Centre for Sustainable Cooling

A COOL WORLD
DEFINING THE ENERGY CONUNDRUM OF COOLING FOR ALL

UNIVERSITY OF BIRMINGHAM | THE INSTITUTE FOR GLOBAL INNOVATION

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About The Centre for Sustainable Cooling

The Centre for Sustainable Cooling (CSC) is a global collaborative coalition, bringing together a consortium of international academic institutions from the fundamental sciences and engineering through to business, economics and social sciences to work with governments, industry, development agencies and NGOs to deliver sustainable and equitable cooling for all. The CSC will develop new systems approaches integrating technological, policy, social, economic, energy, finance and business pathways to better manage cooling demand and deliver sustainable solutions, including to help the most vulnerable in our society. By sharing experiences and expertise, the CSC will lead the way in radically reshaping cooling provision – translating research into practical, affordable solutions applications whilst helping to develop innovative policy and business process that result in a cooler world. A focus for the CSC will be to develop the right mix of novel energy solutions, thermal storage, cooling technologies, business models and policy interventions to give people who need to use sustainable cooling an opportunity to maximise their business whilst helping to limit global warming.

Institute for Global Innovation – University of Birmingham

The Institute for Global Innovation (IGI) aims to inspire, support and deliver world-leading, multi- and inter-disciplinary that seeks to address some of the world's most pressing challenges, affecting humanity at a global level. Their research themes revolve around the factors that challenge, and sometimes threaten, the sustainability and resilience of individuals, communities, societies and countries. These themes include resilient cities, water challenges in a changing world, clean cooling, pollution solutions, antimicrobial resistance, ageing and frailty, gender inequality and artificial intelligence. Their scholars seek, not only to understand these problems, but develop and implement innovative and often disruptive solutions, made possible by their holistic inter-disciplinary approaches.

Flexible Power Systems

Led by Michael Ayres, Flexible Power Systems is a group of cleantech entrepreneurs with experience of power, transport, energy storage and thermal technologies. They apply technology and systems thinking to industrial energy challenges to achieve sustainability and operational goals in the most cost-effective way possible.

EXTERNAL REVIEW

With our sincere thanks to Professor Kostadin Fikiin, R&D Project Manager, Technical University of Sofia (Bulgaria); Academician, International Academy of Refrigeration; Executive Committee, International Institute of Refrigeration (IIR); Past Vice-President of IIR Commission D1 'Refrigerated Storage'; Chairman, EHEDG Working Group 'Food Refrigeration Equipment'; Academic Mirror Group, coolingEU; European Technology Platform 'Renewable Heating and Cooling'; Dr Tim Fox, Royal Academy of Engineering Visiting Professor in Clean Energy and Public Engagement at Exeter University, and Chair, IMechE Process Industries Division Board, and Katharina Arndt, GIZ Proklima.

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Centre for Sustainable Cooling

FOREWORD

The United Nations' (UN) Sustainable Development Goals laid down a new challenge – economic and social development and the environment must live together; you can no longer have one at the expense of the other. Rather, our aim has to be a world where everyone can live well and within the sustainable limits of our planet; cold sits at the nexus of this challenge.

Effective cooling is essential to preserve food and medicine. It underpins industry and economic growth, is key to sustainable urbanisation as well as providing a ladder out of rural poverty. With significant areas of the world projected to experience temperature rises that place them beyond those which humans can survive, cooling will increasingly make much of the world bearable – or even safe – to live in.

Yet the growth of artificial cooling will create massive demand for energy and, unless we can reduce our need for cooling and roll out solutions for clean and sustainable cooling provision, this will cause high levels of CO_2 and pollution. The world must not solve a social crisis by creating an environmental catastrophe; we need to ensure access to affordable Cooling for All (C4A) with minimum environmental impact and maximum efficient use of natural and waste resources.

We are seeing the development of more efficient cooling technologies. However, as our analysis shows, while essential, these alone will not be enough to achieve sustainable Cooling for All in the face of booming global demand.

We need to explore new outcome and needs-driven, integrated, system-level approaches that re-imagine the way we use and deliver cooling. In so doing we need to understand the portfolio of cooling needs, the size and location of the multiple thermal, waste and 'wrong-time' energy resources available. We then need to identify the novel energy vectors, thermal stores and cooling technologies appropriate for the societal, climate and infrastructure context. In short, what we call the Cold Economy: transitioning from technology to system.

Meeting the challenge will also need the policies, social, business and financial models and skills that will enable new fit-for-market approaches to be adopted. To ensure impact, lasting legacy and scalability, sustainable solutions must deliver socio-economic development and unlock growth; must be attractive politically, socially and financially, and the technologies must underpin investor confidence that they are reliable and economically sustainable. We must also consider the unintended consequences; other parts of the socio-economic and environmental systems will likely shift as a consequence of cooling – we need as best as possible to plan for and mitigate both anticipated and currently unforeseen negative impacts as they emerge.

Cooling is finally coming in from the cold. After many years on the side lines of the energy debate, the importance of cooling to modern ways of living for all, but also the damage it causes to the environment and our health, is being recognised. And so it should be sustainable, affordable artificial cooling with minimal global warming or environmental impact is nothing less than critical to societal, environmental and economic sustainability worldwide.

As we look to our energy strategies post fossil-fuels, both built environment and transport, we have a once-in-a-lifetime opportunity to build resilient, future proofed solutions. The challenge now is how to embed a system-led approach to our cooling demands, better harnessing a portfolio of energy resources and adopting efficient clean novel technologies quickly enough to avoid locking-in cooling energy demands and emissions for years or decades. In order to achieve this, we need to think thermally. Stop asking ourselves 'how much electricity do we need to generate?' and start asking 'what is the service we require, and how can we provide it in the most energy resourceful and least damaging way?'.

Professor Toby Peters
Professor in Cold Economy
Fellow of the Institute for Global Innovation

The Cold Economy – 'thinking thermally'

The Cold Economy is the development of cohesive and integrated needs-driven, system-level strategies to meet Cooling for All sustainably, while supporting safe and healthy living and economic growth. This involves understanding the multiple cooling needs, and the size and location of the free, waste and wrong-time energy resources and defining the right mix of novel energy vectors, thermal stores, efficient, clean cooling technologies as well as the novel business models and policy interventions to optimally integrate those resources through self-organising systems.

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	TECHNOLOGY IMPROVEMENTS

There is not currently a comprehensive understanding of the size of the future global cooling demand, let alone its implications on energy systems as we transition to renewables. This piece of work sets out to provide, for the first time, an initial indication of the scale of the energy implications of Cooling for All. It does not deliver the detailed intervention strategies, nor granular, market by market bottom-up numbers; it does though provide an evidence-based indication of the size of the challenge and a framework and steps for more detailed analysis and an intervention roadmap.

While we have recognised sources for our data (GCI, IEA, IIR etc), for a Cooling for All scenario, we have necessarily had to make several assumptions and projections - and account for regional variances to the extent possible. Although ultimately the actual detail of the numbers in a Cooling for All scenario (penetration levels, energy consumption, solution choices, etc) might have some statistical dispersion, given the quantum of the gap between current demand projections and those including Cooling for All, the conclusions are, however, highly likely to be correct.

INTRODUCTION

With global populations increasing, rapid changes in demographics, expanding urbanisation and climate change impacts leading to more frequent heatwaves and seasonal temperatures rises, there is no question that we will demand far more cooling in the decades ahead. Forecasts suggest that the Asia-Pacific middle class will nearly triple by 2030 to more than 3 billion people, i.e. one-third of the global total population[1]. Their increased affluence, changing lifestyles and aspirations will require ever more cooling: air conditioning for comfort; cold chains to support food preference changes and better medical care; and data centre cooling for the digital economy.

By 2050, according to the Green Cooling Initiative (GCI), led by GIZ Proklima, there could be more than 9.5 billion cooling appliances worldwide – more than 2.5 times today's ~3.6 billion. Cooling is however energy intensive. We are seeing the development of more efficient cooling technologies. But even allowing for these and other more aggressive energy mitigation strategies, the cooling sector will, on current trajectory, increase its overall energy consumption[2] by 90% by 2050 to ~7,500TWh annually compared with 2018 levels (3,900TWh); and potentially 9,500TWh if we do not achieve the aggressive energy efficiency improvements[3].

This however is only half the picture

Under these projections much of the world would still only have low penetration levels of cooling: both air conditioning and refrigeration and cold chain. We will still have high levels of food loss; a significant percentage of the world's population in the hottest regions of the world without space cooling, and medicines and vaccines spoiled in the supply chain.

If we are to deliver on the UN's Sustainable Development Goals societal, health and economic targets, Cooling for All will be essential. But what should Cooling for All look like and what would it mean for our renewable energy systems and overall climate change mitigation targets? Can we solve both the challenge of ensuring equitable access to cooling for all humans and mitigate its future, as well as current – and already significant - energy and environmental impacts without radical intervention?

As a first step towards answering this question, we need to better understand the size of the problem. In order to meet our Carbon budget targets for the IEA 2°C Scenario (2DS)[4], we need to know the carbon and energy budget available to work within whilst delivering universal access to cooling. We equally need to understand what we mean by Cooling for All and determine its energy costs.

Based on these circumstances and on current refrigerant phase down via the Kigali Amendment and current technology efficiency projections, what could be the size of the gap between the energy requirements (and emissions) of achieving Cooling for All and the budgets implied by the IEA 2DS.

In short, can we meet the challenge with current cooling technologies, energy efficiency and new renewable energy generation capacity; or do we need a new approach?

[1] www.brookings.edu/wp-content/uploads/2017/02/global_20170228_global-middle-class.pdf
[2] By 2050, global energy consumption from all cooling sectors is predicted to reach 9,500 TWhs annually under the GCI demand forecast (current tech progress); and 7,500 TWhs annually under the GCI demand forecast (accelerated tech progress). See Section 1 for demand forecast descriptions.
[3] TWh – terawatt hours, i.e. 1,000 gigawatts hours or 1 trillion watt hours.
[4] The 2°C Scenario (2DS) is the main focus of IEA's Energy Technology Perspectives which lays out an energy system deployment pathway and an emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C. The 2°C Scenario (2DS) limits the total remaining cumulative energy-related CO_2 emissions between 2015 and 2100 to 1 000 $GTCO_2$; it reduces CO_2 emissions (including emissions from fuel combustion and process and feedstock emissions in industry) by almost 60% by 2050 (compared with 2013).

SUMMARY FINDINGS

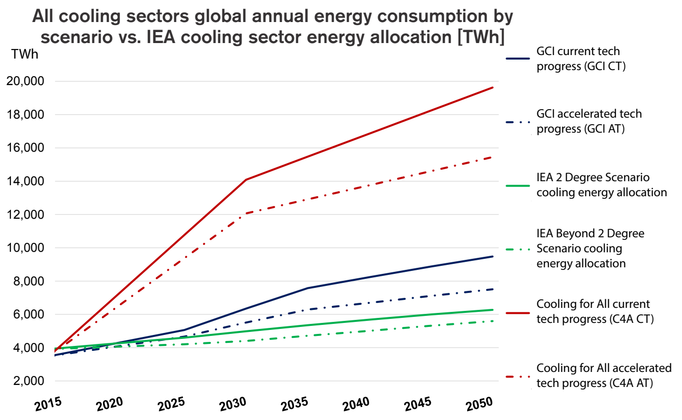


Figure 1

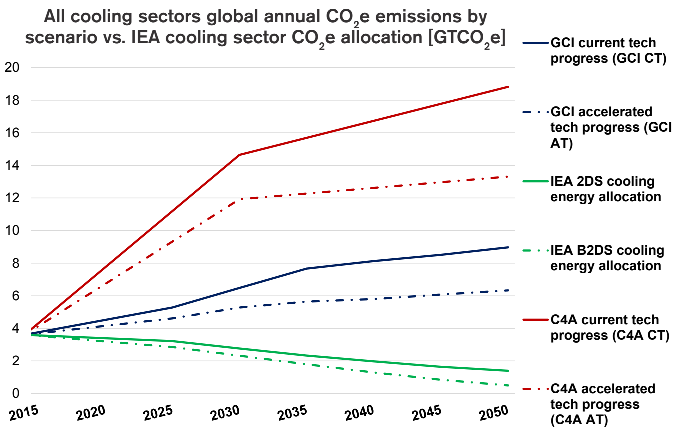


Figure 2

Figures 1 and 2 - Cooling for All Energy Consumption and CO_2e emissions

Figure 1 shows the energy consumption for all cooling sectors for two difference scenarios (GCI's demand forecast and our Cooling for All forecast) allowing for both current technology progress (solid line) and accelerated technology progress (dotted line) versus IEA cooling sector energy allocation (2 Degree Scenario and Beyond 2 Degree Scenario). Figure 2 shows the CO_2 emissions versus IEA cooling sector scenario, using current generation mix. This gap needs to be mitigated either by a reduction in energy demand or renewable energy sources.

- Total (CO_2e) emissions from the cooling sectors amount to approx. 4GT[5] of CO_2e emissions in 2018 – equivalent to 11.8% of the world's direct CO_2 emissions from the power and industrial sectors in the IEA Reference Scenario.

- According to United Nations Environment Programme (UNEP), more than 80% of the global impact of RACHP (Refrigeration, Air Conditioning and Heat Pumps) systems is associated with the indirect emissions of electricity generation to drive the cooling appliances (UNEP TEAP, 2017a).

- Green Cooling Initiative (GCI) projections show rapid growth in the amount of cooling equipment deployed globally, growing from 3.6bn pieces of equipment to 9.5bn by 2050.

- This has significant implications for energy consumption from the sector which will grow under the GCI demand forecast (current technology progress) to 9,500 TWh by 2050. This will exceed the IEA's implied "energy budget" for cooling in its 2°C Scenario (2DS) by more than 50% (6,300 TWh).

- If an aggressive range of technology and operational efficiency improvements can be implemented (GCI demand forecast – accelerated technology progress), then an additional 21% reduction in total sector energy consumption could be achieved by 2050 over and above the current technology improvement trajectory (GCI demand forecast – current technology progress). However, this would still leave consumption from the sector above the IEA 2DS implied energy budget for cooling (see Figures 1 and 2).

- However, Green Cooling Initiative (GCI) projections of cooling equipment uptake also still result in large portions of the world not having access to space cooling, refrigeration or cold chain even in 2050.

- As an indication of the impact of widespread global access to cooling – Cooling for All, a hypothetical scenario is developed whereby refrigeration equipment penetrations globally converge by 2050 with those experienced in the developed world today (USA as the proxy), and air conditioning is made available to all populations experiencing more than 2000 Cooling Degree Days per year[6]. Without action beyond current technology progress equipment efficiency gains, cooling related energy consumption could result in 19,600 TWh of energy consumption per year (Cooling for All demand forecast – current tech progress[7]).

- Even with the accelerated technology progress projections delivering more aggressive energy performance improvements, the energy requirement still equates to 15,500 TWh which is 2.46 times the 6,300 TWh maximum sector allocation envisaged by the IEA 2DS (Figure 1).

- To achieve the required amount of cooling with the energy available requires us to double the efficiency of our cooling devices on average, in addition to the technology progress proposed currently.

- Alternatively to "green" this volume of electricity would consume more than 50% of the projected total renewables capacity under the IEA 2°C Scenario and 80% of the IEA Reference Technology Scenario projected renewables capacity[8] by 2050. This increases to 101% in the event we do not achieve accelerated technology progress.

- The Kigali amendment to the Montreal Protocol is crucial to reduce the sector's environmental footprint, but if we are to plan for a Cooling for All goal, further accelerating the uptake of very low-GWP[9] and natural refrigerants may be necessary in order to meet the Kigali objectives.

[5] GT – GigaTonnes (1 billion tonnes).
[6] A cooling degree day (CDD) expresses the demand for cooling a building. It is the number of degrees that a day's average temperature is above 21° C in this instance multiplied by the number of days per year. China experiences 2,030 cooling-degree days per year, whereas the United Kingdom experiences 135. The UAE experiences over 10,000 cooling degree-days per year.
[7] See demand forecast descriptions in Section 1.
[8] Total renewables capacity reaches 19,359 TWh/year by 2050 in this scenario. Renewables in this analysis are considered as the combination of all biomass, hydro (excl. pumped storage), geothermal, wind (on- and off-shore), solar (PV and CSP) and ocean.
[9] Global Warming Potential.

