history.html
http://www.lubbockappliancerepair.net/a-brief-history-of-cooling-and-food-preservation/



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.

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

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 Wroblewski 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.

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.

Appendix 2 – Ten applications for delivering cooling

	Heat Pumps	**Unitary Air Conditioners**	**Air Conditioning Chillers**	**Mobile Air Conditioning Equipment**
Description	Reversible heat pumps capable of providing heating and cooling to buildings. Most commonly these use air source techniques though versions using other heat sinks are also available.	Air conditioning installations typically aimed at the market for smaller units, incorporates direct expansion (DX), ducted, packaged and split systems.	Air conditioners aimed at large installations. Typical mode of operation is to cool water and then circulate it through a pipe network over which air blows to achieve cooling in the environment external to the chiller.	Car, train and plane air conditioning systems. These systems are most often configured as direct expansion (DX) systems.
Global Parc	160m	918m	6.8m	976m
Annual Sales Volume	25m	106m	385k	107m
2030 Projected Equipment Parc	[redacted]	1.98bn	6.78m	1.50bn
2030 Projected market value	[redacted]	$135bn	$2.9bn	$36bn
Cooling Temperatures	16-25°C	16-25°C	16-25°C	16-25°C
Cooling Power Range	Up to ~30kW	Up to ~30kW	Up to MWs	5kW
Potential Human Impacts	- Increased comfort leading to improved productivity and enhanced learning effectiveness - Health benefits during extreme temperature events	- Increased comfort leading to improved productivity and enhanced learning effectiveness - Health benefits during extreme temperature events	- Increased comfort leading to improved productivity and enhanced learning effectiveness - Health benefits during extreme temperature events	- Increased comfort leading to improved productivity and vehicle control by the driver / aircrew - Health benefits during extreme temperature events
Environmental Impacts	- significant energy demand so potential for primary energy consumption impact - can use high Global Warming potential refrigerants so potential for direct emissions too	- Largest energy demand and so significant potential for impact - 1,400 TWhs of energy consumed per year - 1.4 GTCO2e emitted per year	- Typically, energy intensive systems so significant potential for impact - 245 TWhs of energy consumed per year - 250 mTCO2e emitted per year	- Typically, low efficiency and fossil-fuel powered systems so significant potential for impact - 985 TWhs of energy consumed per year - 1.2 GTCO2e emitted per year

Application	Domestic Refrigeration	Commercial Refrigeration	Industrial Refrigeration
Description	Refrigerators used in homes to keep food produce and products that have reached the customer fresh or frozen.	This category covers the type of equipment installed in restaurants and retail premises, including display cabinets and cold rooms.	Industrial refrigeration is most commonly used on farms, in food processing and pharmaceutical factories, and in product distribution centers. The distinction from commercial refrigeration is its use for reducing, rather than maintaining, the temperature of products.
Global Parc	1.6bn	87m	600k
Annual Sales Volume	135m	7.2m	26k
2030 Projected Equipment Parc	2.56bn	108m	647k
2030 Projected market value	$61bn	$13bn	$3bn
Cooling Temperatures	1-4°C -18°C	-1 to 5°C <-15°C	Product specific 2-12°C Chilled -35 to -45°C for freezing <-18°C frozen storage
Cooling Power Range	<.5kW	2-5kW	Up to hundreds kW
Potential Human Impacts	Increases food shelf life meaning: - greater variety of food produce and products can be consumed with better nutritional outcomes and less food is wasted by consumer - less time can be spent travelling to acquire food as food can be stored for longer	Increases food or vaccine shelf life meaning: - greater variety of food produce and products can be consumed with better nutritional outcomes - more food reaches the point of sale, reducing food losses and increasing rural incomes - more vaccines reach the usage point with maintained integrity, increasing effectiveness of health expenditure	
Environmental Impacts	- Addressing the carbon footprint of domestic refrigeration can significantly reduce greenhouse gas emissions as there are a large number of installed units globally. - Reduced food waste avoids wasted agricultural resources (e.g. soil, water & energy) - 567 TWhs of energy consumed per year - 413 mTCO2 emitted per year	- Significant energy consumption and refrigerant leakage from the equipment deployed in these applications - Reduced food losses avoids wasted agricultural resources (e.g. soil, water & energy) - Industrial and Commercial refrigeration combined consume 670 TWhs of energy per year - Industrial and Commercial refrigeration combined emit 750 mTCO2 per year	

Application	Transport Refrigeration	Shipping Refrigeration	Marine Refrigeration & Processing
Description	Trucks and vans carry small onboard refrigeration units so that they can maintain the temperature of goods they are transporting.	Shipping (reefer) containers have small inbuilt refrigeration units so that they can maintain the temperature of goods they are transporting	Like industrial refrigeration a range of applications for reducing the temperature of fish onboard ships. Incorporates brine cooling, refrigerated sea water, plate systems and blast freezers.
Global Parc	2.7m	1.2m	80-90k
Annual Sales Volume	250k	155k	4-5k
2030 Projected Equipment Parc	3.2m	[redacted]	[redacted]
2030 Projected market value	$750m	[redacted]	[redacted]
Cooling Temperatures	0°C & -20°C	2°C and -18°C	-2 to -20°C for brine or sea water systems -40°C to -70°C for blast freezing
Cooling Power Range	0.5 to 25kW	3-10kW (depending on temp)	hundreds of kW
Potential Human Impacts	Increases food or vaccine shelf life meaning: - greater variety of food produce and products can be consumed with better nutritional outcomes - more food reaches the point of sale, reducing food loss and increasing rural incomes - more vaccines reach the usage point with maintained integrity, increasing effectiveness of health expenditure Also - health impacts of poor air quality (from diesel TRU emissions) could be mitigated	- Enables export opportunity for farm produce that can improve individual and national incomes - Potential benefits for food security by enabling longer food supply chains	- Improving marine products preservation reduces food losses and enables increased incomes for fishermen - Wider access to marine products can have a positive health impact
Environmental Impacts	- Vehicle fuel consumption for refrigeration unit emits significant quantities of CO2 - Lightly regulated diesel power sources contribute to poor air quality, particularly in dense urban environments - 12 TWhs of energy consumed per year - 19 mTCO2 emitted per year	- The primary power source for reefer containers is onboard electricity generators using fossil fuel. Reducing energy consumption creates opportunities to reduce the environmental impact from shipping	- High global warming potential (GWP) refrigerants are still in common use in fishing fleets - Avoiding food losses of marine resources through spoilage on route to market

Appendix 3 – Alternate market size estimates

With the exception of the IEA figures, nearly all of the market estimates are either historic equipment stock/annual sale estimates or very short-term projections. This is because of the differing purposes for which the figures are produced.

- The IEA figures have been developed to support a study of air conditioning and space cooling energy demand globally and future demand projections and energy implications. They cover a similar period to the GIZ Proklima data set.
- The Japan Refrigeration and Air Conditioning Industry (JRAIA) is a trade association that regularly publishes figures covering historic shipments and short term (year ahead) outlooks for air conditioner demand in key markets.
- The International Institute of Refrigeration (IIR) has produced a series of briefing notes for policy makers that aim to describe the nature and scale of various cooling sectors, the equipment parc estimates contained within those are compared with relevant GIZ Proklima figures.
- Markets and Markets are a market research company whose reports are used by industry to inform relatively short-term market and product development strategies. Their estimates and forecasts tend to be based on industry sentiment and persistence models and so are typically short term and would ignore macro factors like the role of urbanization and electrification in product or service demand.