KEY CONCLUSIONS

- Access to cooling is essential for meeting our social and economic goals but equally unmanaged growth in cooling represents one of the largest end user threats to achieving our climate goals for CO_2 emissions.

- While the Kigali Amendment to the Montreal Protocol has established a clear programme for the phase down of the production and use of high GWP refrigerants, we need a step change reduction in primary energy consumption for cooling.

- There is not a comprehensive (all sectors – buildings, food, health, transport, data, industry and commercial) understanding of the size of the cooling demand either today or in the future, nor of the implications this has on energy systems /new build electricity generation requirements and the environment (climate change and pollution). There is therefore also currently no cohesive and integrated strategy to either mitigate or meet cooling needs in the most efficient, economically and environmentally sustainable and resilient way, while sustaining economic growth and taking into account differing cooling needs in different regions of the world.

- If cooling provision is to be sustainable, we need not only more efficient air-conditioners and fridges, but also a fundamental overhaul of the way cooling is provided. What is required is a new needs-driven, system-level approach, first to mitigate demand and second to understand (i) the multiple cooling needs, (ii) the size and location of the thermal, waste and wrong-time energy resources and (iii) define the right mix of the novel energy vectors, thermal stores, and efficient technologies to integrate those resources with service needs optimally.

- Such a complex approach necessitates the integrated development of devices, systems and the skilled people for deployment in key market sector environments. It equally may require new value and business models, as well as end user engagement.

- We are currently profligate with cooling. The start point for intervention is to understand the real needs for cooling, to help facilitate the introduction of socio-technical systems that are fit for purpose.

- Bridging the critical gap in the clean cold innovation landscape requires
  - Needs assessment taking into account region and country specific requirements and financing opportunities;
  - Bringing together technology and system innovations into a cross-sector systems approach;
  - Creating the necessary results-driven economic and impact models;
  - The right policy and financing environments;
  - Developing the skills and workforce to design, install and maintain appliances;
  - Bringing the key intervention delivery partners into a joined-up strategy.

- It is important to recognise that introducing more affordable and readily available means of cooling is not just a matter of adding cooling to the status quo; it is about introducing a major shift to dynamic socio-technical systems. In response, other parts of the system will react and adapt as a consequence, with varying degrees of predictability. We need to identify potential unintended negative social, ecological or economic consequences and engage to mitigate these as initiatives and deployments take place.

We urgently need access to clean cooling[10] for all. In order to achieve this, we need to stop asking ourselves 'how much electricity do we need to generate?' and start asking 'what is the service we require, and how can we provide it in the least damaging way? '.

[10] Clean cooling: Meeting our cooling needs efficiently and sustainably within our climate change, natural resource and clean air targets. Clean cooling necessarily must be affordable and accessible to all to deliver the societal, economic and health goals. It likely starts with mitigating demand.

RECOMMENDATIONS

Based on the analysis

(i) Current energy projections do not consider a Cooling for All scenario and therefore either we meet the UN SDGs or the Paris Climate Targets but not both.

(ii) If we are to meet both the UN SDGs and the Paris Climate Targets, relying on technology efficiency and greening electricity is not sufficient on its own.

(iii) Solutions – climate, policy, social, economics, culture, rural or urban, as well as the localised energy resources - need to be "fit for market", not one size fits all.

Recommendations :

1. Awareness - meeting cooling demand sustainably and affordably creates a direct intersect between three internationally agreed goals for the first time: the Paris Agreement; the Sustainable Development Goals; and the Montreal Protocol's Kigali Amendment. Yet cooling until recently has not been on the agenda and there is still limited recognition of the critical role of access to clean cooling in our energy strategies.

2. More accurately defining cooling needs and targets to meet the Sustainable Development Goals – this consists of updating estimates of demand in a regional context and needs-driven way that does not pre-suppose equipment or technology choices. Furthermore, the same should be used to set specific goals for sustainably reducing the gap by country, sector and timeline[11].

3. A quantitative intervention roadmap and toolkit – this should identify the scope for technical and operational improvements and then the step-change system interventions that are likely to be required (through a ladder of opportunities) as well as the commercial, policy, education/skills and research actions needed to deliver these. In addition to providing a guide to the course of action to be taken, the roadmap, combined with the Cooling Services Model can also be used as a framework to test the implications of action or inaction in certain areas.

4. Cold Community Networks – design of the integrated system level (built environment, logistics and transport) approach to cooling - multi-sector, multi-technology, multi-energy source integrated solutions to cooling provision to deliver – and balance - maximum economic, environmental and societal impact.

5. Cooling Services Methodology and Model - delivery of secure, affordable low-carbon, low-pollution optimised integrated cooling to many thousands of rural and urban communities is not about one size fits all. It requires the ability to make system design and technology choices based on the cooling and service demands and energy needs of the local requirements, as well as an understanding of the specific existing, free, waste and natural energy resources, and the local economic context, cultures, working practices, etc. Comprehensive clean cooling methodologies and models are required so that communities can design 'fit for market' - including 'fit for energy source' - and 'fit for finance' cooling through simulation before capital intensive investment in on-the-ground deployment. This will enable communities to optimise the system for their cooling needs including consider resource pooling and broader energy service, and assess the economic, societal and environmental impact. In so doing, it can support investment and financing proposals.

6. Living Labs – an ecosystem for trialling and developing strategy, revenue and financing and technology mixes at scale and demonstrating impact, providing a launch-pad for accelerated deployment. Living Labs would test and demonstrate not only technologies but also the mitigation, business, governance and funding models. They can provide a network of centres for dissemination and training. They will also explore the indirect and potential consequences – positive and negative.

The UN has set a target of achieving the Sustainable Development Goals by 2030; i.e. we have 12 years to deliver clean and affordable cooling to all. Given the urgency of the challenge and the multi-partner and multi-disciplinary research and delivery mechanisms required, we urge the establishment of a multi-disciplinary Centre of Excellence for Clean Cooling (CEfCC) to lead this work by bringing together the global expertise to research and develop the step-change pathways (culture and social, technology, policy, business models, financing) for achieving (i) cheapest cost (whole of life), (ii) greatest energy system resilience and (iii) lowest carbon emissions while (iv) meeting social and economic cooling needs.

[11] GIZ Proklima has already started this process in various partner countries via their cooling sector inventories.

WHAT NEEDS TO HAPPEN TO DELIVER COOLING FOR ALL SUSTAINABLY?

Roadmap	Delivery	Accelerate
All-stakeholder Engagement Engage and drive collaboration across the main stakeholder groups (policy, customers, industry, developers and financiers).	**Fund Innovation Development** Connect research institutes, OEMs, VCs, policy makers and customers to collaborate on the delivery of high impact innovation.	**Policies to Unlock Finance** Create the market environment (policies and business models) to attract infrastructure investment to deliver Cooling for All.
Systems Level Analysis Assess Cooling for All at the systems level - size of the challenge and alternative technologies, energy sources, business models and cross-industry resource efficiency sharing mechanisms.	**Prove** Eliminate the performance risk and demonstrate impact through live market testing and validation in Living Labs.	**Skills** Identify the skills gap (design through to installation and maintenance) and connect educational institutes, OEMs, policy makers and customers to collaborate on the delivery of accelerated solutions.
Roadmap Create the Intervention roadmap (technology, policy, finance, etc) to deliver 70% reduction in electricity usage for cooling.	**Scale-Up** Design manufacturing processes and engage industry to scale novel technologies; ideally using a global science, local delivery model.	**Effective Knowledge Transfer** Use system level model, in-country living labs and manufacturing accelerator to roll out "fit for market" solutions across new geographies.
Unintended Consequences Identify, plan for and mitigate potential unintended consequences.		

COOLING AND THE UN 'SUSTAINABLE DEVELOPMENT GOALS'

The UN's Sustainable Development Goals laid down a new challenge; economic and social development and the environment must live together; you can no longer have one at the expense of the other. Rather our aim has to be a world where everyone can live well and within the sustainable limits of our planet.

Cold sits at the nexus of this challenge and in fact a report published by the University of Birmingham Energy Institute in January 2017 was the first to point out that achieving all 17 of the Global Goals would depend to a greater or lesser extent on developing clean cooling technologies[12] – and for many Goals, clean cold would be vital. But to date it has been largely ignored and as Sustainable Energy for All states: "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".

The need for cooling is universal but cooling means very different things to different groups of people.

In the developed world, it is about air-conditioned offices, hotel rooms and apartments; a fridge full of fresh food and convenience meals from all over the world; ice in our drinks. In Saudi Arabia, more than 70% of electricity is consumed for air conditioning and cooling[13]. The United States consumes more electricity for space cooling than the 1.1bn people in Africa for everything. In Europe more than 75% of our food goes through the cold chain at some point.

Subsistence farmers to informal urban (slum) dwellers equally have need for cooling but in very diverse and critical ways: extending the life of crops while trying to move them to market; ensuring access to basic vaccines; bearable or even just safe working and living environments.

Lack of access to cooling in many places has severe impacts

- In developing markets, up to 50% of food can be lost post-harvest[14].
  - More than 1 billion people continue to live in extreme poverty; more than 75% of them reside in rural areas, primarily dependent on agricultural production. We cannot address rural poverty without cold chains connecting farmers to market.
  - Equally 800M people globally are malnourished. Malnutrition is in fact the largest single contributor to disease in the world, according to the UN's Standing Committee on Nutrition. More children die each year from malnutrition than from AIDS, malaria and tuberculosis combined.
  - A 2015 World Health Organization report concluded that 600 million people – almost 1 in 10 worldwide – fall ill after eating contaminated food and 420,000 die every year.
- Cold chains and food security are not just about having enough nutritious food to avoid hunger. 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 centres of consumption. However, they must be able to get it there in the same condition as one imported by air-freight from a highly developed global agri-business and cold chain. What's more, the market connectivity afforded by a cold chain enables and incentivises farmers to raise their output because they will earn more from what they produce; whereas its absence means that any effort to increase yield will also cause higher wastage - so dousing the incentive.

Clean Cold Chain (Food)

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

The cold chain enhances economic wealth, cash flow and security for farmers and improves food quality, safety and value to the customer. We need to achieve this with minimum environmental impact – through a clean and efficient cold chain.

- The consequences are far beyond hunger, farmer poverty and inflated food prices. Post-harvest food loss occupies a land area almost twice the size of Australia, consumes 250km^3 of water per year, three times the volume of Lake Geneva; and emits 3.3 billion tonnes of CO_2, making it the third biggest emitter after the US and China.
- The World Health Organization estimates that nearly 25% of liquid vaccines are wasted each year primarily because of broken cold chains. An estimated 1.5 million people die each year from vaccine-preventable diseases.
- Heatwaves already kill an estimated 12,000 people annually across the world. The World Health Organization forecasts that by 2050, deaths from heat waves could reach 260,000 annually unless governments (primarily cities) adapt to the threat. One study suggests that if climate change is not checked, the Gulf will suffer heatwaves beyond the limit of human survival by 2070. The study shows that the hottest days of today would by then be a near-daily occurrence.[15]

Clean cooling provides the rare opportunity to achieve three internationally agreed goals simultaneously: the Paris Climate Agreement; the Sustainable Development Goals; and the Kigali Amendment. In this way we can ensure that:

1. Global access to sustainable, affordable and resilient cooling is achieved to
   - **underpin** health and **deliver** habitable, safe housing and work places;
   - **reduce** post-harvest food loss – thereby protecting food volumes and quality, as well as facilitating efficient movement from farm to consumption centre, so as to
     - -Enhance economic wealth and security for farmers;
     - -Achieve nutritional security and deliver safe food to the wider population;
     - -Improve resource efficiency.
   - **meet** essential demands for data (be it for health centres, weather apps or trading platforms for farmers, or rural education and day to day communications)
   - **reduce** inequality.

2. The massive growth in demand for cooling is managed within the constraints of natural resources and local economies, as well as underpining, *rather than undermining*
   - CO_2, Climate Change mitigation and pollution targets;
   - Energy efficiency and resilience *and*
   - Sustainable and affordable infrastructure.

[12] Clean Cold and the Global Goals: www.birmingham.ac.uk/Documents/college-eps/energy/Publications/Clean-Cold-and-the-Global-Goals.pdf
[13] www.tandfonline.com/doi/abs/10.1080/15567249.2016.1248874?journalCode=uesb20
[14] IMechE Global Food: Waste Not, Want Not. Institution of Mechanical Engineers; Westminster, London, UK: 2013.
[15] https://www.nature.com/articles/nclimate2833

SUSTAINABLE DEVELOPMENT GOAL	EXAMPLES OF IMPACT OF COOLING
1. No Poverty	Cold chains enhance incomes for fishermen and farmers through improved pricing for produce and reduced food waste. Cooling has significant new employment demand from direct jobs around manufacture and maintenance to meet the massive increase in appliances to indirect jobs such as in food processing and preservation.
2. Zero Hunger	It is estimated that 1.3 bn tonnes of food is lost or wasted each year; approx 1/3 of of total food produced for human consumption. Refrigeration enhances food security through extending shelf-life of produce so that less is wasted. In addition, reduced waste increases incomes in farming and fishing communities and leads to more stable food prices.
3. Good Health and Well being	Access to refrigeration and a robust medical cold chain leads to reduced vaccine and medicine spoilage. Access to refrigeration in the food cold chain reduces food waste and food poisoning. Air conditioning offers protection from temperature extremes.
4. Quality Education	Ability to work and thermal comfort are inter-related. Reducing the risk of malnutrition also positively impacts academic performance.
5. Gender Equality	Women make up almost half the agricultural workforce in Africa, and far more in some countries – around 70% in Kenya, Nigeria and Rwanda. If combined with policies to improve women farmers' access to finance and resources, clean cold chains could benefit women preferentially and help narrow the gender gap.
6. Clean Water and Sanitation	Prevented food spoilage saves substantial amounts of water.
7. Affordable and Clean Energy	Refrigeration and air conditioning are responsible for over 17% of the worldwide electricity consumption. Global air conditioning energy demand, driven overwhelmingly by cities in developing countries such as China, India, Indonesia, and Brazil, is forecast to rise 33-fold by 2100 to more than 10,000 TWh, roughly half the total electricity generated worldwide in 2010.
8. Decent Work and Economic Growth	Agriculture and fishing are very significant employers. Enhancing the efficiency of these industries by reducing waste, as well as increasing market connectivity will improve profitability. As an example, in India, the GOI has identified cold chains as a key pillar of doubling farmers' incomes. Productivity and thermal comfort are interrelated **and** by 2050, heat-related work-hour losses in some countries are projected to be as high as 12% — worth billions of US dollars — in the worst-effected regions.
9. Industry Innovation and Infrastructure	All forms of cooling will require substantial infrastructure investments to be delivered and considerable innovation is required to enhance efficiencies. With the industry projected to double in size, there is an opportunity to create new manufacturing opportunities including in-country.
10 Reduce Inequalities	Clean cold technologies reduce inequality both within and between countries. Looking at income inequality, clean cold chains reduce poverty by lowering food prices and raising farmers' income. Better nutrition and thermal comfort would improve the educational outcomes of the most disadvantaged in society. In terms of gender inequality, cold chains combined with support from policy will improve access of agricultural resources to female farmers which reduces the gender gap by providing female farmers with access higher value exports.
11. Sustainable Cities and Communities	Sustainable cooling and design for buildings and transport reduce energy demand and heat island effect. Food security in cities where very little farming land is available is critically dependent on a cold chain.
12. Responsible Consumption and Production	Food and vaccine loss are reduced through proper access to refrigeration and cold chains.
13. Climate Action	Cooling uses substantial quantities of energy and causes direct emissions from refrigerant leakage.
14. Life Below Water	Wastage of marine products before reaching market increases pressure on fish stocks.
15. Life on Land	Reducing food wastage eases the main driver of deforestation and land degradation.
16. Peace and Justice	Clean cold technologies indirectly help to maintain peace by suppressing potential sources of conflict, e.g. rising food prices (Arab Spring) and urban migration due to rural poverty.
17. Partnership for Goals	In most developing countries, cooling infrastructure is currently rudimentary or non-existent. There is a brief opportunity to create partnerships through which developing countries leapfrog direct to clean cold, thereby wmaking an important contribution to every one of the Global Goals.