Parameter	Geographic coverage	Sectors covered	Source	Volume	Reference year for analysis	GCI comparator (2012 projection updated in 2016)	Comments
2016 Stock of AC appliances (units)	Global	Residential + Commercial space cooling	IEA Future of Cooling, 2018	1.62bn units	2016	840m units	Estimates cover different sectors – GCI focuses on AC based space cooling and refrigeration equipment whereas the IEA figures include fans and dehumidifiers alongside air conditioning equipment. The GCI and IEA projection methodologies are different for the demand projections and were conducted from different base years (2012 for GCI, revised in 2016, and 2016 for IEA); as a result, equipment deployment volumes differ between the two projections.
2050 Stock of AC appliances (units)	Global	Residential + Commercial space cooling	IEA Future of Cooling, 2018	5bn units	2016	3.7bn units	
2016 annual sales of AC appliances (units)	Global	Residential + Commercial + Industrial space cooling	JRAIA April 2017 report on World AC demand	102m units	2016	89m units	11% difference between estimates reflecting the global demand in 2018 outstripping the rate projected in 2012 and 2016.
2016 Domestic refrigeration equipment stock	Global	Domestic refrigeration	International Institute of	1.5bn units	2010	1.5bn units	Market estimates consistent

2016 Commercial refrigeration equipment stock	Global	Commercial refrigeration	Refrigeration, 29th Informatory note	90m units	2010	84m units	Market estimates consistent (~7% difference)
2016 Mobile AC equipment stock	Global	Mobile AC		700m units	2010	900m units	Faster growth rate assumption in the GCI data forecast.
2016 Transport refrigeration equipment stock	Global	Road vehicle refrigeration		4m units	2010	2.7m units	Large uncertainty regarding the size of the refrigerated transport market because of the absence of vehicle registration processes; experts disagree on the global market size
2021 Ductless heating and cooling systems market value	Global	Residential, Commercial and Industrial	MarketsAndMarkets	$78.6bn	2015	$55bn	GCI forecasts 2021 market for split ACs to be ~ $55bn (80% of the UAC market is ductless in terms of units as per GCI reports) - MarketsAndMarkets includes both heating and cooling equipment (GCI focuses on cooling) in residential, commercial and industrial sectors. They include refrigerants, aftersales services, software, etc.
2020 Mobile AC market value	Global	All transport sectors	MarketsAndMarkets	$24.28bn	2015	$30.4bn	Likely larger equipment stock and annual sales (in terms of units) in the GCI data forecast leading to higher market value.

Appendix 4 – Projection Methodology

GCI Data Set

The equipment stock, energy consumption and emissions projections in this document are all based on a data set produced by the Green Cooling Initiative. The data set is based on data collected by GIZ under the Proklima program on behalf of the German Federal Ministry for Economic Co-operation and Development and the German Federal Ministry for the Environment Nature Conservation and Nuclear Safety.

The data set considers 193 countries and 7 major equipment families (unitary air conditioners, chillers, industrial refrigeration, commercial refrigeration, mobile air conditioners, transport refrigeration and domestic refrigerators).

The equipment parc estimation (produced in 2012 and updated in 2016) uses actual equipment inventories recorded bottom up by national governments and trade bodies and combines these with estimates when this data is unavailable. Annual sales volumes are calculated in a similar manner. Sales values are calculated using expert input for typical equipment sales prices in each territory.

Equipment parc evolution is modelled based on a combination of expert consultation and mathematical relations between parameters like GDP, climate, electrification, population, and urbanization rates with cooling equipment deployment volumes.

Direct emissions impacts are assessed via refrigerant charge and leakage estimations for the major equipment types during production, operation, and disposal.

Indirect impacts are modelled via climate and equipment specific energy consumption and efficiency assumptions. Through a combination of energy consumption and nationally adjusted emissions factors, indirect emissions are also modelled.

Focus Group Countries

A subset of 14 countries (summarized in the table below) was selected to illustrate differences in cooling access and growth trajectories out to 2050. (Country categories based on OECD Development Assistance Committee (DAC)).

Country	DAC Category	WB Region	Annual Equipment Sales Value ($m)	Energy Consumption (GWh)	Population
World	N/A	N/A	$142,463 m	3,938,655	7,467,229,640
Kenya	Other Low Income	Africa	$343 m	11,699	50,442,810
Ethiopia	Least Developed	Africa	$593 m	12,729	106,489,668
Japan	N/A - OECD	East Asia & Pacific	$5,813 m	155,305	125,956,242
China	Upper Middle Income	East Asia & Pacific	$36,067 m	1,043,190	1,420,355,183
Indonesia	Lower Middle Income	East Asia & Pacific	$2,623 m	100,830	263,931,588
Uzbekistan	Lower Middle Income	Europe and Central Asia	$217 m	5,701	30,781,093
Romania	N/A - OECD	Europe and Central Asia	$737 m	13,783	21,367,354
Brazil	Upper Middle Income	Latin America and the Caribbean	$2,905 m	108,862	208,123,896
Jamaica	Upper Middle Income	Latin America and the Caribbean	$30 m	1,663	2,851,713
UAE	N/A - OECD	Middle East and North Africa	$246 m	15,065	10,191,786
Egypt	Lower Middle Income	Middle East and North Africa	$854 m	24,265	88,519,255
India	Lower Middle Income	South Asia	$8,607 m	328,320	1,324,939,288

Bangladesh	Least Developed	South Asia	$1,120 m	32,355	165,904,075
USA	N/A - OECD	N/A	$21,510 m	547,380	332,840,871

Universal Access Scenario

A universal access scenario was developed for the group of 14 countries along with an example convergence pathway.

Under this scenario, the countries were categorized as high ambient or low ambient based on the number of cooling degree days (CDD) that they experience per year (2000 is taken as a boundary value and 21.1°C as the threshold value, as a comparator Japan experiences ~1365 CDD per year). Refrigeration equipment per household penetrations were set to converge with the United States for all countries by 2050, this is assumed to be required to bring food loss ratios down to the ~9% observed in that country. At the same time, space cooling equipment (stationary and mobile) penetrations for high ambient countries also converge whilst low ambient countries continue on their current trajectories.

A multiplier was then calculated to translate per household GCI projected penetrations for all 7 main equipment types to a convergence pathway. The convergence trajectory selected for this paper between 2026 and 2050 was for a 10% increase towards US penetration levels every 4 years (i.e. 20% in 2026, 30% in 2030, 40% in 2034 etc).

These adjustments to equipment penetrations allow country specific assumptions about climate and efficiency that drive emissions and energy consumption estimates to be scaled up to reflect the higher equipment penetration values.

Technology Performance Assumptions

The GCI data set contains assumptions about equipment performance that are based on individual market and climatic conditions. There is an evolution of device efficiency and reduction in direct emissions from refrigerant leakage over the projection time period under both the business as usual (BAU) and mitigation (MIT) scenarios. As an indication of the scale of improvements assumed per device emissions and energy are summarized in the tables below.

Energy Improvements	BAU	MIT
Space Cooling	-16%	-35%
Industrial and Commercial	-10%	-29%
Mobile Cooling Systems	-10%	-26%
Domestic Refrigeration	-30%	-41%

Table 18 - Energy Efficiency Improvements GCI BAU and MIT scenarios vs. today

Total Emissions Improvements	BAU	MIT
Space Cooling	-18%	-44%
Industrial and Commercial	-10%	-45%
Mobile Cooling Systems	-25%	-40%
Domestic Refrigeration	-26%	-39%

Table 19 – Total Emissions Improvements GCI BAU and MIT scenarios vs. today

Direct Emissions Improvements	BAU	MIT
Space Cooling	-59%	-59%
Industrial and Commercial	-10%	-10%
Mobile Cooling Systems	-52%	-52%
Domestic Refrigeration	-37%	-37%

Table 20 - Direct Emissions Improvements GCI BAU and MIT scenarios vs. today

Country Equipment Growth Comparisons Breakdown

GIZ Proklima Data Set

To provide further detail we have provided tables comparing equipment stock, energy in GWh and emissions growth in mTCO2e across the four main sectors for the 14 focus countries for the business as usual scenario in the tables below.