METHODOLOGY

The study relies on combining existing data sets to explore access to cooling alongside the associated energy and carbon implications.

SOURCES OF DATA

Green Cooling Initiative Data Set

The first data set is that produced by Green Cooling Initiative (GCI) – a network of companies, non-governmental organisations, universities and governmental organisations. The data has been collected by GIZ under the Proklima programme on behalf of the German Federal Ministry for Economic Cooperation and Development and the German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety.

The data set is based on a combination of bottom up and inferred estimations of the current cooling equipment parc[16] in 193 countries across seven major equipment families. Projections are then established based on population, GDP growth, urbanization, climate mitigation and electricity access parameters that indicate a future scenario for equipment penetrations.

By assuming a number of representative equipment types within these sectors, estimates of direct and indirect impacts have been made:

- Direct impacts – based on estimated refrigerant charge and leakage rates and estimated emissions during manufacture and disposal of the equipment.
- Indirect impacts – based on energy consumed during use (a function of cooling energy demand, equipment performance and carbon intensity of fuel used).

The data set was developed in 2012 and updated in 2016 (up to 2050), and is still more expansive in terms of its attempt to cover the entire cooling sector than anything subsequently developed.

IEA Data Set

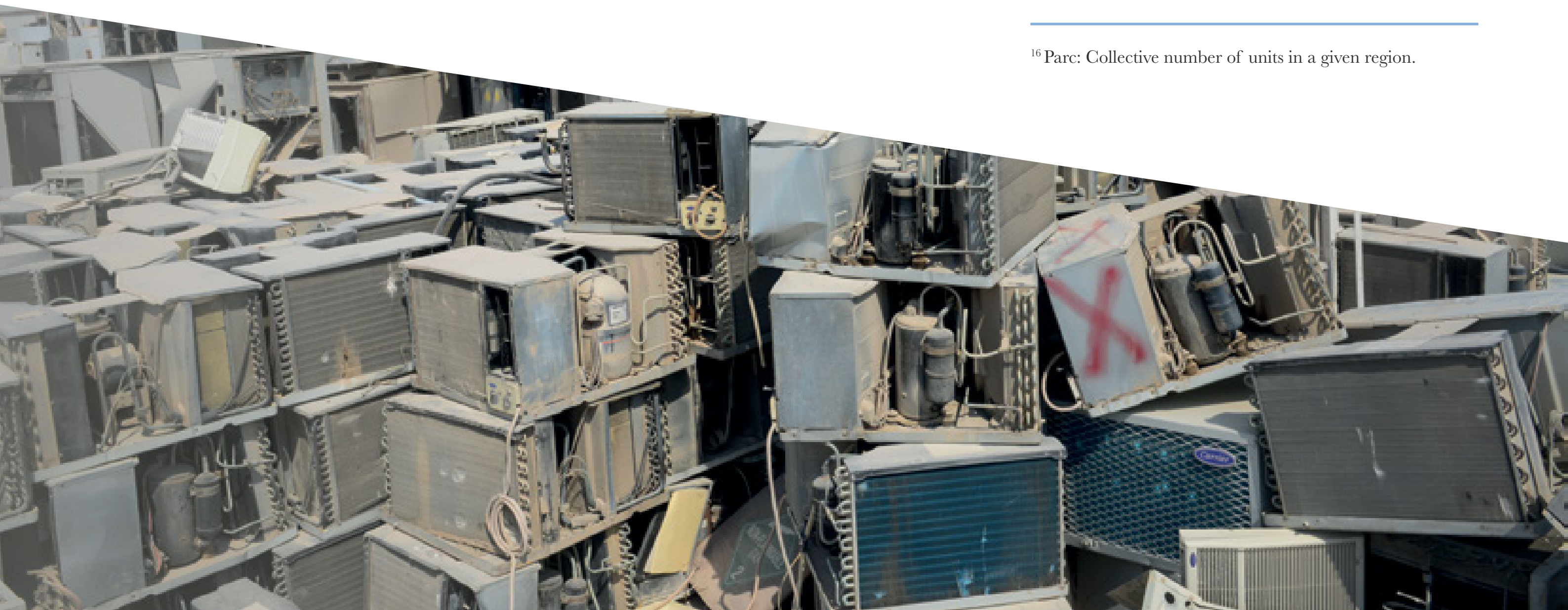
The IEA dataset is taken from the most recent Energy Technology Perspectives 2017 publication (ETP2017). The ETP modelling approach incorporates models of global energy demand across industry, buildings and transport. The demand models are based on a combination of economic, policy and process data that feeds in to sectoral sub-models that further breakdown demand.

Space cooling, transport and overall appliance energy consumption are modelled within the data; from these figures indicative cooling budgets can be implied. The energy supply part of the model incorporates fossil fuel, renewable and nuclear resources as well as energy conversion processes to meet the specific energy demands. Both supply and demand elements of the model are capable of incorporating varying production and consumption technology choices.

The annual ETP study utilises a scenario-based approach to show the current position and what would have to change to meet climate change mitigation targets. Three scenarios are modelled:

- **Reference Technology Scenario (RTS) –** is based on today's commitments to limit emissions and improve energy efficiency and then an extension of current trends. This already represents a substantial departure from business as usual (BAU) and requires further major shifts in policy and technology in the period to 2060. These efforts would result in an average increase of ~2.7°C by 2100 and an ongoing upwards trajectory.
- **2°C Scenario (2DS) –** is a back-cast pathway to a CO_2 trajectory with 50% chance of limiting temperature increase to 2°C by 2100 by using currently available technologies. As an indication of its ambition level, it requires a 70% decrease in emissions from energy production by 2060 and an ongoing pathway to carbon neutrality by 2100.
- **Beyond 2°C Scenario (B2DS) –** is intended as an indication of how far beyond 2°C available and in development technologies could take us. All improvements and deployment rates are pushed to maximum feasible limits to get the energy system to net zero by 2060 and then push it into negative emissions through Carbon Capture and Storage (CCS) and bioenergy measures beyond this point. This scenario gives a 50% chance of limiting average temperature increase to 1.75°C.

[16] Parc: Collective number of units in a given region.



Other data sets

IEA – The Future of Cooling

The International Energy Agency recently published a report focusing on the space cooling sector which describes the global space cooling markets for air-conditioners and chillers including fans and de-humidifiers. It estimates the global stock of air-conditioning appliances (both commercial and residential) to be 1.62 billion units by the end of 2016 – higher than the GCI stock of 840 million units at the same time. The IEA further expects the global stock to continue to grow rapidly to reach a total of approximately 5 billion units by 2050[17]. This is against 3.7 billion units in the GCI projections.

It is also worth noting that the difference in estimates is lower when it comes to total energy consumed by the space cooling sector – an estimated 2,000 TWh in 2016 for the IEA vs. 1,550 TWh in 2016 for GCI (a 22.5% difference compared to the IEA estimate). While the IEA expects space cooling energy consumption to grow to 6,200 TWh in 2050 (in the absence of efficiency measures), GCI predicts between 4,200 TWh (accelerated tech progress, see below) and 5,500 TWh (current tech progress) for the sector by 2050[18].

There are several reasons for the difference in GCI and IEA scenarios:

- They cover different sectors – GCI focuses on air conditioning 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; as a result, equipment deployment volumes differ between the two projections.
- GCI and IEA have different projections on the likely/feasible penetration of improved efficiency equipment for their respective mitigation scenarios; this impacts the expected energy consumption (and indirect emissions estimates).

However, neither the IEA nor the GCI figures attempt to capture universal access to cooling in their projections. Both models are based on GDP growth in effect determining affordability of accessing cooling equipment in combination with other measures like climate, electricity access and existing equipment stocks etc.

JRAIA – The Japan Refrigeration and Air-Conditioning Industry Association

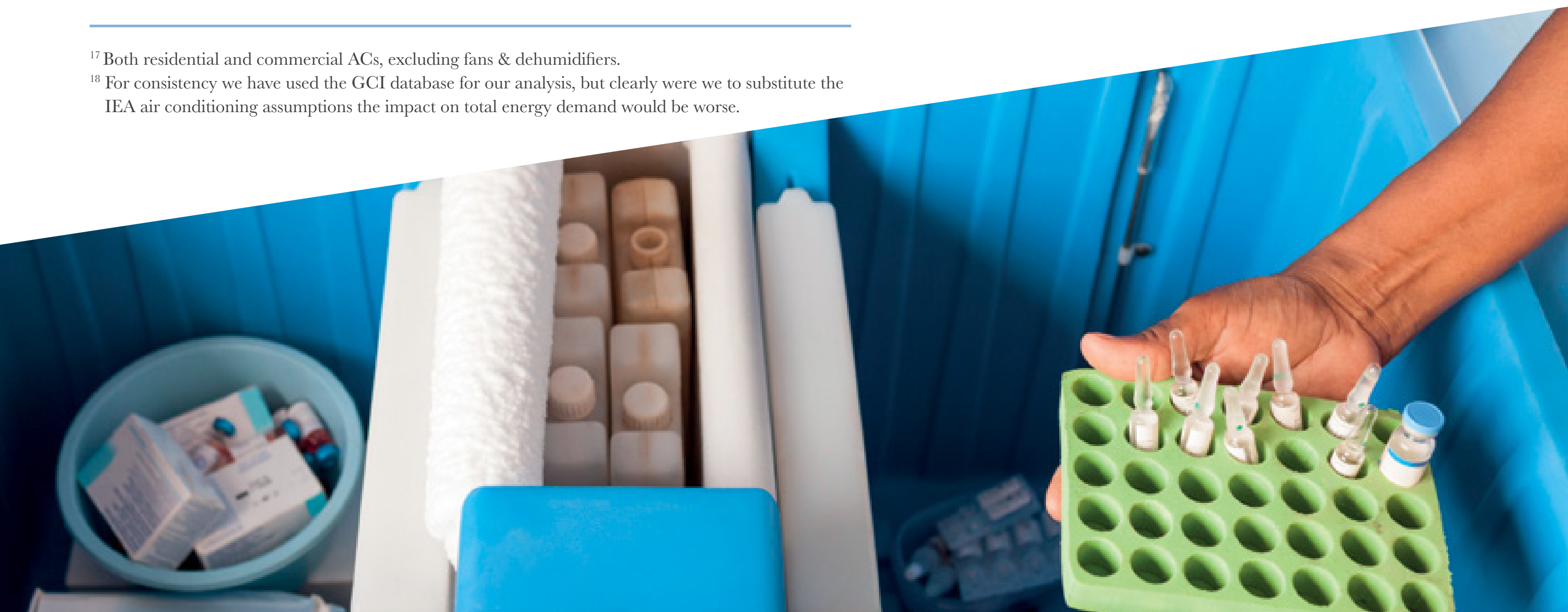
The JRAIA regularly collects and compiles market data based on market demand surveys reported by the member companies of the JRAIA's Air Conditioning Global Committee, and projects the estimated demand in each major market. In its April 2017 report on the World Air Conditioner Demand by Region it reports global sales of AC units across all sectors of 102 million units – compared to an estimated 89 million unit sales in the GCI database (an 11% difference).

JRAIA does not detail equipment stocks. Again, this is a case of global demand in 2018 outstripping the rate projected by GCI back in 2012.

Lawrence Berkeley National Laboratory

Following the Kigali amendment to the Montreal protocol, the "Opportunities for Simultaneous Efficiency Improvement and Refrigerant Transition in Air Conditioning" report aimed to provide an initial sense of the opportunities to improve efficiency and transition to low Global Warming Potential (GWP) refrigerants by reviewing the Hydrochlorofluorocarbons (HCFC) and Hydrofluorocarbons (HFC) regulatory framework and energy efficiency standards and labelling programs. The AC unit market data it builds upon originates from the JRAIA publications described above.

[17] Both residential and commercial ACs, excluding fans & dehumidifiers.
[18] For consistency we have used the GCI database for our analysis, but clearly were we to substitute the IEA air conditioning assumptions the impact on total energy demand would be worse.



HOW HAS THE DATA BEEN USED?

- The GCI data set has been used to provide a picture of cooling demand across all sectors and the technical assumptions in the work have been used here to develop scenario-based projections of emissions and energy consumption for:

  a) A scenario where technology innovation continues at the current pace and

  b) An ambitious scenario where technology progress at the device level is accelerated to deliver increased energy efficiency improvement steps via technology and maintenance enhancements alongside replacement of high GWP refrigerants with very low to zero GWP refrigerants.

- The IEA data has been used to provide an energy and carbon budget for cooling consistent with the 2°C Scenario (2DS) and the Beyond 2°C Scenario (B2DS) (i.e. a lower level of warming limited to 1.75°C) for comparison. From this we have:

  1. Calculated a Cooling Sector Energy Budget.

  2. Considered Cooling Energy Sector Demand for Cooling for All Scenario versus Cooling Sector Energy Budget.

1. A Cooling Sector Energy Budget

In order to put the cooling sector's dynamics in the context of the global energy sector's evolution, we have defined a cooling sector "energy budget". Because the space cooling sector is already a large consumer of energy and is expected to grow very rapidly over the coming decades (see below), the IEA already defines an energy trajectory specific to the space cooling sector in each of its scenarios. Knowing what share of final energy consumption cooling represents within the stationary refrigeration and mobile cooling sectors today, using the space cooling data points, we can also derive comparable trajectories (or "budgets") for these cooling sectors if we are to meet the IEA 2°C Scenario and the Beyond 2°C Scenario. By design these trajectories are built on the assumption that the share of cooling energy as a percentage of final energy consumption in these sectors must not increase for the budgets to be met[19]. This enables the definition of an "energy budget" for the cooling sector as a whole.

Today, stationary refrigeration equipment represents 22.5% of appliances' energy use within buildings on average whilst mobile AC and mobile refrigeration represents 3.3% of total transport energy demand[20].

With these assumptions and the IEA energy trajectories[21] from ETP2017, we estimate the total energy budget for cooling sectors to be

- By 2030 between 4,400 TWh/year (B2DS) and 5,000 TWh/year (2DS)

- By 2050 between 5,500 TWh/ year (B2DS) and 6,300 TWh/year (2DS)

2. Cooling Energy Sector Demand for Cooling for All Scenario versus Cooling Sector Energy Budget.

Initially, a simple comparison as to whether the IEA energy and carbon budget was sufficient to accommodate the projected growth in demand for cooling was undertaken. This was then extended in a number of ways to:

- Review implied equipment penetrations and then posit a Cooling for All scenario;

- Explore implications at a high-level of a Cooling for All scenario in terms of energy and carbon;

- Provide an indication of how large the improvements may need to be to deliver this outcome without exceeding the carbon and energy budgets;

- Explore the implications in terms of renewable energy demand for a business as usual and mitigation scenario;

- Review the impact of the Kigali Amendment to the Montreal Protocol on proposed levels of mitigation.

[19] It is understood that there are ways to meet our overall energy and carbon targets with sub-sector "budgets" whose relative share of energy use change over time – nonetheless this approach is likely representative of the level of change required in the cooling sector.

[20] Ratio of sector's energy consumption as per GCI data over broader sector energy use as per IEA ETP2017.

[21] See "IEA Dataset" above for definitions.

[22] The GCI energy consumption projections incorporate factors like technology improvements, penetration rates driven by policy and varying climatic conditions between global markets. We have used these as an input assumption to this analysis. To provide readers with an indication of improvement anticipated by GCI across the equipment park we have simply divided total energy consumption in each segment by the total number of devices in use to provide an indication of the direction of travel of energy efficiency. A reduction in per device energy consumption could be caused by reduced cooling need or enhanced efficiency of delivering cooling. Given that a great deal of the growth projected is in high ambient temperature countries, we have taken the view that these per unit energy consumption reductions are broadly representative of efficiency improvements.
With regard to a definition of technology efficiency and energy reduction, a halving of energy consumption to achieve the same level of cooling implies a doubling in technology efficiency. Cutting energy to a third but achieving the same level of cooling would require a 3-fold (300%) increase in efficiency levels e.g. if 1,000 cooling units consume 3,000KWhs of energy and we wanted to reduce this to 1000KWhs i.e. one third, the efficiency of each unit would need to increase by 300%. (e.g. a device with a COP of 5 that consumed 30kWh of energy to deliver a 150kWh of cooling effect would need to increase its COP to 15 to deliver the same cooling effect with only 10kWh of energy input)

[23] The technology improvements for the Accelerated Technology Scenario and associated equipment penetrations, are forecast by GCI and described in numerous areas as "optimistic". Potential sources for these improvements are described in the Appendix have been sourced from GCI publications. They also include projected cost implications.