Space Cooling	Equipment Stock			Energy		Emissions	
	2018	2050	Change	2018	2050	2018	2050
Kenya	913,267	9,732,133	966%	5,270	28,060	3	14
Ethiopia	1,161,667	4,832,800	316%	4,527	13,613	3	9
Japan	44,092,000	46,367,333	5%	52,387	43,307	35	26
China	343,226,667	2,321,226,667	576%	537,067	2,884,067	688	3,146
Indonesia	12,453,733	64,973,333	422%	45,593	165,280	40	132
Uzbekistan	812,273	2,068,267	155%	1,747	3,629	2	4
Romania	892,600	1,377,467	54%	1,770	1,762	3	2
Brazil	23,842,400	64,752,733	172%	46,707	109,713	17	26
Jamaica	203,581	427,641	110%	653	1,197	1	1
United Arab Emirates	2,092,073	5,833,527	179%	5,460	14,273	6	15
Egypt	4,778,000	16,827,800	252%	9,527	27,140	8	20
India	20,488,667	145,258,667	609%	125,867	462,600	190	674
Bangladesh	3,503,800	20,646,067	489%	13,447	43,547	13	37
United States	247,507,333	368,618,000	49%	293,267	368,133	212	252
Group Total	705,968,061	3,072,942,434	335%	1,143,287	4,166,321	1,218	4,357

Table 21 - Space Cooling Growth BAU

Industrial & Commercial	Equipment Stock			Energy		Emissions	
	2018	2050	Change	2018	2050	2018	2050
Kenya	586,763	1,264,587	116%	3,822	7,850	3	6
Ethiopia	1,234,273	2,448,200	98%	5,693	10,707	4	8
Japan	2,286,300	2,190,067	-4%	35,283	30,133	31	22
China	16,539,333	17,939,333	8%	130,233	129,433	208	213
Indonesia	3,075,417	4,188,367	36%	21,097	27,430	22	31
Uzbekistan	359,134	474,453	32%	1,556	1,959	2	2
Romania	387,440	360,073	-7%	5,870	4,856	8	5
Brazil	2,427,940	3,014,747	24%	13,863	16,427	8	10
Jamaica	33,183	36,622	10%	231	243	0	0
United Arab Emirates	118,367	202,324	71%	831	1,361	1	2
Egypt	1,031,870	1,588,320	54%	5,303	7,780	5	8
India	10,824,333	14,770,433	36%	78,333	102,300	132	179
Bangladesh	1,932,270	2,630,353	36%	10,593	13,763	12	16
United States	5,023,767	6,726,600	34%	51,933	59,867	46	45
Group Total	45,860,390	57,834,480	26%	364,643	414,109	482	548

Table 22 - Industrial and Commercial Cooling Growth BAU

Mobile Cooling Systems	Equipment Stock			Energy		Emissions	
	2018	2050	Change	2018	2050	2018	2050
Kenya	569,690	4,726,600	730%	1,610	8,693	2	9
Ethiopia	762,200	4,592,100	502%	1,319	5,401	2	8
Japan	47,863,000	43,657,000	-9%	46,835	44,057	62	56
China	153,367,000	431,400,000	181%	261,890	506,970	347	562
Indonesia	10,030,300	51,255,000	411%	18,940	76,044	20	68
Uzbekistan	931,700	2,206,210	137%	818	1,782	1	2
Romania	4,857,700	9,565,900	97%	3,923	5,832	6	5
Brazil	25,631,800	59,039,500	130%	28,392	59,228	30	53
Jamaica	342,436	604,480	77%	544	884	1	1
United Arab Emirates	4,761,550	7,872,650	65%	7,414	11,323	7	9
Egypt	4,203,500	14,920,800	255%	4,315	13,196	5	13
India	22,842,000	189,194,000	728%	54,520	307,730	57	269
Bangladesh	2,035,300	10,634,500	423%	4,045	13,989	5	15
United States	141,431,000	169,582,000	20%	140,780	177,180	179	218
Group Total	419,629,176	999,250,740	138%	575,344	1,232,309	724	1,287

Table 23 - Mobile Cooling System Growth BAU

Domestic Refrigeration	Equipment Stock			Energy		Emissions	
	2018	2050	Change	2018	2050	2018	2050
Kenya	2,720,000	24,800,000	812%	997	6,480	0	2
Ethiopia	4,080,000	37,300,000	814%	1,190	7,930	0	1
Japan	73,700,000	76,000,000	3%	20,800	16,700	10	8
China	295,000,000	654,000,000	122%	114,000	167,000	115	168
Indonesia	36,600,000	122,000,000	233%	15,200	33,700	11	24
Uzbekistan	4,130,000	9,710,000	135%	1,580	2,420	1	1
Romania	7,820,000	9,100,000	16%	2,220	2,000	2	2
Brazil	51,300,000	111,000,000	116%	19,900	27,800	2	3
Jamaica	530,000	1,020,000	92%	235	292	0	0
United Arab Emirates	3,220,000	8,870,000	175%	1,360	2,500	1	2
Egypt	14,200,000	40,300,000	184%	5,120	9,430	3	5
India	162,000,000	557,000,000	244%	69,600	159,000	95	215
Bangladesh	12,200,000	54,900,000	350%	4,270	13,300	3	9
United States	191,000,000	286,000,000	50%	61,400	71,000	35	40
Group Total	858,500,000	1,992,000,000	132%	317,872	519,552	280	482

Table 24 - Domestic Refrigeration Growth BAU

Universal Access Scenario Figures

To provide further detail we have provided tables comparing equipment stock, energy in GWh and emissions growth in mTCO2e across the four main sectors for the 14 focus countries for the universal access scenario in the tables below.

Space Cooling	Equipment Stock			Energy		Emissions	
	2018	2050	Change	2018	2050	2018	2050
Kenya	913,267	74,184,379	8023%	5,270	211,087	3	104
Ethiopia	1,161,667	143,198,244	12227%	4,527	374,462	3	239
Japan	44,092,000	46,367,333	5%	52,387	43,307	35	26
China	343,226,667	2,321,772,649	576%	537,067	2,908,131	688	3,179
Indonesia	12,453,733	245,348,314	1870%	45,593	633,467	40	505
Uzbekistan	812,273	27,717,208	3312%	1,747	46,184	2	45
Romania	892,600	1,377,467	54%	1,770	1,762	3	2
Brazil	23,842,400	176,443,530	640%	46,707	306,531	17	75
Jamaica	203,581	2,143,880	953%	653	6,029	1	6
United Arab Emirates	2,092,073	11,817,097	465%	5,460	29,865	6	31
Egypt	4,778,000	92,983,861	1846%	9,527	150,055	8	110
India	20,488,667	1,236,792,402	5936%	125,867	3,928,897	190	5,723
Bangladesh	3,503,800	154,172,568	4300%	13,447	321,181	13	274
United States	247,507,333	368,618,000	49%	293,267	368,133	212	252
Group Total	705,968,061	4,902,936,930	594%	1,143,287	9,329,092	1,218	10,570

Table 25 - Space Cooling Growth UA

Industrial & Commercial	Equipment Stock			Energy		Emissions	
	2018	2050	Change	2018	2050	2018	2050
Kenya	586,763	1,353,728	131%	3,822	18,784	3	15
Ethiopia	1,234,273	2,613,104	112%	5,693	24,370	4	20
Japan	2,286,300	2,190,067	-4%	35,283	30,133	31	22
China	16,539,333	19,294,333	17%	130,233	198,845	208	332
Indonesia	3,075,417	4,477,155	46%	21,097	65,807	22	75
Uzbekistan	359,134	497,042	38%	1,556	4,210	2	6
Romania	387,440	360,073	-7%	5,870	4,856	8	5
Brazil	2,427,940	3,219,770	33%	13,863	38,731	8	25
Jamaica	33,183	39,122	18%	231	585	0	1
United Arab Emirates	118,367	215,640	82%	831	3,286	1	5
Egypt	1,031,870	1,696,784	64%	5,303	18,033	5	20
India	10,824,333	22,569,185	109%	78,333	353,658	132	622
Bangladesh	1,932,270	2,813,366	46%	10,593	32,377	12	39
United States	5,023,767	6,726,600	34%	51,933	59,867	46	45
Group Total	45,860,390	68,065,970	48%	364,643	853,542	482	1,231

Table 26 - Industrial and Commercial Growth UA

Mobile Cooling Systems	Equipment Stock			Energy		Emissions	
	2018	2050	Change	2018	2050	2018	2050
Kenya	569,690	34,128,380	5891%	1,610	62,752	2	64
Ethiopia	762,200	65,878,076	8543%	1,319	76,944	2	114
Japan	47,863,000	43,657,284	-9%	46,835	44,058	62	56
China	153,367,000	486,422,807	217%	261,890	576,204	347	643
Indonesia	10,030,300	112,872,019	1025%	18,940	169,218	20	151
Uzbekistan	931,700	12,759,600	1269%	818	10,326	1	13
Romania	4,857,700	9,565,900	97%	3,923	5,832	6	5
Brazil	25,631,800	81,172,506	217%	28,392	82,502	30	74
Jamaica	342,436	986,288	188%	544	1,460	1	1
United Arab Emirates	4,761,550	7,888,658	66%	7,414	11,462	7	10
Egypt	4,203,500	42,777,046	918%	4,315	38,159	5	38
India	22,842,000	568,983,959	2391%	54,520	935,464	57	825
Bangladesh	2,035,300	70,926,793	3385%	4,045	93,355	5	102
United States	141,431,000	169,582,000	20%	140,780	177,180	179	218
Group Total	419,629,176	1,707,601,314	307%	575,344	2,284,916	724	2,314

Table 27 - Mobile Cooling Systems Growth UA

Domestic Refrigeration	Equipment Stock			Energy		Emissions	
	2018	2050	Change	2018	2050	2018	2050
Kenya	2,720,000	57,557,505	2016%	997	15,039	0	5
Ethiopia	4,080,000	111,103,358	2623%	1,190	23,621	0	4
Japan	73,700,000	77,290,656	5%	20,800	16,984	10	8
China	295,000,000	820,351,941	178%	114,000	209,478	115	211
Indonesia	36,600,000	190,358,631	420%	15,200	52,583	11	37
Uzbekistan	4,130,000	21,519,061	421%	1,580	5,363	1	3
Romania	7,820,000	12,706,239	62%	2,220	2,793	2	3
Brazil	51,300,000	136,897,410	167%	19,900	34,286	2	4
Jamaica	530,000	1,663,374	214%	235	476	0	0
United Arab Emirates	3,220,000	9,168,542	185%	1,360	2,584	1	2
Egypt	14,200,000	72,143,477	408%	5,120	16,881	3	9
India	162,000,000	959,591,303	492%	69,600	273,923	95	371
Bangladesh	12,200,000	119,618,018	880%	4,270	28,978	3	19
United States	191,000,000	286,000,000	50%	61,400	71,000	35	40
Group Total	858,500,000	2,875,969,516	235%	317,872	753,989	280	717

Table 28 - Domestic Refrigeration Growth UA

Appendix 5 – Energy and emissions reductions from the Global Cooling Prize

			BAU			UA		
			No Prize	With Prize	Saving	No Prize	With Prize	Saving
Energy (GWh)		% Market	2050	2050		2050	2050	
Kenya	Unitary AC	50%	26,600	18,088	8,512	202,883	137,961	64,923
Ethiopia	Unitary AC	50%	12,300	8,364	3,936	367,095	249,625	117,470
Japan	Unitary AC	50%	38,400	26,112	12,288	38,400	26,112	12,288
China	Unitary AC	50%	2,830,000	1,924,400	905,600	2,830,000	1,924,400	905,600
Indonesia	Unitary AC	50%	160,000	108,800	51,200	603,851	410,619	193,232
Uzbekistan	Unitary AC	50%	3,370	2,292	1,078	45,297	30,802	14,495
Romania	Unitary AC	50%	1,210	823	387	1,210	823	387
Brazil	Unitary AC	50%	107,000	72,760	34,240	291,311	198,091	93,219
Jamaica	Unitary AC	50%	1,150	782	368	5,764	3,920	1,845
United Arab Emirates	Unitary AC	50%	14,000	9,520	4,480	28,330	19,264	9,065
Egypt	Unitary AC	50%	26,000	17,680	8,320	143,662	97,690	45,972
India	Unitary AC	50%	442,000	300,560	141,440	3,763,764	2,559,359	1,204,404
Bangladesh	Unitary AC	50%	41,300	28,084	13,216	308,575	209,831	98,744
United States	Unitary AC	50%	349,000	237,320	111,680	349,000	237,320	111,680
Total			4,052,330	2,755,584	1,296,746	8,979,142	6,105,817	2,873,325
% Of Total Cooling Budget from Sector					20%			22%

Table 29 - Energy Reductions from Success in the Global Cooling Prize

			BAU			UA		
			No Prize	With Prize		No Prize	With Prize	
Emissions (mTCO2e)		% Market	2050	2050	Saving	2050	2050	Saving
Kenya	Unitary AC	50%	13.0	7.8	5.2	99.1	59.4	39.6
Ethiopia	Unitary AC	50%	7.8	4.7	3.1	234.0	140.4	93.6
Japan	Unitary AC	50%	22.6	13.5	9.0	22.6	13.5	9.0
China	Unitary AC	50%	3,073.0	1,843.8	1,229.2	3,073.0	1,843.8	1,229.2
Indonesia	Unitary AC	50%	126.7	76.0	50.7	478.2	286.9	191.3
Uzbekistan	Unitary AC	50%	3.3	2.0	1.3	44.2	26.5	17.7
Romania	Unitary AC	50%	1.3	0.8	0.5	1.3	0.8	0.5
Brazil	Unitary AC	50%	25.1	15.1	10.1	68.4	41.1	27.4
Jamaica	Unitary AC	50%	1.1	0.6	0.4	5.3	3.2	2.1
United Arab Emirates	Unitary AC	50%	14.3	8.6	5.7	28.9	17.4	11.6
Egypt	Unitary AC	50%	18.8	11.3	7.5	103.9	62.4	41.6
India	Unitary AC	50%	642.1	385.3	256.8	5,467.7	3,280.6	2,187.1
Bangladesh	Unitary AC	50%	35.0	21.0	14.0	261.5	156.9	104.6
United States	Unitary AC	50%	238.6	143.2	95.4	238.6	143.2	95.4
Total			4,222.7	2,533.6	1,689.1	10,126.7	6,076.0	4,050.7
% Of Total from Sector					25%			27%

Table 30 - Emissions Reductions from Success in the Global Cooling Prize

Appendix 6 – CLASP Global LEAP Off-Grid Cold Chain Challenge (OGCCC)

The Global LEAP Off-Grid Cold Chain Challenge (OGCCC) is an international competition to identify and promote the most energy-efficient, sustainable and cost-effective technologies that can meet the cold storage requirements for fresh fruits, vegetables and dairy products in the following countries: Kenya, Nigeria, Rwanda, Tanzania, and Uganda.

In June 2018, 10 companies were selected to progress to the second stage of the OGCCC competition. The 10 finalists are as follows:

ColdHubs were one of 10 finalists in the Global LEAP OGCCC for their cold storage facility which will enable Nigerian small farmers, retailers, and wholesalers to store 3 tons of food, saving 1,095 tons of food from spoilage a year. The walk-in cold room is a 100% green cooling solution. Completely powered by rooftop solar panels, and connected to a set of deep-cycle, long-lasting batteries, off grid and on grid inverters, the power generated is sufficient to keep the temperature at 5-15° Celsius in all weather conditions.