Scenario definition. This document explores four scenarios, defined below.

1. GCI DEMAND FORECAST – CURRENT TECH PROGRESS (GCI CT): combines the GCI equipment stock forecast with the assumption that technical innovation in the sector (as a whole) continues to follow its current pace of technical development and efficiency improvements, either in terms of low GWP refrigerant adoption or equipment efficiency. This scenario leads to unit equipment energy use per cooling appliance reducing (on average, between 2018 and 2050) by 15% in space cooling and 38% in stationary refrigeration (no reduction in mobile cooling equipment energy use). [22]

2. GCI DEMAND FORECAST – ACCELERATED TECH (GCI AT)[23]: equipment stock forecast identical to GCI CT; however technology innovation is accelerated to deliver a range of device energy efficiency improvement steps via technology and maintenance enhancements alongside replacement of synthetic refrigerants with very low to zero GWP refrigerants. The accelerated tech progress scenario is entirely focused on evaluating the impacts (for both the GCI and C4A equipment stock projections) of introducing additional, more aggressive, mitigation options to the current tech progress scenario – including switching to very low-GWP refrigerants, leakage reductions, improvements in equipment energy efficiency, opting for more efficient system types (i.e. district cooling in-lieu of unitary AC units), etc. The accelerated tech progress scenario disregards barriers to adoption that could limit take up of efficiency improvements. The GCI AT projections translate to unit equipment energy efficiency improving on average, between 2018 and 2050 by 34% in space cooling, 49% in stationary refrigeration and 14% in mobile cooling.

3. C4A DEMAND FORECAST – CURRENT TECH PROGRESS (C4A CT): assumes that equipment stocks in the sector (as a whole) grow faster than in the GCI scenarios – with refrigeration equipment penetrations globally converging with those experienced today in the United States by 2050 and air conditioning being made available to all households experiencing more than 2000 Cooling Degree Days per year. On the technology progress side, technical innovation in the sector (as a whole) is assumed to continue following its current pace.

4. C4A DEMAND FORECAST – ACCELERATED TECH (C4A AT): equipment stock forecast identical to C4A CT. On the technology progress side, technology innovation is accelerated in the same way as scenario two, to deliver a range of device energy efficiency improvement steps via technology and maintenance enhancements alongside replacement of synthetic refrigerants by natural ones with very low to zero GWP.

DEFINING DEMAND FOR COOLING

SECTORS CONSIDERED

The three largest sources of global cooling demand today include:

- **Space Cooling** – which we define as the provision of comfort cooling through buildings' air-conditioning (residential, commercial and industrial premises). Although there are still less AC units than domestic refrigerators globally, given its energy consumption, space cooling already is the largest energy consumer amongst the cooling sectors, accounting for 41% of global cooling energy consumption.
- **Stationary Refrigeration** – which we define as any refrigeration equipment used in buildings (residential, commercial and industrial[24]) to maintain and/or reduce the temperature of air for process cooling, product storage and goods and equipment cooling (e.g. industrial processes). It is today the second largest consumer of energy within the cooling sectors, with 34% of global cooling energy use.
- And **Mobile Cooling** – which we define as the provision of cooling for both vehicle air-conditioning equipment (AC in cars, buses & coaches, trains, etc.) and transport refrigeration equipment (refrigeration for vans, trucks, containers, etc.). It accounts for the remaining 25% of the cooling sectors' energy use.

Today these combined sectors represent a stock of 3.6 billion pieces of equipment, of which nearly 45% are domestic refrigerators, and annual sales of more than 350 million units in 2018, 38% of which are domestic refrigerators.

Projected Equipment Stocks from now to 2050

The cooling equipment stock growth forecast below (Figures 3 and 4) has been produced by the Green Cooling Initiative (GCI, see details above in Green Cooling Initiative Data Set). It describes a single scenario for equipment growth which sees the global stock reaching a total of over 9.5 billion units in-use by 2050[25] – with cumulative equipment sales between 2018 and 2050 of 19 billion new appliances.

The largest growth is expected in the space cooling sector, with four times as many appliances in-use by 2050 than there are today. Despite growing at a slower rate, stationary refrigeration and mobile cooling stocks are also expected to more than double in the same timeframe.

Number of cooling appliances in-use globally, by sector (# of units)

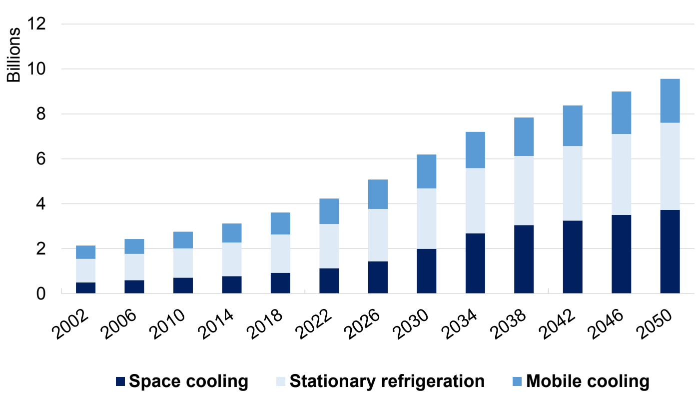


Figure 3

Annual sales of cooling appliances globally, by sector (# of units)

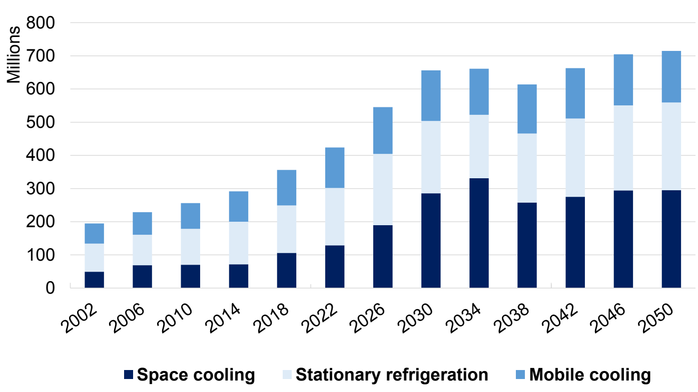


Figure 4

[24] Commercial refrigeration relates to refrigeration systems deployed in retail and restaurant premises whereas industrial refrigeration relates to food processing and upstream distribution channels.

[25] Approx. 3.76bn of these will be domestic refrigerators.

Implied per capita stock levels and Implications

Per capita equipment ownership ratios at regional levels shows that despite the significant growth in equipment stock, some regions remain considerably under-served compared to the most advanced nations.

In the Space Cooling sector, China's staggering growth in equipment penetration continues until the early 2030's at which point it surpasses the equipment penetration rates observed in the USA (Figure 5).

At the other end of the spectrum, uptake in ASEAN, India and Sub-Saharan Africa grow much slower – so much so that uptake in ASEAN remains 5 times lower than it is in the USA by 2050 while uptake in India[26] and Sub-Saharan Africa remains 10 times lower than in the USA by 2050[27].

Within the Stationary Refrigeration sector, domestic refrigeration ownership is where most of the growth takes place – and together with commercial refrigeration where the gap between developed and developing nations is the smallest (Figure 6). In the 2018 to 2050 period, China domestic refrigeration grows to ~65% of the uptake in the USA; ASEAN and India grow to ~50% of the uptake in the USA; and Sub-Saharan Africa grows to 37% of the uptake in the USA[28].

For commercial refrigeration, China grows to ~80% of the uptake in the USA by 2050; India grows to <60% of the uptake in the USA by 2050; and ASEAN and Sub-Saharan Africa grow to 80% of the uptake in the USA by 2050 (Figure 7, overleaf).

Industrial refrigeration is where the gap between developed and developing nations remains the widest in the stationary refrigeration sector – with uptake in China 3 times lower than in the USA by 2050; uptake in India over 10 times lower than in the USA; and uptake in ASEAN and Sub-Saharan Africa 8 times lower than in the USA (Figure 8, overleaf).

Within the Mobile cooling sector, it is the mobile AC segment which exhibits the fastest growth – with uptake in China growing to ~65% of the uptake in the US; uptake in ASEAN and India growing to ~50% of the uptake in the USA; and uptake in Sub-Saharan Africa growing to 37% of the uptake in the USA (Figure 9, overleaf).

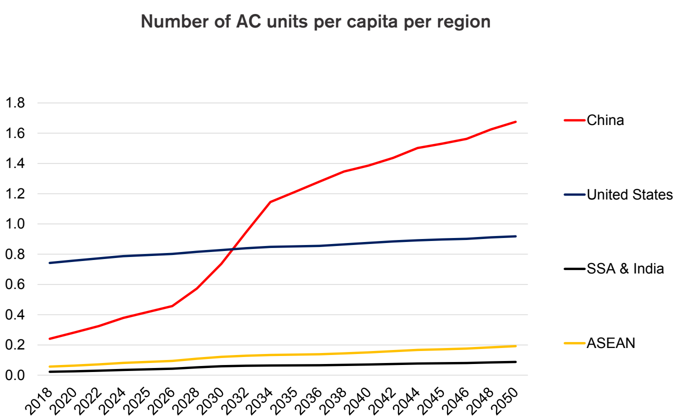


Figure 5

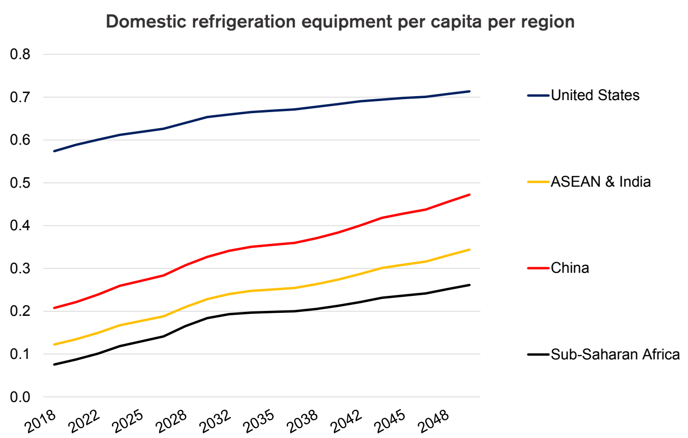


Figure 6

[26] In 2050, India projections are 150m units vs. 400m for the USA, despite a population 3 to 4 times larger.
[27] A major driver for this lower penetration seems to be affordability concerns, persistently lower levels of GDP per capita in these countries is expected to lead to lower equipment penetrations under GCI's modelling approach.
[28] For consistency with other types of equipment, we have analysed domestic fridge deployments in respect to per capita penetrations as opposed to household ownership levels.

Transport refrigeration however shows no sign of significant reduction in the gap between developed and developing nations. Even China, which outperforms its neighbours in most other sectors, is characterised by an uptake five times lower than in the USA by 2050; uptake in India stays >10 times lower than in the USA; and uptake in ASEAN and Sub-Saharan Africa stays ~8 times lower than in the USA (Figure 10).

Although in the first instance lagging uptake in industrial and transport refrigeration equipment may appear to affect individuals less directly than the lack of domestic refrigeration or air-conditioning, it could become a significant issue as it implies insufficient cooling equipment (lack of pre-cooling, industrial refrigeration for processing, refrigerated transport, etc.), to bring food from production facilities to the retail outlets or to support storage and transport of medical supplies.

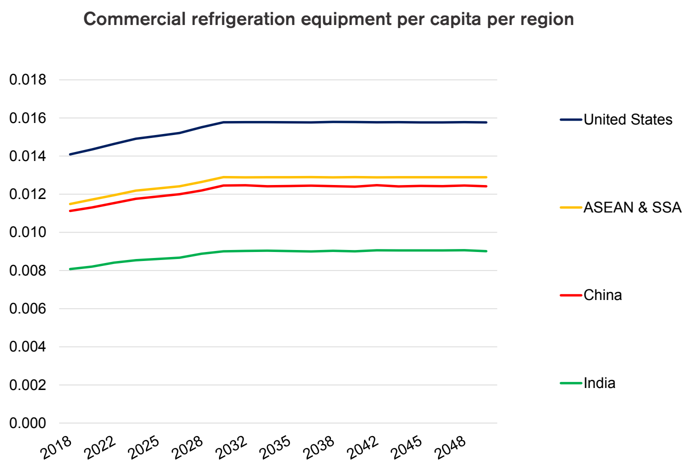


Figure 7

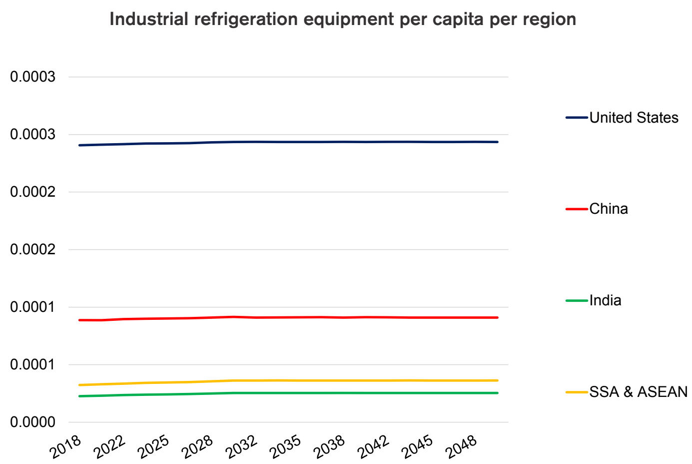


Figure 8

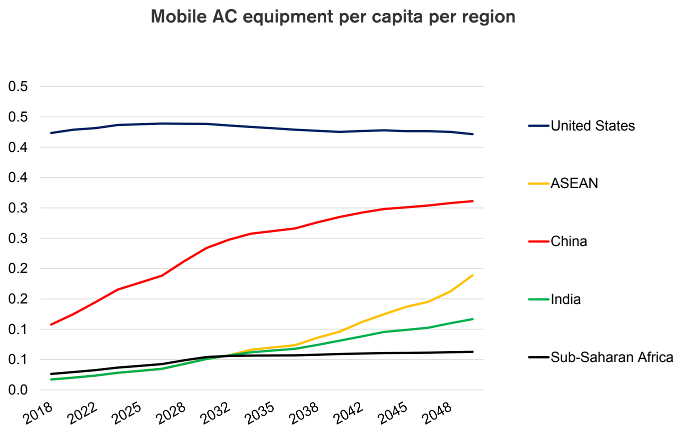


Figure 9

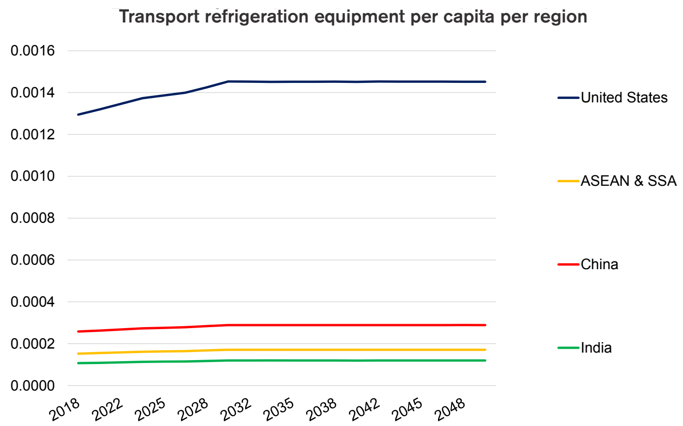


Figure 10

A COOLING FOR ALL SCENARIO

Considering per capita equipment penetrations at regional level, it becomes clear that 9.5 billion cooling appliances by 2050 will, on the current technology pathways, not be sufficient to deliver universal access to cooling, let alone meet the UN SDGs 2030 targets[29]. Food and medicine loss in the supply chain will still be high; food poisoning from lack of cold chain and domestic temperature management will still be significant; farmers will lack market 'connectivity' or 'access'; hundreds of millions of people will not have safe, let alone comfortable, living or working environments; medical centres will not have temperature-controlled services for post-natal care, etc.

Closing the gaps across a range of cooling segments in ASEAN, China, India and Sub-Saharan Africa without step-change interventions will require much larger equipment uptakes. Fully understanding and quantifying this (as well as what can be done about it) will require a much larger regionally-based technology and socio-economic study. But as a start point to understand the potential implications of this higher growth and to define an upper bound to the issue, we have chosen to define a Cooling for All scenario in terms of the following four key high-level goals:

- Domestic refrigeration: >95% of households have at least one appliance (within the stationary refrigeration sector) – domestic temperature-controlled food management is not a luxury but key within the cold chain to reduce food waste, temperature caused food poisoning as well as even play a part in facilitating SDG changes to gender equality.
- Reduction in Food Loss: <9% of food is lost in the temperature-controlled supply chain through a lack of refrigeration, as is reported as standard in developed countries[30]. For the purpose of this analysis we express this as a target per capita temperature-controlled supply chain capacity which is aligned to per capita ratios observed in the USA:
- Within Stationary Refrigeration:
  - 0.2407 pieces of industrial refrigeration equipment per thousand inhabitants.
  - 14.09 pieces of commercial refrigeration equipment per thousand inhabitants.
- Within Mobile Cooling:
  - 1.29 pieces of transport refrigeration equipment per thousand inhabitants.
  - Vaccines lost in the supply chain: within defined target per capita temperature controlled supply chain capacity across industrial, commercial and transport refrigeration.
- Thermal comfort: in countries which experience over 2,000 cooling degree days[31] per year, every household owns at least one cooling appliance. In countries which experience less than 2,000 cooling degree days per year[32], 40% of households on average have one cooling appliance (ratio in-line with that observed in Italy, which experiences 731 cooling degree days per year). This is applied to the space cooling equipment stock.

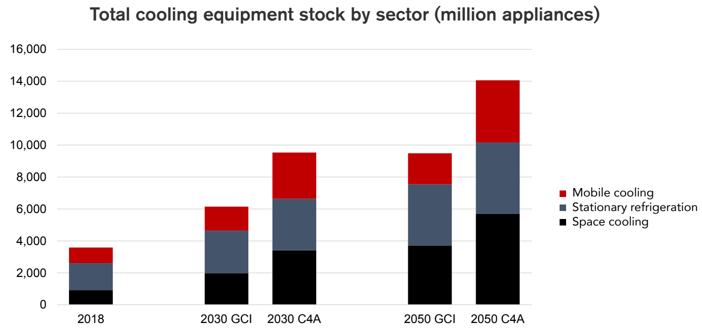


Figure 11

This approach presupposes technology solutions, uses US or European penetration levels as the basis of cooling need and excludes social intervention to mitigate demand. Cooling for All may in fact result in different solutions and appliance mixes being selected by different populations. But the purpose of this convergence approach is to provide a start point to understand Cooling for All in a business as usual environment so as to set the size of the challenge and identify the likely level of intervention required (social to new systems to new technology).

Propagating these adjustments to the base equipment inventory dataset, we can estimate the equipment requirements to deliver this definition of universal access to cooling[33] (Figure 11):

- By 2030, would require a total of 9.5 bn cooling appliances spread across the space cooling, stationary refrigeration and mobile cooling sectors – effectively accelerating the current pace of equipment adoption by 20 years.
- By 2050, would require a total of 14 bn cooling appliances – an additional 4.5 bn appliances compared to the baseline forecast – or 4 times as many pieces of cooling equipment than are in use today.

In absolute terms, the equipment growth from the space cooling and mobile AC sectors again dwarfs the growth from other sectors. However, it is interesting to note that at the current pace of development, it is in the transport and industrial refrigeration sectors that the gap between developed and developing countries remains the largest by 2050. Predicted transport and industrial equipment stocks in 2050 would still need to more than double to meet the Cooling for All target – while there are approx. 3 million transport refrigeration units in use today, nearly 12 million would be required in the Cooling for All scenario.

[29] See Clean Cold and Global Goals, University of Birmingham, Jan 2017 www.birmingham.ac.uk/Documents/college-eps/energy/Publications/Clean-Cold-and-the-Global-Goals.pdf
[30] International Institute of Refrigeration, 5th Informatory Note on Refrigeration and Food.
[31] 21.1°C basis, as per the data compiled in "A global degree days database for energy-related applications", King Abdullah Petroleum Studies and Research Center (KAPSARC), 2015.
[32] China experiences 2,030 cooling-degree days per year, whereas the United Kingdom experiences 135. Several countries including Mauritania, Niger, Sudan and the UAE experience over 10,000 cooling degree-days per year.
[33] These equipment stock forecasts are the basis of scenarios C4A CT and C4A AT described in Section 1.

ENERGY AND EMISSIONS IMPLICATIONS

BASELINE PROJECTIONS - GCI CURRENT TECH PROGRESS

Today – 2018

Today's cooling equipment stock is projected to consume ~3,900 TWh of energy in 2018 (globally) – or 3.4% of the world's total energy demand[34] - with space cooling accounting for the largest share of cooling energy use (1,600 TWh), followed by stationary refrigeration (1,300 TWh) and mobile cooling (1,000 TWh) (Figure 12).

China is already by far the largest consumer of cooling energy – with nearly twice as much energy consumed as the second largest user, the USA – whereas very low equipment adoption rates in ASEAN, India and Sub-Saharan Africa translate to low energy use from the cooling sector.

Total CO_2 equivalent (CO_2e) emissions[35] from the cooling sectors in turn will amount to 4.1GT of CO_2e emissions in 2018 – equivalent to 11.3% of the world's direct CO_2 emissions from the power and industrial sectors in the IEA Reference Scenario[36] (Figure 13).

Furthermore:

- **Mobile cooling** accounts for 31% of total cooling emissions despite only consuming 25% of the sector's energy. Contrary to other cooling sectors, it consumes primarily fossil-fuels and is characterised by a higher share of CO_2e emissions from refrigerant leakage, equipment manufacture and disposal (37% of the sector's CO_2e emissions).
- For **Space Cooling** and **Stationary Refrigeration**, the share of CO_2e emissions from refrigerant leakage and equipment manufacture and disposal is ~27%.

The largest cooling energy consumer, China, is also the largest emitter of CO_2e emissions with 33% of the world's total – to which the country's large equipment manufacturing base is a large contributor.

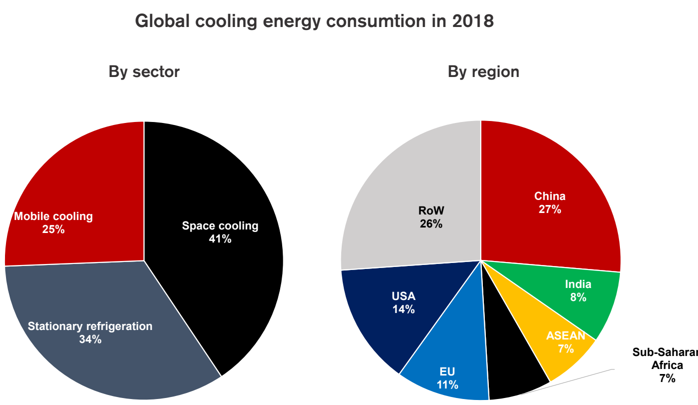


Figure 12

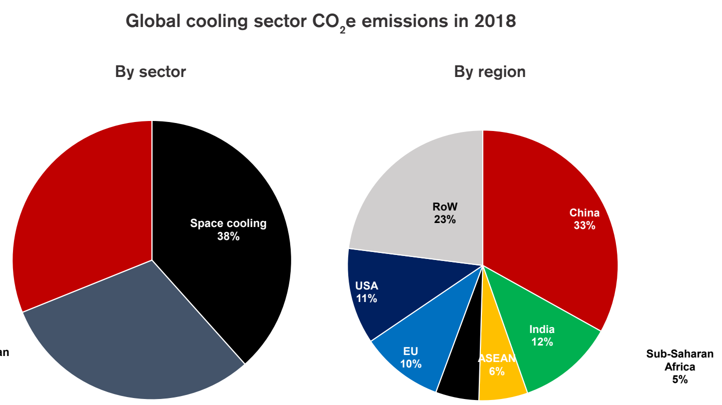


Figure 13

[34] Life Cycle Climate Performance calculation based on current technology and energy mix. It includes TEWI emissions (from energy consumption and refrigerants) and equipment manufacture and disposal.

[35] GCI global grid energy demand as described in IEA Energy Technologies Perspectives 2017.

[36] Note that the cooling sector's total CO_2 equivalent comparison is not directly a like for like comparison with the IEA direct CO_2 emissions from the power and industrial sectors. The IEA figure does not include refrigerant emissions, equipment manufacture and disposal (approx. 30% of the cooling sector's CO_2 equivalent emissions). It should also be noted that cooling energy consumption varies by country, with each country having a more or less carbon intensive energy mix – high energy consumption in regions where the energy mix is highly carbon intensive will therefore disproportionately increase the CO_2 emissions contribution.

Projection – 2050

To describe the impact of equipment stock growth on future cooling sector energy use and carbon emissions, we first consider the baseline GCI demand forecast current tech progress (GCI CT) scenario – which assumes the GCI penetration rates across all sectors and no accelerated technical innovation in the sector (as a whole) either in terms of low GWP refrigerant adoption or equipment efficiency beyond what is currently known. This scenario leads to unit equipment energy use reducing (on average, between 2018 and 2050) by 15% in space cooling and 38% in stationary refrigeration; no reduction in mobile cooling equipment energy use[37] (Figure 14).

In this scenario, total energy use grows from 3,900 TWh in 2018 to 9,500 TWh by 2050 – with space cooling's share growing to 58% (from 41%) of cooling sectors' energy use at nearly 5,500 TWh of energy. In this scenario, space cooling alone would consume more energy in 2050 than the entire cooling sector consumes today and equal to the entire implied energy budget for cooling under the IEA's 2DS.

As described in the methodology section previously, the total energy budget for cooling sectors will be between 4,400 and 5,000 TWh/year by 2030 and 5,500 and 6,300 TWh/year by 2050, with the lower bound based on a projected 1.75°C of warming by 2100 (IEA Beyond 2°C) and upper bound for 2°C (IEA 2°C).

Total energy consumption from the cooling sectors in the GCI CT scenario therefore exceeds its budget by at least 3,200 TWh by 2050 (Figure 15).

Similarly, the challenge can be illustrated from a CO_2e emissions perspective. If electricity is continued to be produced with the current energy mix[38], and cooling equipment energy efficiency followed the GCI CT trajectory, CO_2e emissions from the cooling sectors would grow from 4.1 GTCO$_2$e today to more than 8.9 GTCO$_2$e by 2050 – of which CO_2e emissions tied to energy use alone would account for 7.4 GT. This is an additional 6 to 6.9 GT compared to the CO_2 emissions budget[39] implied by the IEA's 2DS and 2BDS energy trajectories from ETP2017 of 0.5 to 1.4 GT of CO_2 respectively (Figure 16).

Cooling sectors energy consumption by end-use in GCI CT scenario (TWh/year)

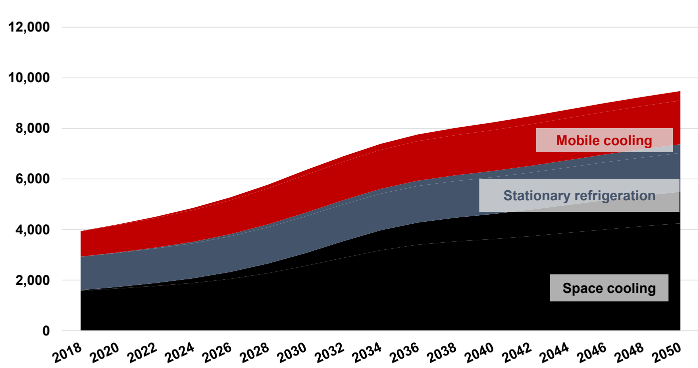


Figure 14

All cooling sectors global annual energy consumption [TWh]

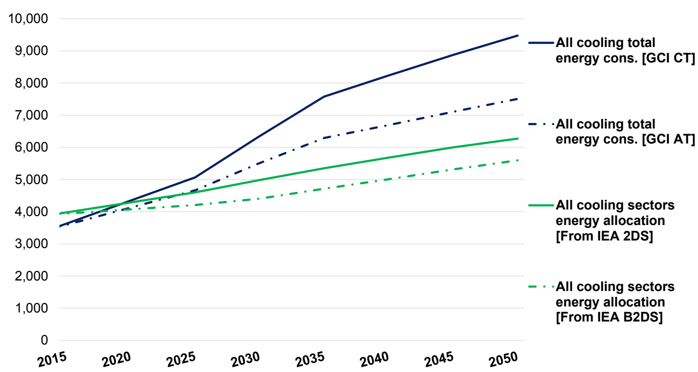


Figure 15

Total CO_2e emissions from all cooling sectors (million TCO$_2$e) with current energy mix

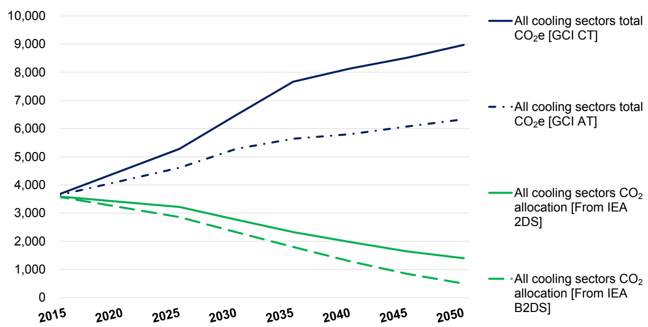


Figure 16

[37] This originates from the GCI data and has been calculated for each of the cooling sub-sectors (Unitary ACs, commercial refrigeration, transport refrigeration, etc.) in each country to factor local climate conditions affecting demand for cooling. It is the ratio of appliance energy use over number of appliances in use – which is presented here as a global weighted average for each of the space cooling, stationary refrigeration and mobile cooling sectors.

[38] The CO_2 trajectories shown here for the cooling sectors assume no decarbonisation of our energy supply. It is understood that it is not realistic to assume energy production's carbon intensity to remain constant, however it enables the scale of the challenge from a technology perspective.

[39] Note that this only relates to CO_2 emissions from the sector's energy use.

COOLING FOR ALL DEMAND FORECAST – CURRENT TECH PROGRESS (C4A CT)

Now we consider the impact of delivering accelerated cooling equipment uptake to meet the Cooling for All objectives with equipment energy efficiency following the BAU trajectory. As expected, the extremely rapid growth in equipment stocks leads to an explosion in energy use across all sectors – up to 19,600 TWh by 2050 (i.e. more than double the GCI CT projections). Space and mobile cooling energy use in particular witness spectacular growth due to a combination of rapid growth in equipment stocks and very small, if any, improvements in equipment efficiency (Figure 17).

By 2050, the gap with the IEA 2DS energy budget could exceed 13,000 TWh – more than double the energy budget and four times as large as the gap in the baseline GCI CT case.

Figure 18 shows the cooling sector's total CO_2e emissions evolution in the C4A CT scenario – with CO_2 budgets overlaid to show the scale of the emissions gap. Not only do CO_2e emissions grow faster in this scenario (to 18.8 $GTCO_2$e), but the CO_2 budgets shrink over time making the gap in 2050 more than 13.6 $GTCO_2$e compared to IEA 2DS (net of 3.8 $GTCO_2$e embedded in refrigerant emissions and equipment manufacture & disposal) – more than the world's total target budget for direct CO_2e emissions for 2050 (13GT) if we are to hold temperature increases to 2°C.

NB. The implications on "green" electricity and how much of the gap can be closed by using renewables within the wider energy system are explored in "Implications for Renewables and Green Electricity".