DGridEnergy's The Solar Cool CubeTM has already been deployed in Zambia and the Democratic Republic of Congo.

The refrigerated storage unit comes with an off-grid solar-electric system and a battery bank so it can run 24 hours a day. It also has multiple USB ports to charge cellphones and laptops and provides external LED lighting for communities without reliable electricity.

EcoLife is a women-run organization which works with women farmers growing vegetables in Uganda. Their Eco Cold Room is manufactured and assembled in Kampala, Uganda from recycled locally available materials.

Eco Cold Room has an inside and outside wall made from fire clay bricks, and an air gap filled with recycled PET water bottles for insulation, placed in specific orientations to minimize air movements. The cold room is powered by both hydroelectricity and solar energy.

Ecozen Solution's, Ecofrost, is to be deployed in Kenya. Ecofrost is a cold room that runs on solar energy and uses innovative thermal energy storage technology that can provide backup power for up to 30 hours. These thermal batteries are much more efficient than conventional batteries, with at least twice the life and much lower replacement costs.

FreshBox, is an early-stage social enterprise based in Nairobi, Kenya that is paving the way forward for sustainable refrigeration in East African produce markets. Assembled locally in Nairobi, Kenya, their flagship unit is a solar-powered, walk-in cold room that can reach freezing temperature and holds over 2100kg of fruits and vegetables. With 100mm thick panels comprised of a polyurethane interior and aluminum exterior, FreshBox can increase the longevity of a fruit or vegetable's selling period by up to 950% depending on the fruit or vegetable. They use a pay-as-you-go subscription model.

InspiraFarms automated, and remotely monitored refrigerated storage and food processing unit that can be ready to deploy anywhere with minimal preparation. The 16-24 pallet capacity unit requires only single-phase power, can run entirely on solar and has two levels of in-built back up, both thermal and electrical. All components are manufactured in Italy and assembled on site with full international food safety standard compliance.

Inviro Choice's Cold Change is a walk-in cold store product that can be used with a range of perishable produce including fruit, vegetables, dairy products, meat, and fish. Solar power is integrated with on-board lithium ion battery energy storage, allowing the unit to be fully operational for two consecutive days without recharging.

SunDanzer's cold storage container is manufactured in the US from Chinese parts, the 14m^3 solar-powered cool room has integrated thermal storage and minimal electrical energy storage. The unit can run on stand-alone solar or with an intermittent or mini-grid and can hold the interior chamber within an acceptable temperature range for 2 days without using power. If running only on a mini grid, the unit will maintain cold internal temperature based on only 3-6 hours per day of available power.

The Village Fridge, made by the Off-Grid Factory, is a stand-alone solar-powered cooling machine with a cool motor that needs no inverter, batteries, or generator. The prefabricated, insulated storage room also includes a social space, that can be used as a shop or for sorting agricultural produce. The cooling wall between the cold storage room and the social room can be shifted so the cooling capacity can be adjusted to future growth.

Tiger Power combines a refrigerated container with a foldable PV-array and a lead crystal battery bank to store surplus electricity produced during the day. Designed to be easily transported and mobile to reduce logistical and transportation barriers when operating in off-grid and rural areas, the cold storage solution can be up and running in less than an hour. Tiger Power envisages its unit can be used in refugee or internal displacement camps to increase the quality of food supply to those in need.

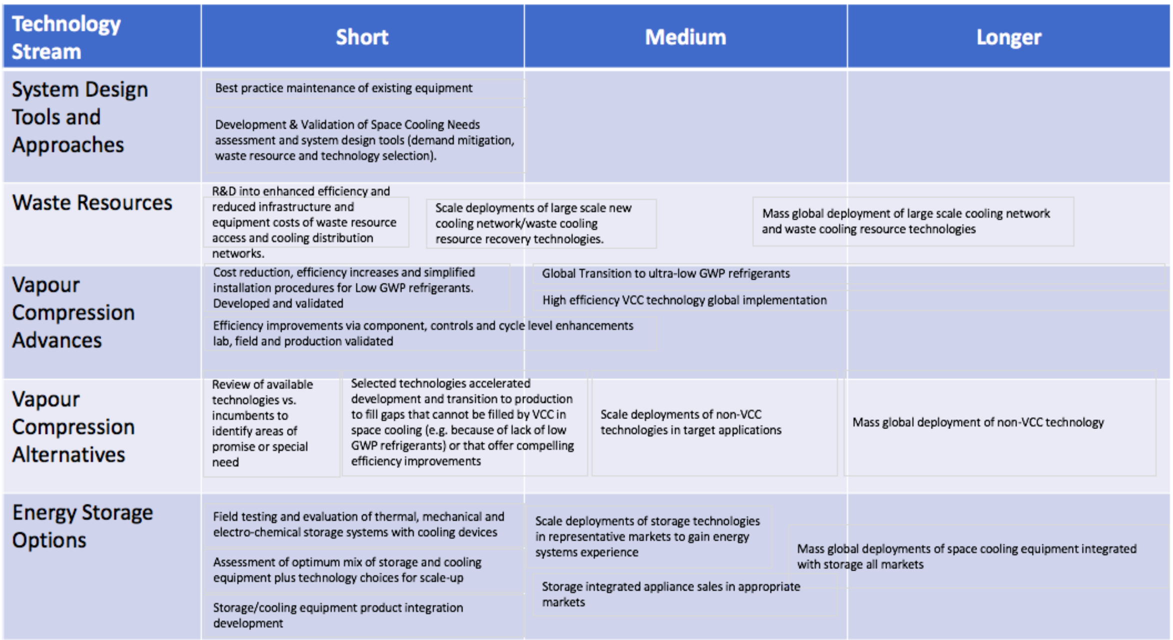
Each nominated product will undergo field testing that will comprise of technical performance captured through remote monitoring equipment and qualitative surveys administered on site and over the phone. Data will be collected from February – May of 2019. All data will be reviewed and evaluated by a panel of off-grid market experts. Final prize winners will be announced in July 2019.

The Challenge was developed in partnership with Energy 4 Impact and support from the UK Department for International Development through the Ideas to Impact Program to stimulate off-grid cold chain refrigeration for farmers and small traders, enabling better commercialization of agricultural produce.

Appendix 7 – Technology Roadmaps

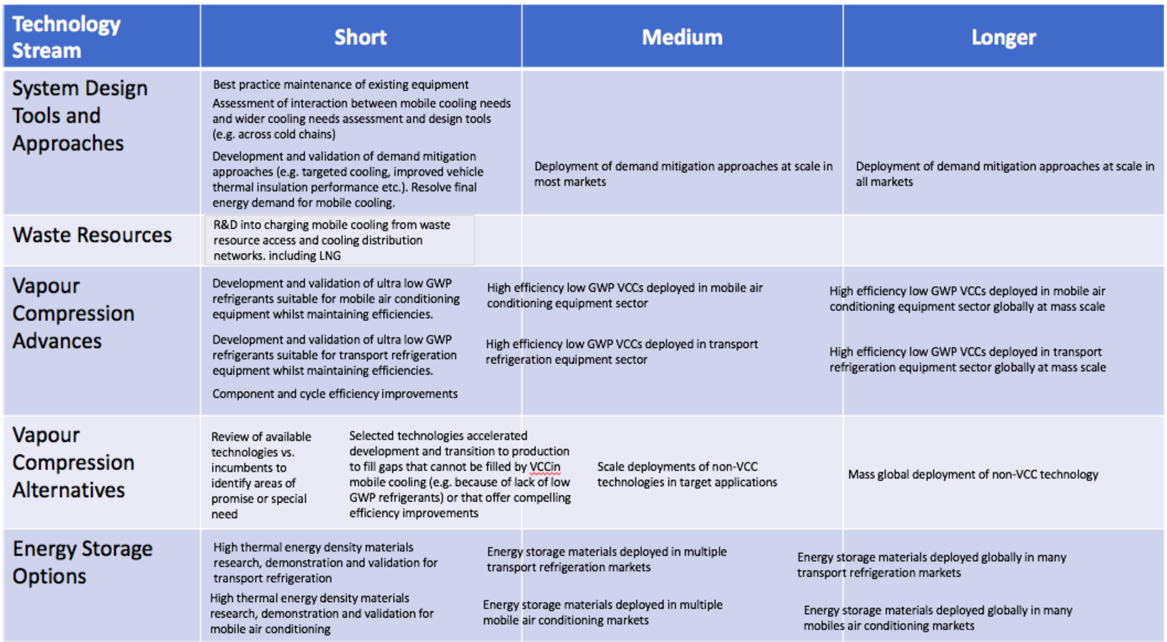
High level technology roadmaps (to catalyze discussions under the next round of this work program).