Total cooling sector energy consumption by sector in current tech progress scenarios (TWh/year)

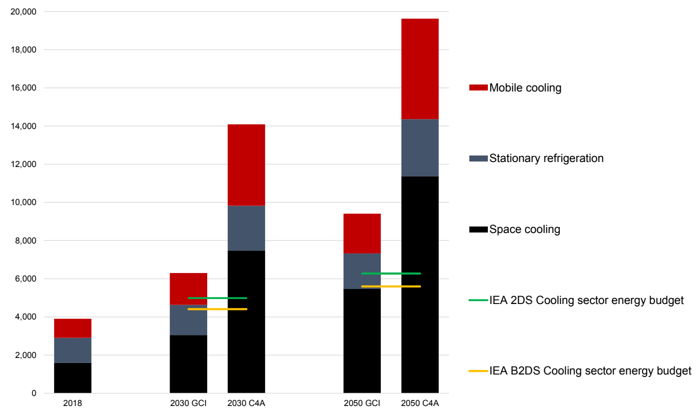


Figure 17

Total cooling sector CO_2e emissions by sector in current tech progress scenarios ($GTCO_2$e/year)

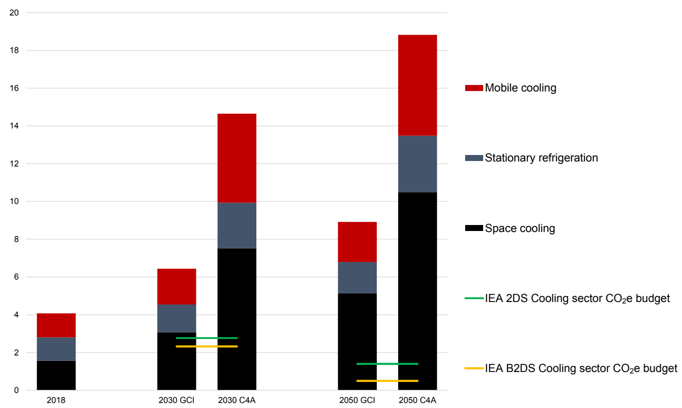


Figure 18

ACCELERATED TECH PROGRESS OPTIONS PROPOSED BY GCI AND THEIR IMPACT

Whether from an energy use or from a CO_2e emissions' perspective, meeting the Cooling for All target would have a substantial negative impact if delivered under the current tech progress equipment efficiency assumptions.

In this section, we evaluate the potential of the accelerated tech progress scenario to address these challenges as access to cooling becomes more widespread.

The accelerated tech progress scenario is entirely focused on evaluating the impacts (for both the GCI and C4A equipment stock projections) of introducing additional, more aggressive, mitigation options to the current tech progress scenario – including switching to low-GWP refrigerants, leakage reductions, improvements in equipment energy efficiency, opting for more efficient system types (i.e. district cooling in-lieu of unitary AC units), etc. The accelerated tech progress scenario assumes solutions to barriers to adoption that could otherwise limit take up of efficiency improvements. The GCI AT projections[40] translate to unit equipment energy efficiency improving on average, between 2018 and 2050 by 29% in space cooling, 49% in stationary refrigeration and 14% in mobile cooling via a combination of technology and efficiency measures.

Similar to the GCI CT scenario, this analysis relies on the assumption that our electricity generation mix remains as carbon intensive as it is today – thereby illustrating the role that technology efficiency improvements can play in addressing both energy use and carbon emissions.

Understanding the impact of potential energy consumption measures is essential to deriving the scale of the low-carbon electricity capacity requirement without more radical intervention over and above energy efficiency.

The accelerated tech progress scenario delivers a total reduction in global energy consumed by the cooling sector of 21% by 2050, enabled by a per cooling appliance average energy consumption reduction of 28% in the accelerated tech progress scenario vs. a 9% reduction (per appliance) in the current tech progress scenario. Energy consumption from the cooling sector however still increases four fold in the CA4 AT scenario compared to today's level and remains well over the cooling sectors' energy budgets (Figure 19).

The accelerated tech progress scenario does benefit from significant overall energy consumption savings – bringing the total down by over 4,000 TWh (more than today's total cooling energy use) to 15,500 TWh in 2050. Yet it remains more than double the budget allocation under IEA 2DS and more than three times under IEA B2DS (green and yellow lines on Figure 19).

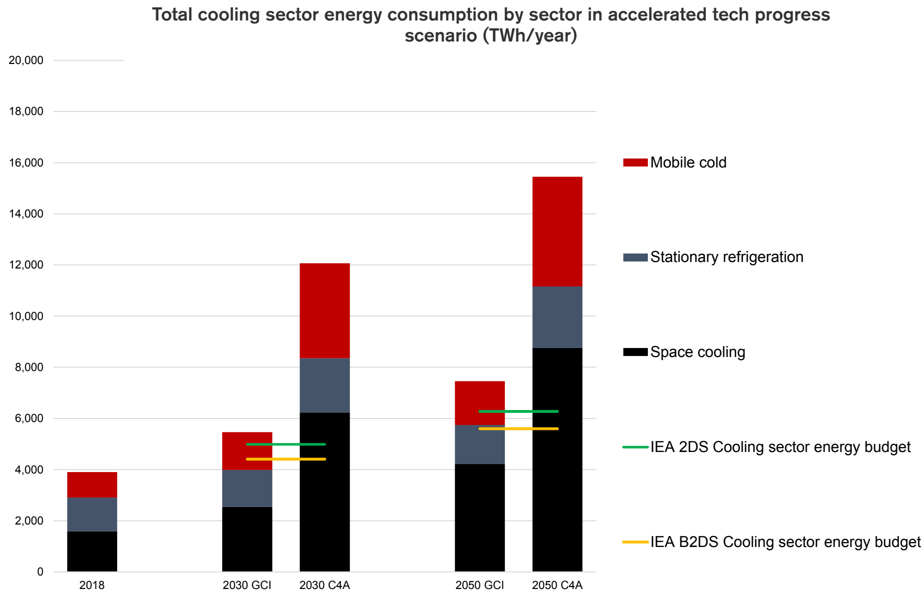


Figure 19

[40] As for the BAU scenario these figures originate from the GCI data. They are the ratio of appliance energy use over number of appliances in use in the mitigation scenario, which is presented as a global weighted average for each of the space cooling, stationary refrigeration and mobile cooling sectors. The technology improvement assumptions for each sub-sector are described in detail in Appendix 2 – they were derived and collated from expert feasibility assessments by GCI.

Figure 20 shows the cooling sector's total CO_2e emissions evolution in the accelerated tech progress scenario with equipment energy efficiency improvements as described above – with CO_2 budgets overlaid as green and yellow lines to show the scale of the emissions gap. By 2050, total CO_2e emissions reach 13.3 $GTCO_2e$.

In this scenario the gap in 2050 is more than 10.4 $GTCO_2e$ compared to the IEA 2DS (excluding 1.5 $GTCO_2e$ embedded in refrigerant emissions and equipment manufacture & disposal).

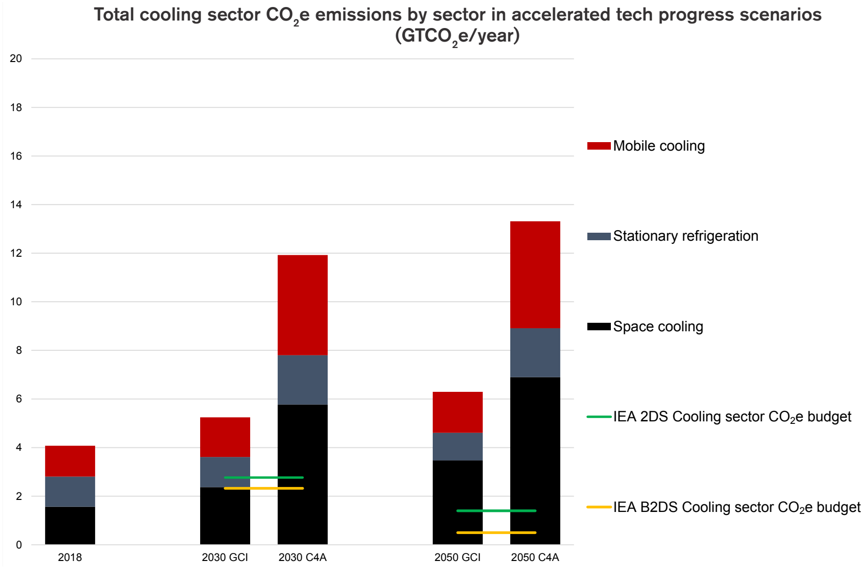


Figure 20

Impact of Kigali Amendment on Direct Emissions

While the IEA defines "budgets" for CO_2 emissions embedded in the production and distribution of energy, the cooling sector must also account for direct emissions of refrigerant gases (as well as emissions from equipment manufacture and disposal) which today contribute 20% (nearer to 30% according to GCI) of the sectors' total CO_2e emissions; the rest being indirect emission from energy consumed. Since 2016, the Kigali Amendment to the Montreal Protocol[41] limits the nearly 200 signatory countries' total CO_2e emissions from HFC usage to approximately 235 $mTCO_2e$ by 2050 – an 80 to 85% reduction in equivalent CO_2e emissions from years defined as baseline[42] (and compared to today's ~1,200 $mTCO_2e$).

In the GCI AT scenario where equipment growth remains moderate and equipment performance in terms of leakage and adoption of natural refrigerants increases, the signatory countries achieve an ~60% overall reduction from today's levels but fall short of meeting the Kigali targets by approx. 260 $mTCO_2e$ in 2050. So meeting the Kigali targets could be challenging.

In the Cooling for All scenarios however, assuming that the Kigali direct emissions budgets are unchanged, the situation becomes:

- C4A CT scenario: Global cooling sector direct emissions of 3,800 $mTCO_2e$ vs. a Kigali allocation of 235 $mTCO_2e$ – a gap of over 3,500 $mTCO_2e$.

- C4A AT scenario: Global cooling sector direct emissions of more than 1,510 $mTCO_2e$ vs. a Kigali allocation of 235 $mTCO_2e$ – a gap of more than 1,200 $mTCO_2e$.

It is also worth noting that China and Sub-Saharan Africa are part of the Article 5 Group 1 signatories – for whom the Kigali "allocations" will be calculated based on annual consumption of HFCs in years 2020 to 2022. India is part of the Article 5 Group 2 signatories – for whom the Kigali "allocations" will be calculated based on annual consumption of HFCs in years 2024 to 2026[43]. Market growth over the next 5 to 10 years in these territories could therefore have a very significant impact on the size of these countries' allocations under the Kigali programme and impact on its overall effectiveness as an emissions reduction tool – as these countries' Kigali "budgets" could be significantly higher if equipment adoption took place faster in the first half of the 2020 to 2030 period. For example, if equipment uptake in India was to increase linearly between now and 2030 to meet the Cooling for All equipment demand by 2030, India's Kigali "baseline budget" could amount to more than 390 $mTCO_2e$ instead of 90 $mTCO_2e$ – adding another 300 $mTCO_2e$ to the global Kigali "baseline budget". That would make India's "baseline budget" more than 3 times as large as the USA's "baseline budget".

The Kigali amendment to the Montreal Protocol is crucial to reduce the sector's environmental footprint but if we are to plan for a Cooling for All goal it suggests that further accelerating the uptake of low-GWP and natural refrigerants may be necessary in order to meet the Kigali objectives.

[41] The Montreal Protocol mandates the phase down of the production and consumption of HFCs. The Kigali Amendment to the Protocol which will come in to force in January 2019 includes Global Warming Potential values for a number of HFCs, HCFCs and CFCs. Further the Amendment establishes national budgets for HFCs in terms of CO_2e from based on production and consumption during defined years with 85% phase down trajectories.

[42] Note that for countries within the Article 5 Groups, baseline years will be taken beyond 2020, therefore Kigali emission "budgets" can only be estimated at this stage.

[43] The Main Group Countries have already measured and declared their CO_2e HFC budgets (using 2011-13 as a base year); for countries which have ratified the Kigali amendment they are legally committed to reducing their use of HFCs and HCFCs substantially (85%) in line with the amendment. However, the Article 5 Group use future years for the purpose of budget setting. There is therefore a significant risk that selecting high GWP solutions now is in some respects incentivised because it will maximise their budgets for the phase down period. Engaging these countries now will be important to influencing their growth up to the base years.

IMPLICATIONS FOR RENEWABLES

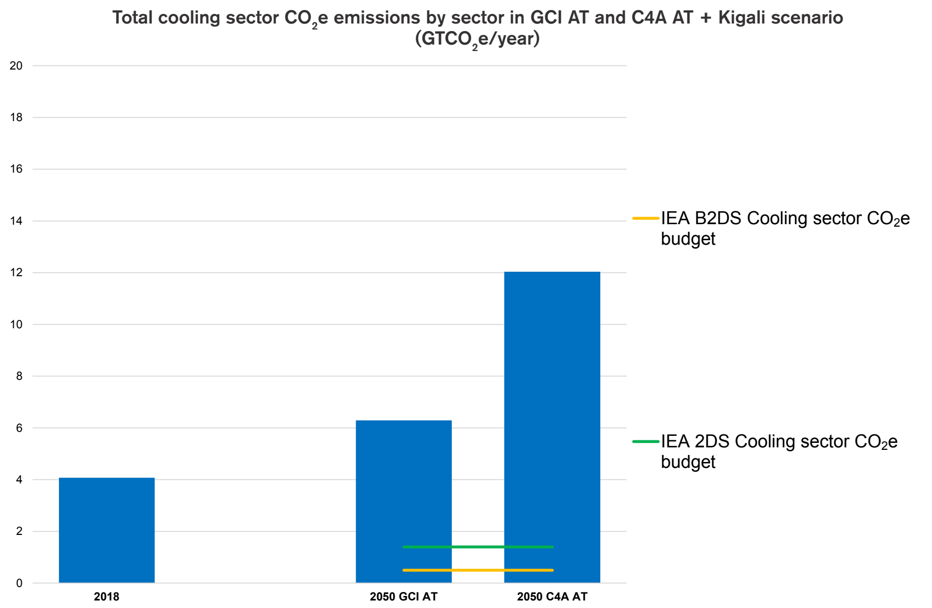


Figure 21

THE IMPLICATIONS FOR RENEWABLES AND "GREEN ELECTRICITY"

One of the most important findings of the scenario mapping for Cooling for All is to start to quantify the likely energy "gap". In the absence of more radical intervention in how we mitigate cooling demand or provide cooling, this has significant implications for electricity demand and therefore the need for low-carbon generation capacity.

In short, can we green the resulting additional demand for electricity generation, especially alongside the other demands for electrification such as in the transport sector?

In a Cooling for All equipment growth scenario where equipment energy efficiency follows the accelerated technology progress path outlined by our 'best case' aggressive C4A AT scenario, the cooling sector still "overconsumes" by 9,100 TWh in 2050 compared to the IEA 2DS cooling energy budget, and by 9,850 TWh compared to the IEA B2DS cooling energy budget. This gap would have to be met by increased deployments of low-carbon generation capacity, which we consider here to be renewable energy based[44], or there will be a significant indirect emission (i.e. emissions from energy consumption) implication from a scaling-up of today's 'business as usual' generation mix.

As an indication of the quantum leap required, assuming that further to the equipment improvements proposed in the accelerated tech progress pathway the cooling sector additionally reduces direct emissions to meet the current Kigali HFC emission budgets, total CO_2e emissions from the cooling sector could still amount to 12 $GTCO_2e$ by 2050 without a proportionate growth in renewable generation capacity. Consequently, emissions will have overshot the "cooling budget" in IEA 2DS by more than 10.6 $GTCO_2e$ in 2050 (750%), 12 $GTCO_2e$ would represent more than 75% of the world's total CO_2 budget for that year, all sectors accounted for (Figure 21).

This analysis is an indication of the scale of the challenge we face if we are to enable universal access to clean cooling. While the Kigali programme focuses on the critical task of cutting down direct emissions of harmful HFC refrigerants, there remains an immense challenge from an energy use perspective – with the sector potentially demanding up to 15,500 TWh by 2050 in our accelerated tech progress scenario (C4A AT), despite significant improvements in equipment energy efficiency. The IEA 2DS budget of 6,300 TWh would only be able to supply around 40% of this amount of energy.

If it proves impossible to reduce energy consumption to the limits of its budget through efficiency measures (possibly requiring a more than 68% energy reduction in our projected 'worst case' demand for 2050), is it possible to further reduce the sector's carbon footprint by deploying renewable energy sourced electricity generation? This is a route that could relax some of the equipment efficiency improvement requirements, but in turn would lead to an increased reliance on energy storage to efficiently manage renewable intermittency.

It is important to note, however, that relying on renewable energy based generation without energy consumption reduction measures from the cooling sector would mean the sector consumes much of the world's projected renewable capacity for 2050, or we need additional capacity.

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 capacity available increases to 13,729 TWh – which is still less than the 15,500 TWh required by the cooling sector globally in C4A AT (Figure 22 overleaf).

[44] Our analysis has focused on renewable energy resources as the costs of nuclear energy are too high for many of the countries that are experiencing rapid demand growth.

Currently stationary cooling represents about 14% of global electricity demand. Recognising that renewable electricity is also required to support other electrical demands, the quantities of renewable energy capacity implied in the table below are clearly disproportionately large.

As a result it is unlikely that the "overconsumption" of energy by the sector will be met entirely by the IEA's forecast deployment of renewables. The alternative is conventional thermal power generation so indirect emissions from meeting this energy demand without action would be substantial.

To avoid this scenario without radically reducing energy consumption would require very substantial expansions in renewable capacity. In the most extreme case a doubling of current 2050 projections could be needed which would have enormous infrastructure cost implications.

It is also important to remember that with renewable energy sourcing, alongside generation capacity, there is a need for energy storage to meet demand on a temporal and location basis. Many locations that are rich in renewable resources – or even industrial waste heat - are not co-located with the residential, commercial, agricultural or industrial areas where cooling is required. Few high density urban environments have sufficient free suitable space to erect meaningful quantities of solar PV electricity generation capacity or wind turbines. Equally, cooling demands in refrigeration are relatively inflexible as produce and medicines need to be consistently refrigerated 24/7/365. Space cooling demands are heavily correlated with high ambient temperatures, but these do not always correspond exactly to peak renewable production periods. In order to address this mismatch, it is likely that a significant amount of energy storage will be required to integrate and manage cooling demands with renewable resources.

At a more macro level, some of the increases in cooling capacity required may further shift the grid mix in affected countries to much higher penetrations of renewables than would otherwise be required. This will have implications for flexibility in the form of thermal generation, demand side response and energy storage that will need to be built in to the system to cope. Some of the energy storage capacity should be thermal and directly integrated into cooling systems to achieve the required levels of economic flexibility.

This brief review of implied capacity suggests that, without action, cooling could consume a disproportionate share of renewable electricity production. The result will either be very substantial indirect emissions from higher carbon electricity generation to meet demand or very substantial costs associated with further renewables deployments. These costs will be direct (in terms of deploying generation assets) and indirect (through re-enforcing the system at a network and flexibility level to cope with the higher levels of renewables penetration).

MEETING COOLING FOR ALL WITH RENEWABLE ELECTRICITY

GCI Current Technology Progress	49%	33%
GCI Accelerated Technology Progress	39%	26%
C4A Current Technology Progress	101%	68%
C4A Accelerated Technology Progress	80%	53%

Figure 22

[45] Total renewables capacity reaches 19,359 TWh/year by 2050 in this scenario. Renewables in this analysis are considered as the combination of all biomass, hydro (excl. pumped storage), geothermal, wind (on- and off-shore), solar (PV and CSP) and ocean.

[46] Total renewables capacity reaches 29,074 TWh/year by 2050 in this scenario. It is defined as described above.

RECOMMENDATIONS

HOW CAN WE MANAGE THE GAP?

The C4A CT scenario, that does not change the demand for cooling and only envisages conventional technology and operations with slow improvements in performance through to 2050 from today's status quo, results in an energy requirement of 19,600 TWh vs. an IEA 2DS budget of 6,300 TWh for all forms of cooling. To come within the energy budget and still provide the cooling required under the SDGs, either energy use per unit of cooling would have to be reduced to about a 1/3 of the levels envisaged, or penetration of renewable generation capacity (solar and wind) would have to increase substantially, maybe even double.

The GCI CT already includes some improvement in baseline technologies over the period (i.e. 15% reduction in energy consumption per unit of stationary space cooling equipment in service and 38% reduction in per unit energy consumption per unit of stationary refrigeration equipment in service), so the implication is that efficiencies need to be more than three times those achieved today to provide Cooling for All within the IEA's energy budget[47].

The resulting challenge will, to some extent, vary across sectors based on factors like progress already made and packaging constraints in transport applications. In the Appendix, we have included GCI's analysis of technical potential in each sector as an indication of what could currently be achieved.

However, there is no sector in which GCI is currently proposing a tripling of device efficiency from today's levels as being feasible, suggesting a substantial gap in technology availability exists. In fact, the maximum envisaged is approximately doubling device efficiency in some cases, with the mobile equipment having much lower potential for efficiency improvement with current technology (see Appendix). This is alongside the political challenge of gaining acceptance for improvements that could more than double equipment costs according to GCI analysis.

From the analysis to date, it is clear that if we are successful in delivering Cooling for All, and even assuming we achieve the GCI's most optimistic accelerated tech progress pathway (GCI AT), Cooling for All represents a material challenge to our energy budgets, CO_2 targets and climate goals.

Alongside ensuring we deploy maximum efficiency technologies now, and deliver consistent and effective maintenance, there are future options we need to explore with urgency to manage the challenge if we are to act early enough and take a systems approach. We therefore propose a series of pieces of work that we believe are essential if we are to calibrate a detailed response and develop and demonstrate a mitigation strategy for our demand for cooling.

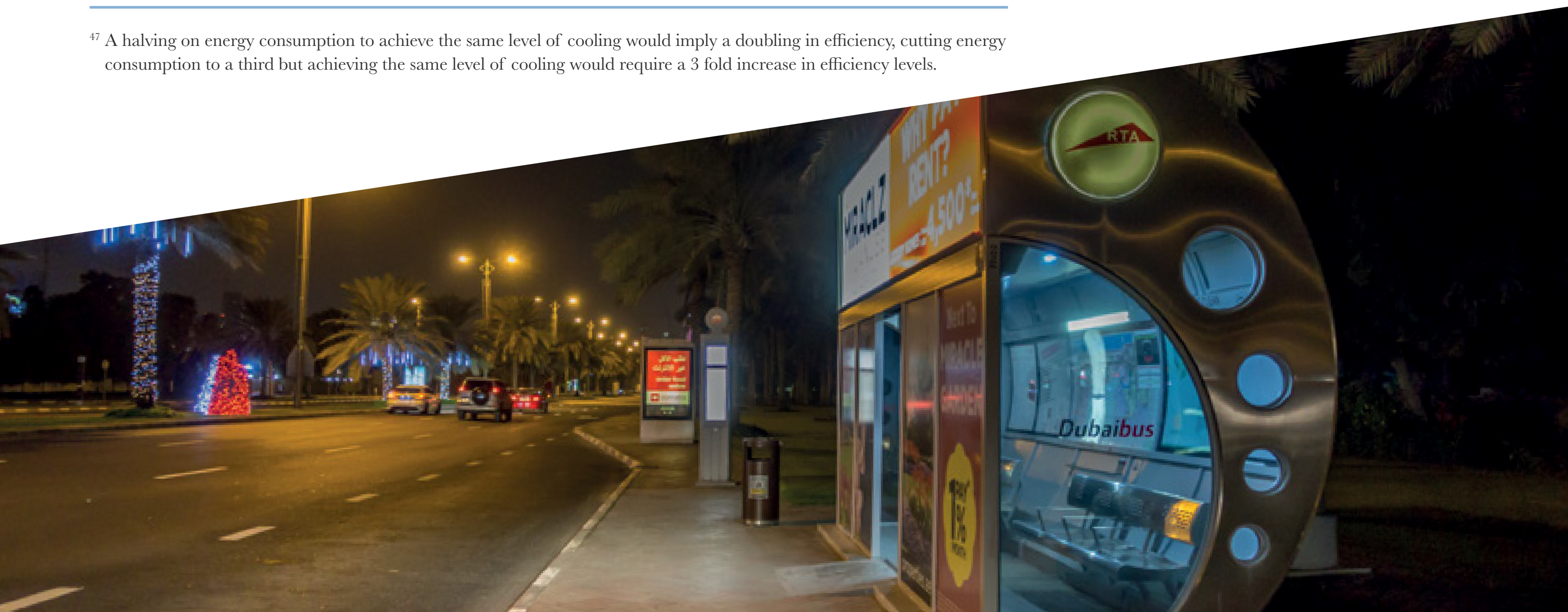
1. Definition of the Challenge

Equipment based projections of cooling demand are an essential element of producing meaningful emissions and energy consumption data and so have been used in this approach. However, from our work here it is clear that they suffer from three significant weaknesses:

i) **Pre-supposes a need** – Penetration levels are based on assumptions of the US and European standards and preferences will automatically be aspired to and adopted. While this provides a logically sound baseline from which to start to understand the scenario without intervention, the first interventions must be focussed on testing the assumed need for cooling, and the opportunities for alternative social interventions to reduce unnecessary demand within the local cultural context.

Cooling for All may result in different solutions and appliance preferences being expressed by different populations, leading to quite different equipment mixes. Therefore in the first instance, we should build on the work of GIZ Proklima, including their cooling sector inventories, to gain a real understanding of localised market needs and related assessments; not just thinking in terms of replicating North American and European norms and appliance choices.

[47] A halving on energy consumption to achieve the same level of cooling would imply a doubling in efficiency, cutting energy consumption to a third but achieving the same level of cooling would require a 3 fold increase in efficiency levels.



ii) **Poor quality data** – data in relation to unit stocks in each of the cooling categories is somewhat unreliable as verified sales and disposal figures and second-hand transfers of equipment are not universally available. As a result, the equipment parc is genuinely difficult to estimate and projections can therefore be uncertain.

iii) **Pre-supposing a solution** – the focus on per capita equipment penetration rates 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.

We propose the development of a template for national or regional needs-based analysis that will require assessment of at least the following elements:

- 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, and
- A comfort cooling related air conditioning demand – domestic and commercial;
- Domestic refrigeration and food management.

These demand models need to be service or outcome based as far as possible taking national or regional circumstances, culture and sociological preferences into account, as well as resource availability 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 to be made.

2. Intervention Roadmap and Tool-kit (Figure 23)

Developing a roadmap requires several elements:

- A Destination
- Needs inventories
- Technology inventories
- An integrated picture of where we are today and where we aspire to go by when.

From this activity a package of measures can be proposed that address:

- **Research requirements –**
  - Social interventions and approaches to mitigate need;
  - Enable the realisation of the optimum technology (incl. thermal energy storage) packages and increase the probability of emerging technologies (incl. supply chain and manufacturing).
- **Skills and education requirements** – to support the research agenda and enable the optimum deployment and maintenance of cooling technologies current and future.
- **Changes to business models** – to leverage market-based incentives and fit-for-market commercial offerings to promote optimum technology selection and operational behaviours.
- **Policy interventions** – to enable incentives, legislative and regulatory levers and barrier removal to be aligned to deliver the optimum technology and operations package.

The integrated picture activity outputs can also be used as a tool to track progress in terms of the status and trajectory of expanding cooling access provision and emissions reductions.

Intervention Roadmap – Meeting Cooling Demand Growth within the 2 Degrees Budget

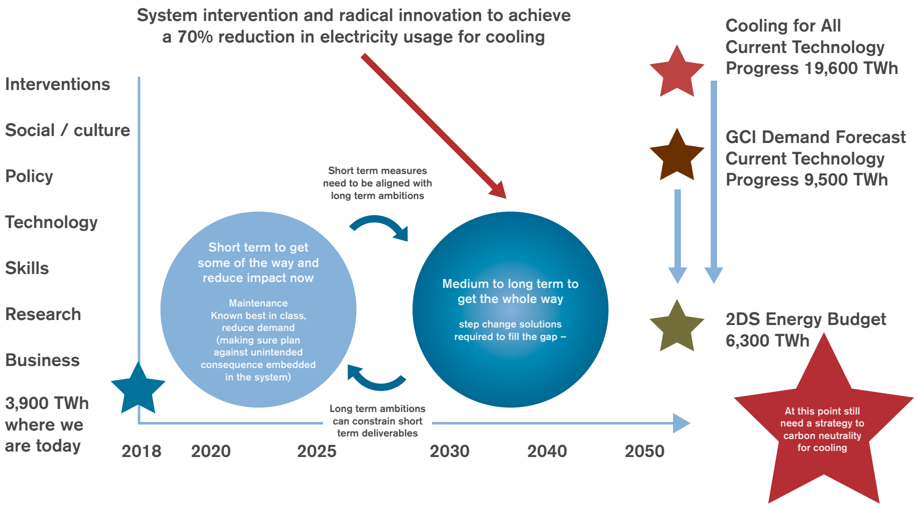


Figure 23

Summary – Ladder of Opportunities

Given the scale of the demand and the need for both urgent immediate intervention as well as a long-term sustainable strategy, we need a roadmap and pathways based on a ladder of opportunities (Figure 24) meeting immediate needs sustainably and within our energy budgets while future proofing the system.

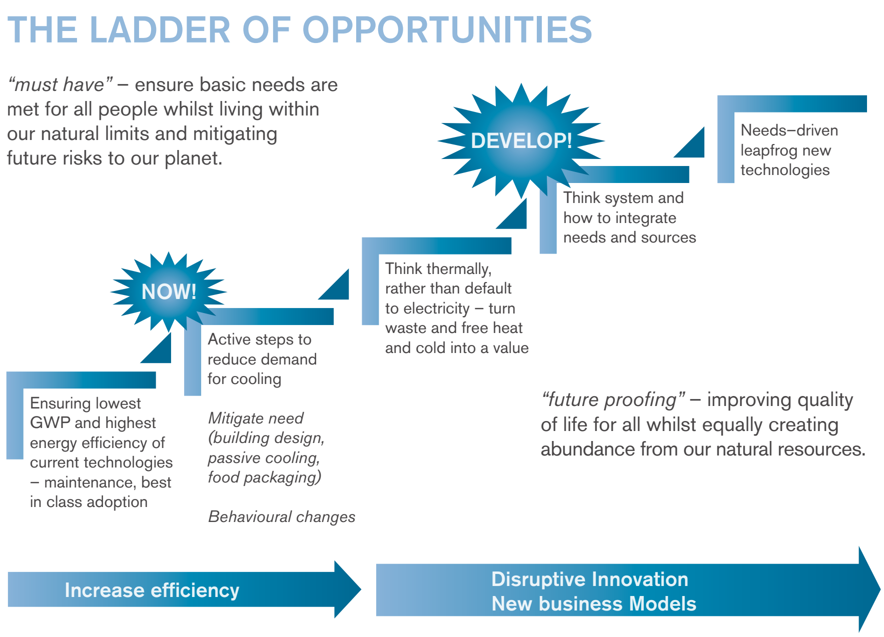


Figure 24

Key stages

- **Reduce the energy required for cooling**: getting industry to adopt high efficiency cooling technologies and using maintenance to deliver performance.
- **Reduce cold load/cooling work required:** better building design, logistics systems, vaccines that survive at higher temperatures;
- **District and community system level thinking across built environment and transport**
  - **Integrated community services:** across built environment and transport needs.
  - **Smart Cooling / Thermal Services:** 'wrong time' renewables; free and waste heat and cold.
  - **Thermal energy storage** to warehouse and shift wrong time energy to replace peak electricity demand and diesel consumption in built environment and transport applications.
- **Needs-driven new technologies**

NOVEL TECHNOLOGIES

Alongside improvements in, and deployment of, existing technologies, it is likely that the very substantial improvements in efficiency required to achieve Cooling for All within our energy budget may necessitate the development and adoption of completely new technologies and thermal energy storage solutions.

In fact the Rocky Mountain Institute has launched the Global Cooling Prize, an international competition to develop and scale a residential cooling solution that consumes five times (5x) less grid energy than today's standard products. The prize is a minimum of $1M.[48]

Figure 25 provides an overview of technology families:

Technology Landscape

A wide range of potential technologies exist that can be applied to this challenge. Further details about them are included in the technology primer.