Technology change will be required in all sectors to achieve the goal of radically reducing emissions from the sector. High-level multi-decade transition pathways are proposed in the figures below. It should be noted that in some sectors, 20-year equipment lives mean that to achieve transitions by 2050, mass equipment deployments must begin by 2030. This has the implication that product validation and mass manufacturing preparations and a business case need to be in place by then too.



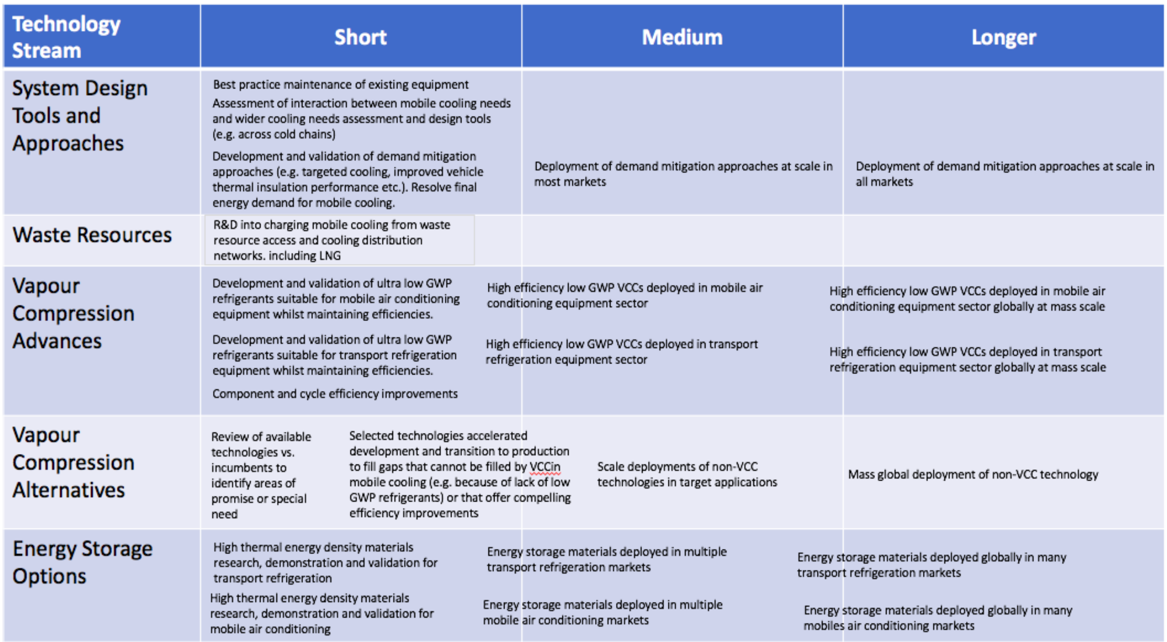
Technology Stream	Short	Medium	Longer
System Design Tools and Approaches	Best practice maintenance of existing equipment Development & Validation of Space Cooling Needs assessment and system design tools (demand mitigation, waste resource and technology selection).		
Waste Resources	R&D into enhanced efficiency and reduced infrastructure and equipment costs of waste resource access and cooling distribution networks.	Scale deployments of large scale new cooling network/waste cooling resource recovery technologies.	Mass global deployment of large scale cooling network and waste cooling resource technologies
Vapour Compression Advances	Cost reduction, efficiency increases and simplified installation procedures for Low GWP refrigerants. Developed and validated Efficiency improvements via component, controls and cycle level enhancements lab, field and production validated	Global Transition to ultra-low GWP refrigerants High efficiency VCC technology global implementation	
Vapour Compression Alternatives	Review of available technologies vs. incumbents to identify areas of promise or special need Selected technologies accelerated development and transition to production to fill gaps that cannot be filled by VCC in space cooling (e.g. because of lack of low GWP refrigerants) or that offer compelling efficiency improvements	Scale deployments of non-VCC technologies in target applications	Mass global deployment of non-VCC technology
Energy Storage Options	Field testing and evaluation of thermal, mechanical and electro-chemical storage systems with cooling devices Assessment of optimum mix of storage and cooling equipment plus technology choices for scale-up Storage/cooling equipment product integration development	Scale deployments of storage technologies in representative markets to gain energy systems experience Storage integrated appliance sales in appropriate markets	Mass global deployments of space cooling equipment integrated with storage all markets

Figure 18 - Space Cooling Technology Roadmap



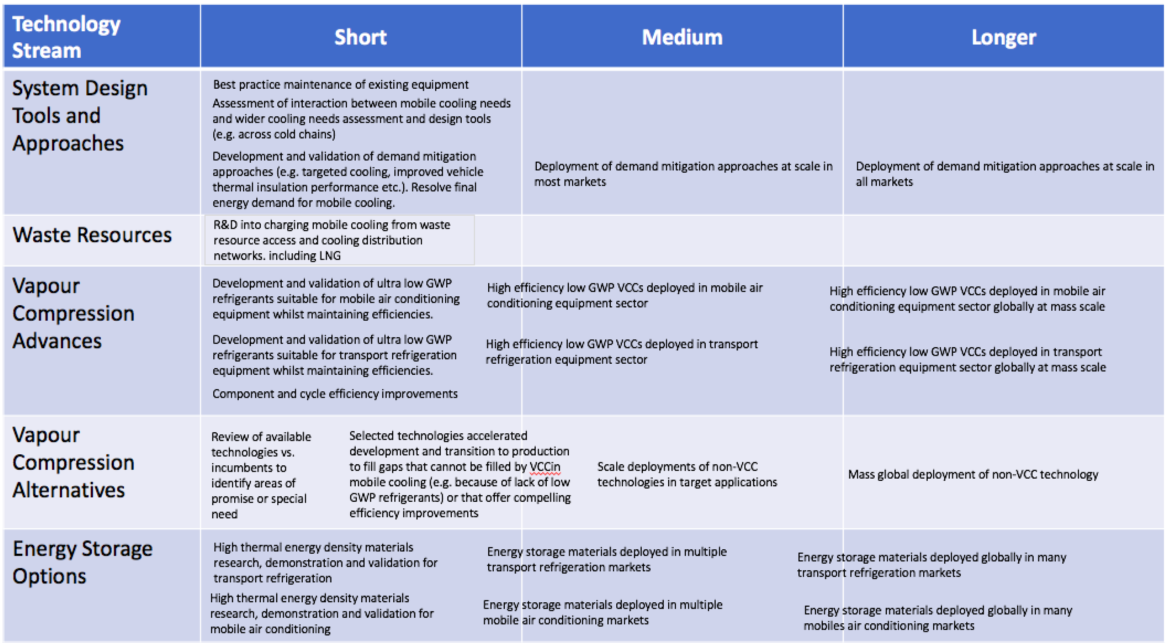
Technology Stream	Short	Medium	Longer
System Design Tools and Approaches	Best practice maintenance of existing equipment Assessment of interaction between mobile cooling needs and wider cooling needs assessment and design tools (e.g. across cold chains) Development and validation of demand mitigation approaches (e.g. targeted cooling, improved vehicle thermal insulation performance etc.). Resolve final energy demand for mobile cooling.	Deployment of demand mitigation approaches at scale in most markets	Deployment of demand mitigation approaches at scale in all markets
Waste Resources	R&D into charging mobile cooling from waste resource access and cooling distribution networks. including LNG		
Vapour Compression Advances	Development and validation of ultra low GWP refrigerants suitable for mobile air conditioning equipment whilst maintaining efficiencies. Development and validation of ultra low GWP refrigerants suitable for transport refrigeration equipment whilst maintaining efficiencies. Component and cycle efficiency improvements	High efficiency low GWP VCCs deployed in mobile air conditioning equipment sector High efficiency low GWP VCCs deployed in transport refrigeration equipment sector	High efficiency low GWP VCCs deployed in mobile air conditioning equipment sector globally at mass scale High efficiency low GWP VCCs deployed in transport refrigeration equipment sector globally at mass scale
Vapour Compression Alternatives	Review of available technologies vs. incumbents to identify areas of promise or special need Selected technologies accelerated development and transition to production to fill gaps that cannot be filled by VCCin mobile cooling (e.g. because of lack of low GWP refrigerants) or that offer compelling efficiency improvements	Scale deployments of non-VCC technologies in target applications	Mass global deployment of non-VCC technology
Energy Storage Options	High thermal energy density materials research, demonstration and validation for transport refrigeration High thermal energy density materials research, demonstration and validation for mobile air conditioning	Energy storage materials deployed in multiple transport refrigeration markets Energy storage materials deployed in multiple mobile air conditioning markets	Energy storage materials deployed globally in many transport refrigeration markets Energy storage materials deployed globally in many mobiles air conditioning markets