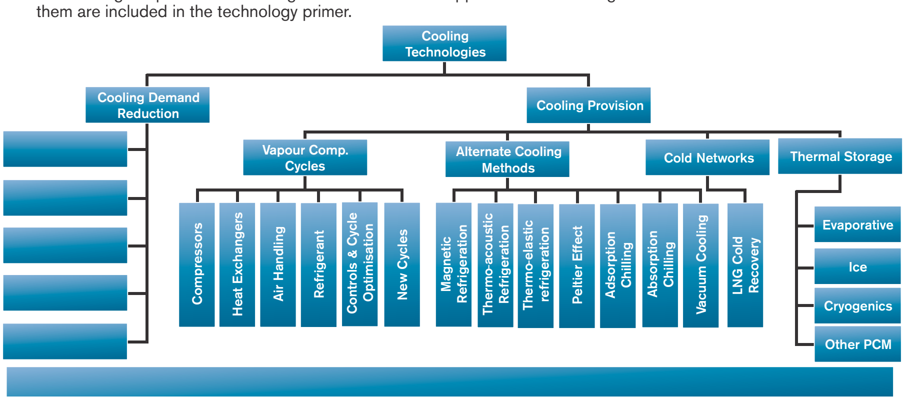


Figure 25

[48] www.rmi.org/our-work/global-energy-transitions/the-global-cooling-prize/

3. Cold Systems and Cooling Services Model - Socio-techno-economic design of energy systems driven by community needs

Alongside the roadmap and tool-kit outlined above, sustainable delivery of secure, affordable low-carbon thermal energy also requires market specific design methods, with the cooling needs and energy resources of the community as a specific focus. Traditional energy system approaches tend to view and aggregate energy supply and energy demand as the start and end-point of the system, and do not adequately consider the actual services, and specific thermal needs and temperatures that individuals and communities need. Likewise, the resources that are identified to supply energy to meet those needs are typically specified generically, and lack either a local focus or a circular economy approach.

A key activity should be the design of the system level (built environment, logistics and transport) approach to cooling , that is a multi-sector, multi-technology, multi-energy source integrated approach to cooling, to deliver maximum economic, environmental and societal impact.

This should include a culturally context informed needs assessment process and a model (open-source) for all communities (rural and urban) to identify the service needs, so as to both mitigate them and reduce their energy demand, and then marry them to the local energy resources using "fit for market" technology solutions. The model will help quantify the economic, societal and environmental impact to underpin support investment and financing proposals, as well as support the design of the novel finance and business models required to create an economically sustainable, end-to-end system.

4. Skills Development

Maintenance is quite correctly seen as a way of maximising efficiency and reducing energy demand. But forward projections assume the rated efficiencies will be achieved; poor maintenance could see energy figures increased by upwards of 20%.

We must therefore consider the strategies and skills required to not only install at least 9.5 billion appliances, and more likely significantly more, but also maintain them. Today, cooling employs more than 12 million people globally with 3.5 billion appliances. This will need to increase rapidly, and ahead of the demand curve, if an increasingly environmentally friendly industry is to be sustained.

A lack of qualified engineers is already seen as a challenge during the shift to natural refrigerants, but it also has the potential to be a significant limiting factor if, when specifying technology, we fail to consider long-term maintenance to reduce leaks and deliver rated energy efficiency. Equally we should consider how we can design for efficiency using approached that range from embedded sensoring to selecting technology solutions and designing appliances with minimum maintenance requirements.

5. Consequences of Cooling[48]

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 a number of 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 CO_2 emissions, and thereby potentially reduce the need for deforestation by ensuring an increased proportion of production reaches the market from existing land resources utilised 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 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 will over time allow farmers to transition into larger scale, more diverse agri-businesses. This can reverse or stem urban migration by increasing farmers' incomes. However, ambitions to reach distant, or even international markets, using conventional refrigeration technology could lead to an increase in transport related emissions, rather than a reduction.

Equally more processing at the farm could lead to increased local CO_2e emissions, environmental pollution and packaging demand – with implications for waste streams and resource use. Packaging needs to be kept minimal and to easily degradable materials.

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 are 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.

Refrigeration in the home can change cooking styles and patterns – especially the case if coupled with more processed food and the convenience products that cold chains enable. 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 as well as cooking skills, indigenous diets and health. Domestic refrigeration can also reduce the frequency of shopping which can affect local marketplaces. Traditional market stalls selling fresh produce daily may struggle.

These are but a small number of examples, yet they illustrate clearly that it is critical to identify potential unintended negative social, ecological or economic consequences and engage to mitigate them as soon as possible.

[48] University of Birmingham - Dr Rosie Day, School of Geography, Earth and Environmental Science and Professor Toby Peters, Birmingham Energy Institute.

6. Living Labs

Proposed work programmes should not only include district, community and system design but also the development of an ecosystem within which the system can be demonstrated - a series of real world 'living labs' for defined demographic groups and markets – for (i) trialling, proving and developing in local cultural contexts, technology, service and methods of operation mixes at scale and (ii) thereby demonstrating local impact, providing a launch-pad for accelerated deployment with a proven tool-kit.

The Living Labs will test and demonstrate not only technologies but also the socio, business, governance, policy and funding models. They will prove the total system, not simply one technology nor one element. This will ensure that new thinking on systems and service integration and business models can be properly designed and tested, impacts on stakeholders and the system as a whole benchmarked, audited and demonstrated.

These demonstration projects will then provide the platform to engage with sales, supply chain, manufacture and assembly partners; training programmes for installation, maintenance and after-sales service; and full-scale commercialisation. The Centres will also support the essential knowledge transfer, capacity building and training - including maintenance to marketing – to create local jobs, skills and livelihoods in the heart of the communities.

Living Labs (Figure 26)

- **Engage at community-level and build trust and confidence.**
- **Create the tools and provide a portfolio approach to ensure right methods of operation and technologies are matched to specific market and service requirements and local energy sources.**
- **Identify sector and cross-sector value chain opportunities; drive consideration of how the benefits can be equitable / widely realised.**
- **Understand the new cross-industry skills and manufacturing requirements ensuring they are met concurrently to accelerate technology industrialisation. And skills need to include after-sales service.**
- **Provide the market-drive knowledge and environment to set national and international multi-discipline research agendas.**
- **Define the policy frameworks to make this happen in time.**
- **Act as central hubs and advocacy points to drive scale-up.**

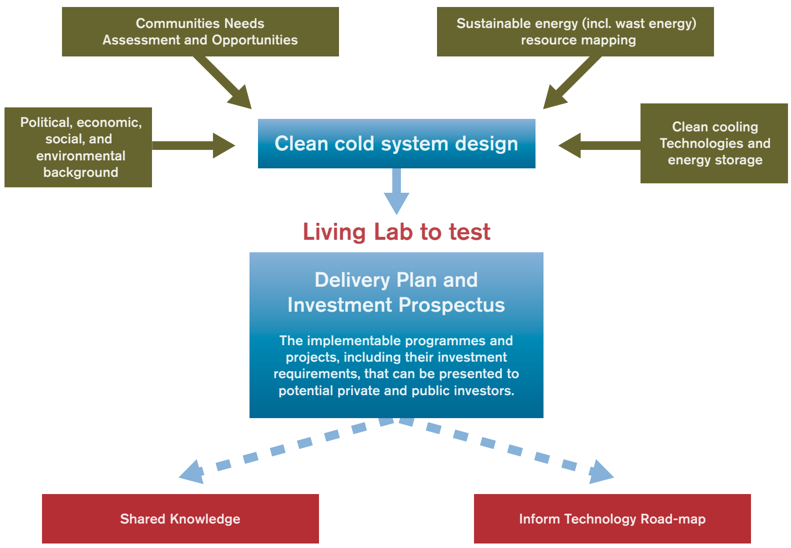


Figure 26

NEXT STEPS

If we are to achieve the aims laid out in the UN's Sustainable Development Goals, we have to provide Cooling for All – access to cold chains for food, vaccines and medicines, access to medical services, thermal comfort, safe working environments and the many other everyday services that require cooling to function. In so doing the benefits are far reaching from saving hundreds of thousands of lives, helping subsistence farmers out of the cycle of poverty to using our natural resources more efficiently.

For the first time, through this report, we have taken a comprehensive look at cooling and assessed the potential impact of meeting all these goals. Even if some of components of the analysis presented here turn out to be only partially correct, our results and findings highlight the unquestionable fact that Cooling for All represents a material challenge to our energy budgets, CO_2 targets and climate goals.

The challenge is clear - How can we meet everyone's cooling needs affordably, reliably and also sustainably?

As we transition from hydro-carbons to renewables, we need a whole system approach so as to develop new, efficient paradigms for cooling. We need to cost-effectively smooth intermittent renewable generation and unreliable grid supply as well as provide zero-emission temperature controlled transport. Optimised strategies will necessarily need to be from energy resource to service user incorporating technology, data connectivity and energy management and consider the role of energy storage as well as the specification of resource pooling protocols.

Alongside ensuring we reduce demand and deploy maximum efficiency technologies now, there are future options we need to explore with urgency to manage the challenge in time. This will also create new opportunities to blend servitisation, community energy services and value creation.

However, delivery of secure, affordable low-carbon, low-pollution optimised integrated cooling to many thousands of rural and urban communities throughout the world is not about one size fits all. It requires the ability to make system design and technology choices based on a full inventory of local input factors, including for example, societal and culture, climate, technical capacity, affordability and resource availability.

Comprehensive, open-access but flexible clean cooling methodologies are required so that communities can design 'fit for market' - including 'fit for energy source' - and 'fit for finance' cooling, rather than approaching the problem with pre-ordained assumptions. In so doing, it can support investment and financing proposals. It will also show the gaps in the technology portfolio, establishing an innovation pipeline driven by need.

Given both the urgency and opportunity of the global challenge and the multi-partner and multi-disciplinary research and delivery mechanisms required, to lead this work we urge the establishment of a multi-disciplinary International Centre of Excellence for Clean Cooling (ICEfCC). This will bring together the global expertise and connectivity with all key stakeholders to research, develop and accelerate to market the step-change pathways for achieving cheapest cost and lowest carbon emissions while meeting the wider social and economic cooling needs - access to clean cooling for all.

International Centre of Excellence for Clean Cooling

- Enhance awareness and understand the challenge – through evidence based research, ensure that the impact of cooling on the Paris Agreement, Kigali amendment and Sustainable Development Goals (SDGs) is fully understood working with others to disseminate finding to key stakeholders.
- Deliver a quantitative intervention roadmap to identify the scope for technical and operational improvement and then step change innovations to reduce the impact of cooling.
- Integrated design of the system level (built environment, logistics and transport) approach to cooling - design multi-sector, multi- technology, multi-energy source integrated approaches to cooling provision to deliver – and balance - maximum economic, environmental and societal impact.
- Business model innovation to ensure that the optimum mix of technologies and operational best practice is deployed.
- Identify the policy Interventions required to deliver the strategy and enable incentives to be aligned to deliver the optimum technology and operations package.
- Provide Skills and education – to support the research agenda and enable the optimum deployment and maintenance of cooling technologies.
- Lead on Demonstration – developing in-market proving grounds for trialling technology mixes at scale and demonstrating impact, providing a launch-pad for accelerated deployment.

Two fisherman fill barrels with water to keep the caught fish cool in transit.

APPENDIX 1 – ACCELERATED TECH PROGRESS SCENARIOS TECHNOLOGY IMPROVEMENTS

The GCI in the technical options annex of their handbook for Nationally Appropriate Mitigation Actions summarize a range of potential improvements across all major cooling sectors. The options considered incorporate design changes, maintenance improvements and refrigerant shifts. The main options and their appropriateness to specific sectors are shown in the tables below.

TABLE 6
Applicability of the different technical options of different RAC systems

Technical option	Unitary air conditioning							Chillers		Mobile AC	
	Self-contained	Split residential	Split commercial	Duct split residential	Commercial ducted splits	Rooftop ducted	Multi-splits	Air conditioning chillers	Process chillers	Car	Large vehicle
Leak reduction (design/const.)	×	×	×	×	×	×	×	×	×	×	×
Leak reduction (maintenance)	×	×	×	×	×	×	×	×	×	×	×
Charge size reduction	×	×	×	×	×	×	×	×	×	×	×
Recovery and recycling	×	×	×	×	×	×	×	×	×	×	×
R-600a											
HC-290 / HC-1270	×	×	×	×				×	×	×	
R-717								×	×		
R-744				×	×	×	×	×	×	×	×
unsat-HFC	×	×	×	×	×	×	×	×	×	×	×
HFC / unsat-HFC blends	×	×	×	×	×	×	×	×	×	×	×
Low-GWP + liquid secondary (centralised)					×	×	×				
Low-GWP + liquid secondary (discrete)		×	×	×	×	×				×	
Low-GWP + evap. secondary					×	×	×				
Low-GWP + cascade											
Distributed water-cooled	×	×	×	×	×	×	×				
District cooling	×	×	×	×	×	×	×	×			

TABLE 6
Applicability of the different technical options of different RAC systems

Technical option	Domestic	Commercial refrigeration			Industrial refrigeration			Transport
	Domestic refrigeration	Stand-alone equipment	Condensing units	Centralised for supermarkets	Stand-alone equipment	Condensing units	Centralised systems	Refrigerated trucks/trailerse vehicle
Leak reduction (design/const.)	×	×	×	×	×	×	×	×
Leak reduction (maintenance)	×	×	×	×	×	×	×	×
Charge size reduction	×	×	×	×	×	×	×	×
Recovery and recycling	×	×	×	×	×	×	×	×
R-600a	×	×			×			
HC-290 / HC-1270		×	×		×	×		×
R-717				×		×	×	
R-744		×	×	×	×	×	×	×
unsat-HFC	×	×	×		×	×	×	×
HFC / unsat-HFC blends	×	×	×		×	×	×	×
Low-GWP + liquid secondary (centralised)				×			×	
Low-GWP + liquid secondary (discrete)			×			×		×
Low-GWP + evap. secondary				×			×	
Low-GWP + cascade				×			×	
Distributed water-cooled			×	×		×	×	
District cooling								

The table below summarises the possible efficiency improvements in the different refrigeration and air-conditioning sub-sectors that could be achieved by applying all of the appropriate measures.

TABLE 7
Overview of the RAC subsectors and the possible efficiency improvements

Sector	Subsector	Efficiency improvement	Efficiency measure**	Additional cost	Reference year	Source
Domestic refrigeration	Domestic refrigeration	50%	TEC	90%	2030	TREN Lot 13
Commercial Refrigeration	Centralised systems for supermarkets	60%	TEC	[30%]*	[2020]*	Various
	Condensing units	31%	TEC	148%	2020	ENTR Lot 1
	Stand-alone equipment	52%	TEC	11%	2025	TREN Lot 12
Industrial refrigeration	Centralised systems	30%	TEC	[50%]*	[2030]*	Various
	Condensing units	31%	TEC	148%	2020	ENTR Lot 1
	Stand-alone equipment	75%	TEC	262%	2020	ENTR Lot 1
Unitary air conditioning	Commercial ducted splits	73% (from 3.97 to 6.87)	Seasonal COP	74%	2030	ENTR Lot 6
	Duct split residential air conditioners	118%	Seasonal COP	46%	2030	TREN Lot 10
	Multi-splits	56% (from 3.53 to 5.51)	Seasonal COP	19%	2030	ENTR Lot 6
	Self-contained air conditioners	118%	Seasonal COP	46%	2030	TREN Lot 10
	Rooftop ducted	80% (from 3.88 to 7.00)	Seasonal COP	50%	2030	ENTR Lot 6
	Split residential air conditioners	118%	Seasonal COP	46%	2030	TREN Lot 10
	Split commercial air conditioners	73% (from 3.97 to 6.87)	Seasonal COP	74%	2030	ENTR Lot 6
Chillers	Air conditioning chillers	55% (from 3.58 to 5.56)	Seasonal COP	49%	2030	ENTR Lot 6
	Process chillers	50%	TEC	100%	2020	ENTR Lot 1
Mobile AC	Car air conditioning	30%	TEC	[50%]*	[2020]*	Various
	Large vehicle air conditioning	30%	TEC	[50%]*	[2020]*	Various
Transport Refrigeration	Refrigerated trucks/trailers	50%	TEC	[50%]*	[2030]*	Burke and Grosskop (2011)

NOTE: For additional cost, a value of 100% is equivalent to doubling the baseline cost of the product.
* Approximated value.
** Two alternative indicators, Total Energy Consumption (TEC) and Co-Efficient of Performance (COP), indicate the Efficiency Improvement as "Efficiency Measure". TEC shows the Efficiency Improvement where the auxiliaries have a proportionally significant share of the energy consumption of the subsector appliances and systems. COP shows the Efficiency Measure for appliances and systems where the compressors is the (single) dominating factor for the energy consumptions.

Source: Module 3 – Technical Options, NAMAs in the refrigeration, air conditioning and foam sectors. A technical handbook, GIZ.

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Designed by SCS Marketing

Editorial support provided by Karen Dehal, Sam Peters and Priyanka Sharma