Figure 19 - Mobile Cooling Equipment Technology Roadmap



Technology Stream	Short	Medium	Longer
System Design Tools and Approaches	Best practice maintenance of existing equipment Assessment of interaction between mobile cooling needs and wider cooling needs assessment and design tools (e.g. across cold chains) Development and validation of demand mitigation approaches (e.g. targeted cooling, improved vehicle thermal insulation performance etc.). Resolve final energy demand for mobile cooling.	Deployment of demand mitigation approaches at scale in most markets	Deployment of demand mitigation approaches at scale in all markets
Waste Resources	R&D into charging mobile cooling from waste resource access and cooling distribution networks. including LNG		
Vapour Compression Advances	Development and validation of ultra low GWP refrigerants suitable for mobile air conditioning equipment whilst maintaining efficiencies. Development and validation of ultra low GWP refrigerants suitable for transport refrigeration equipment whilst maintaining efficiencies. Component and cycle efficiency improvements	High efficiency low GWP VCCs deployed in mobile air conditioning equipment sector High efficiency low GWP VCCs deployed in transport refrigeration equipment sector	High efficiency low GWP VCCs deployed in mobile air conditioning equipment sector globally at mass scale High efficiency low GWP VCCs deployed in transport refrigeration equipment sector globally at mass scale
Vapour Compression Alternatives	Review of available technologies vs. incumbents to identify areas of promise or special need Selected technologies accelerated development and transition to production to fill gaps that cannot be filled by VCCin mobile cooling (e.g. because of lack of low GWP refrigerants) or that offer compelling efficiency improvements	Scale deployments of non-VCC technologies in target applications	Mass global deployment of non-VCC technology
Energy Storage Options	High thermal energy density materials research, demonstration and validation for transport refrigeration High thermal energy density materials research, demonstration and validation for mobile air conditioning	Energy storage materials deployed in multiple transport refrigeration markets Energy storage materials deployed in multiple mobile air conditioning markets	Energy storage materials deployed globally in many transport refrigeration markets Energy storage materials deployed globally in many mobiles air conditioning markets

Figure 20 - Industrial and Commercial Cooling Equipment Technology Roadmap



Technology Stream	Short	Medium	Longer
System Design Tools and Approaches	Best practice maintenance of existing equipment Assessment of interaction between mobile cooling needs and wider cooling needs assessment and design tools (e.g. across cold chains) Development and validation of demand mitigation approaches (e.g. targeted cooling, improved vehicle thermal insulation performance etc.). Resolve final energy demand for mobile cooling.	Deployment of demand mitigation approaches at scale in most markets	Deployment of demand mitigation approaches at scale in all markets
Waste Resources	R&D into charging mobile cooling from waste resource access and cooling distribution networks. including LNG		
Vapour Compression Advances	Development and validation of ultra low GWP refrigerants suitable for mobile air conditioning equipment whilst maintaining efficiencies. Development and validation of ultra low GWP refrigerants suitable for transport refrigeration equipment whilst maintaining efficiencies. Component and cycle efficiency improvements	High efficiency low GWP VCCs deployed in mobile air conditioning equipment sector High efficiency low GWP VCCs deployed in transport refrigeration equipment sector	High efficiency low GWP VCCs deployed in mobile air conditioning equipment sector globally at mass scale High efficiency low GWP VCCs deployed in transport refrigeration equipment sector globally at mass scale
Vapour Compression Alternatives	Review of available technologies vs. incumbents to identify areas of promise or special need Selected technologies accelerated development and transition to production to fill gaps that cannot be filled by VCCin mobile cooling (e.g. because of lack of low GWP refrigerants) or that offer compelling efficiency improvements	Scale deployments of non-VCC technologies in target applications	Mass global deployment of non-VCC technology
Energy Storage Options	High thermal energy density materials research, demonstration and validation for transport refrigeration High thermal energy density materials research, demonstration and validation for mobile air conditioning	Energy storage materials deployed in multiple transport refrigeration markets Energy storage materials deployed in multiple mobile air conditioning markets	Energy storage materials deployed globally in many transport refrigeration markets Energy storage materials deployed globally in many mobiles air conditioning markets

Figure 21 - Domestic Refrigeration Technology Roadmap

Appendix 8 – The 'packaging' of LNG

The global trade in liquefied natural gas (LNG) has increased significantly in recent years and is vital to the energy security of a growing number of countries. Yet a significant amount of the energy contained in the cryogen is simply thrown away. LNG is natural gas that has been refrigerated to -162°C to make it compact enough to transport by tanker, but this cold energy or 'coolth' is normally discarded during re-gasification at the import terminal.

At the last review, of the 111 LNG import terminals worldwide, only 23 do any form of cold recovery. Even here the use of the waste cold is usually limited to industrial plants close to the terminal, and only at times when LNG is actually being re-gasified, which in many cases occurs only intermittently. These factors limit the amount of cold that can be recycled.

A potential key to recycling more LNG waste cold to displace primary energy demand for cooling is, alongside co-located services, to separate the generation and consumption of cold in both time and place. If the waste cold could be converted into a 'vector' or form that is storable and transportable, the energy could then be consumed in 'distant' locations on demand, rather than tied to the location and regasification schedule of the LNG terminal. This should not only allow more of the waste cold to be recycled, but also put to the more valuable economic use.

One approach is to use liquid air (LAir) or liquid nitrogen (LiN) as such a vector. These cryogens are produced by the industrial gases industry refrigerating air to -196C, and pre-cooling the air with LNG waste cold could reduce the electricity required by up to 70% and production costs by up to half. Recycling waste cold in this way would produce cheap, low carbon, zero-emission cryogenic 'fuel' to provide distributed cold and power for vehicles and buildings.

Technologies are already being developed that could exploit large amounts of LNG waste cold as LAir. The Dearman engine, for example, runs on liquid air / liquid nitrogen delivering distributed cold and power to vehicles and buildings through a range of applications. Ricardo working with Brighton University is developing a split cycle diesel – liquid nitrogen engine. A consortium of European Universities, including London South Bank and University of Birmingham is developing Cryogenic Energy Storage at refrigerated warehouses (the Cryohub project) to integrate services across the built environment and transport.

Using a system-level approach to create a comprehensive and intelligently integrated portfolio of solutions to meet the full breadth of thermal services technologies, LNG waste cold in developed economies could be integrated to provide cooling that is both cheaper and zero-emission in many applications across food and pharmaceutical cold chains and the built environment.

High level analysis shows that this model could generate revenues both from sales of LAIR by producers and savings for the vehicle operator worth a combined £30 per ton of LNG and a project IRR of 26% in some markets. This figure does not include the value of the *social* benefits of liquid air transport refrigeration from reduced emissions of CO2, NOx (nitrogen oxides) and PM (particulate matter), which research suggests equate to a further £11 per ton of LNG recycled.

Harnessing Waste Cold of LNG

The cold of LNG can be considered the packaging in which natural gas is transported. When natural gas is cooled to -162°C it liquefies and shrinks 600-fold in volume, making it economic to transport by super-tanker to a customer on the other side of the world. On arrival, the LNG must be re-gasified before entering the natural gas pipeline, at which point the cold in which it was 'packaged' is usually discarded. The heat needed to make the LNG boil and re-gasify is provided through a heat exchanger typically warmed by sea water or by burning some of the gas. In either case, vast amounts of cold are lost to the environment. During re-gasification, each ton of LNG releases up to 240kWh of 'coolth' or cold energy,[80] which is quite separate from the chemical energy contained in its molecules. In the EU, there is a waste cold availability of 858 MWh of cold to sell to large cold consumers per year; however, today it is being lost with a negligible economic profit.

Traditional approaches

There is nothing new about recycling waste cold from LNG re-gasification, but it remains constrained.

---

[80] *LNG cold energy supply for CO2 reduction and energy conservation in Mitsui Chemicals ethylene plant*, Yukio Fujiwara, Osaka Gas Co, International Gas Union Research Conference 2011, http://members.igu.org/old/IGU%20Events/igrc/igrc2011/igrc-2011-proceedings-and-presentations/poster%20paper-session%201/P1-25_Yukio%20Fujiwara.pdf

Of 111 LNG import terminals worldwide, only 23 practice any form of cold recovery, and it has always been restricted to industrial uses close to the terminal. LNG cold recovery has been pioneered over the past thirty years by Osaka Gas at three import terminals in Japan, to supply cooling to industrial processes including air separation, ethylene production, carbon dioxide liquefaction, cryogenic power generation, and gas turbine air inlet cooling. All of these processes save energy and operating cost by making use of LNG waste cold, and at one of the terminals Osaka Gas has managed to create a system that re-gasifies all its LNG without wasting any coolth to sea water. However, even this may not represent the best possible use of LNG waste cold.

In Europe there is only a small pilot plant aiming to demonstrate its potential in Huelva, Spain. Further, large cold consumers need to produce the cold they need by means of costly and polluting systems.

The approach taken in Osaka suffers a number of drawbacks because cold is delivered to ‘over the fence’ customers in the petrochemical hub nearby, and the timing of re-gasification is determined by the needs of the gas grid rather than those of the cooling loads. These factors limit the use of the waste cold to the immediate vicinity of the LNG terminal; restrict customers’ use of waste cold to periods when the LNG is actually being re-gasified, which may be intermittent; and also potentially restricts the amount of cold that can be used in the most efficient way.

Given the limited use of cold recovery among the 111 LNG import terminals worldwide, it seems reasonable to conclude either that there is insufficient local demand for waste cold in many locations, or that the business case is not compelling. All the constraints of the Osaka approach could be solved if liquid nitrogen were viewed not as an industrial gas but a zero-emission ‘cold and power’ energy vector - a means of moving both cold and power in time and place.

New approach

The phase change expansion of liquid nitrogen (LIN) or Liquid Air (LAir) can be used to drive a turbine or a piston engine, while simultaneously giving off large amounts of cold, and the main potential applications are in zero emission cold and power, electricity storage, back to base transport propulsion and the recovery of waste heat. Several technologies are now being developed to run on LIN or LAIR, which would liberate LNG waste cold from its geographic and temporal constraints. The problem in future may not be drumming up sufficient demand for LNG waste cold but deciding how to allocate existing supply between competing sources of demand.

The Dearman cryogenic expansion engine, for example, runs on liquid air / liquid nitrogen delivering distributed cold and power to vehicles and buildings through a range of applications. The first application of the Dearman engine, a zero-emission transport refrigeration unit (TRU) to displace the highly polluting secondary diesel engines used on trucks and trailers today, is now in commercial trials with Marks and Spencer and Sainsbury’s in the UK and Unilever in mainland Europe. Using this example, the projected global trade of 500mtpa LNG in 2025 could produce enough liquid air to cool almost 4 million fleet-average refrigerated trucks – equal to the entire global TRU fleet today.

Another use would-be air-conditioning system for electric buses (eBuses), a mobile blast chiller to reduce post-harvest food losses and a back-up electricity and cooling generator for data centers and food distribution centers.

Ricardo working with Brighton University is developing a split cycle diesel–liquid nitrogen engine, while other technologies could include Blueeze, a commercially available LiN evaporation-only transport refrigeration system, or earlier stage technologies such as Epicam’s cryogenic expansion engine (<TRL4).

Another company, Highview, has also developed and is demonstrating at MW-scale a large-scale electricity-to-electricity energy storage solution using liquid air (Liquid Air Energy Storage); this again can harness the waste cold of LNG regasification. As a large-scale electricity storage technology, LAES would seem to have distinct operational advantages over batteries, compressed air and pumped hydro and is likely to be among the lowest cost large scale electricity storage solutions.

The Cryo-Hub is a pan-European project with €7 million in EU funding to explore the potential efficiency gains that might be achieved by integrating LAES with existing cooling and heating equipment found in refrigerated warehouses and food processing plants.

Waste cold for district cooling: Heriot-Watt University is undertaking a study with UTP and Petronas on harnessing waste cold of LNG for district cooling.

Appendix 9 - World-First Cold Storage Road/Rail Container

University of Birmingham researchers have worked with one of China's biggest railway rolling stock companies to develop the world's first shipping container using materials that store and release cold energy.

Using phase change material (PCM), Birmingham scientists and their counterparts at CRRC Shijiazhuang have developed a 'refrigerated' truck-to-train container that is easier and more efficient to operate than conventional equipment.

Once 'charged', PCM inside the container - which can be transferred from train to truck and vice versa - can keep the inside temperature between 5-12 ˚C for up to 120 hours. The technology has recently completed commercial trials carrying real goods for 35,000 kilometers of road and 1000 kilometers of rail transport across different climate zones.

Work on the project began in October 2017 with Birmingham researchers developing PCM materials and fabrication techniques, cold storage device design and testing, cold charging method and design.

CRRC was the project sponsor and their work included manufacturing and installing of cold storage devices into the container, data-logging and IT, real application demonstration and testing.

Two standard containers were used for trials with a range of goods including vegetables, flowers, and fruits. Researchers used organic-based composite PCM which was reformulated for enhanced thermal properties and charged using a fast-acting mobile device.

The container does not need a power supply during its journey making transfer between road and rail easier. The container's location and temperature can also be monitored in real time using mobile communication technologies.

Appendix 10 – Technology Links

Ice Energy - https://www.ice-energy.com/

Sure Chill - http://www.surechill.com/

Sky Cooling - http://skycoolsystems.com/

Dearman - https://dearman.co.uk/

District Cooling in India - https://www.utilities-me.com/news/12412-tabreed-signs-first-district-cooling-concession-in-india

Radiant Cooling - https://www.todayonline.com/singapore/cold-tube-beat-heat-humid-singapore-without-aircon