Technology Collaboration Programme on Heat Pumping Technologies (HPT)

# Annex 53

# Advanced Cooling/Refrigeration Technologies Development

## Executive Summary

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# IEA/HPT Annex 53 Advanced Cooling/Refrigeration Technologies Development – Executive Summary Report

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# Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

### The IEA

The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

### The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or "Annexes", in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.
The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

### Disclaimer

The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes or TCPs. The TCPs are organised under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

### The Heat Pump Centre

A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimise the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organisations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
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Italy, ENEA, Energy Technologies Department
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## Abstract

This report documents work done under the International Energy Agency (IEA) Heat Pumping Technologies collaborative project IEA Annex 53, *Advanced Cooling/Refrigeration Technologies Development*. Research and development institutes in five Heat Pumping Technologies member countries—Germany, Italy, the People's Republic of China, South Korea, and the United States of America—shared information on a range of advanced, lower-carbon heat pump/air-conditioning (AC) technologies. This annex was launched in response to the anticipated heavy growth in worldwide demand for AC and refrigeration by 2050.

The technical scope of Annex 53 was very broad by design. It is unlikely that there will be only one or even a few so-called *right* solutions to the challenge. Therefore, the participants were free to investigate a wide range of possible technology solutions. Research, development, and demonstration efforts focused on advanced, higher-efficiency technology solutions for future AC and refrigeration systems. Technologies included those based on enhancements of the time-proven vapor compression cycle, electrochemical compression, absorption and adsorption (including compressor-assisted) systems, and others based on nontraditional cycles (including magnetocaloric, elastocaloric, electrocaloric, heat pipe–assisted caloric cycles, and more). Technology readiness levels for the investigated technology options ranged from approximately 2 to about 8 by the end of the annex.

# 1. Executive Summary

Air-conditioning (AC) and refrigeration systems account for a large share of current global energy consumption, and this demand is expected to increase sharply over the next 50 years unless actions are taken to ameliorate the increase. The adoption of AC in developed countries increased rapidly in the twentieth century, and the twenty-first century is expected to see increased adoption in developing countries—especially those with hotter climates and large, growing populations, such as India, China, Brazil, and Middle Eastern and African nations. The International Energy Agency (IEA) projects that by 2050, AC energy consumption levels will increase by 4.3× over the 2010 levels for non-Organisation for Economic Co-operation and Development (OECD) countries vs. only 1.5× for OECD countries (Figure ES-1) [1].

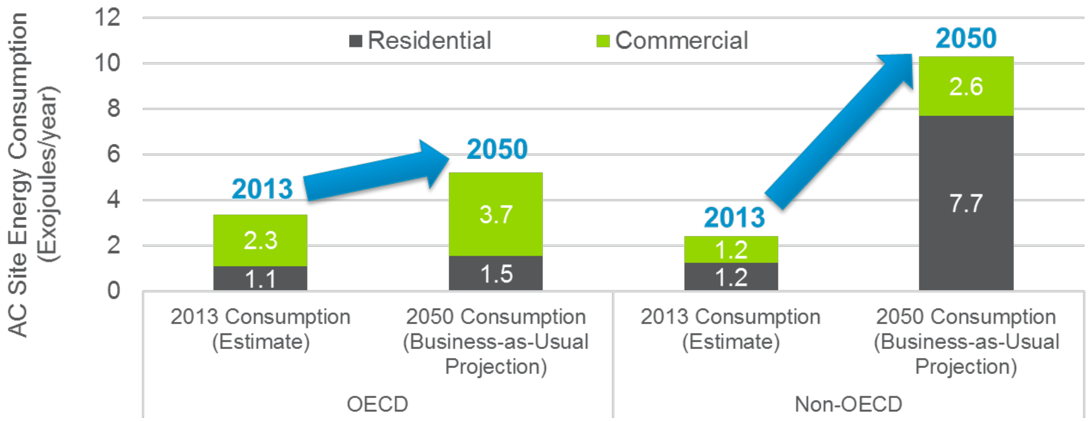


*Figure ES-1 Anticipated global AC demand increases (courtesy of Navigant Consulting, Inc.; source: IEA Energy Technology Perspectives 2016)*

The demand for refrigeration is expected to increase at similar rates, driven primarily by food preservation and storage needs; food demand is expected to increase 70% by 2050 relative to 2010 [2]. India, for example, has the largest refrigerated warehouse capacity of any country in the world, which is expected to reach approximately 40.7 MMT [3]—almost a 35% increase since 2014 [4]. Moreover, a huge increase in refrigerated transport capacity is also needed to properly serve the warehouse capacity and reduce food wastage. India is estimated to currently have 9,000 refrigerated trucks, but the country needs >600,000 [2]. The need for much cleaner and more efficient refrigeration systems is critical. The United Nations Food and Agriculture Organization (FAO) estimates that approximately one-third of all global food produced is wasted, resulting in huge environmental consequences. FAO estimates that this wastage occupies a land area the size of Mexico, its production consumes 250 $km^3$/year of water, and it accounts for 3.3 billion t per year of $CO_2$ emissions.

Global action, both short-term (e.g., increasing the deployment of current best technologies) and long-term (research, development, and demonstration [RD&D] for advanced, higher-efficiency technology solutions), is urgently needed to address this challenge. Annex 53 was initiated in October 2018 to help address the long-term RD&D need. Its main objective is to share information to encourage the development of high-efficiency and low–global warming potential (GWP) AC, refrigeration, and heat pump (HP) technologies. The annex was led by the United States, with participation by research and development (R&D) institutes in the People's Republic of China, Germany, Italy, and South Korea.

This report provides a summary of the current RD&D status of the leading technologies examined by each R&D institute involved in the annex. Technologies of interest follow two distinct paths: those based on the well-known and widely used vapor compression (VC) system and those based on nontraditional cooling approaches that are being increasingly investigated (Figure ES-2). VC could continue to be the system of choice, especially for the near future and possibly for the long-term. To the extent, however, that VC cycle systems continue to use refrigerants with nonzero GWPs—even in small amounts—they will remain vulnerable to further international refrigerant restrictions. Nontraditional technologies (e.g., caloric or other types) generally are not subject to this challenge because they do not rely on refrigerants in the traditional sense. However, all the nontraditional technologies discussed herein will require additional development before they can significantly affect the market.


*Figure ES-2 Two possible future paths for refrigeration and AC systems (courtesy of Navigant Consulting, Inc.; source: US Department of Energy Building Technologies Office, Emerging Technologies Program)*

Table ES-1 provides a snapshot summary of each VC-related project investigated by the Annex 53 participants. Nontraditional technologies investigated during the annex are shown in Table ES-2. Capsule descriptions and estimated technology readiness levels (TRLs) are given for each technology option. The tables also include each participant's thoughts about most likely initial end-use applications for the technologies they investigated during Annex 53.

Table ES-1 Advanced VC focus

| R&D institute | Technology description | Initial target market/application | TRL estimate |
|---|---|---|---|
| Korea Institute of Machinery and Materials and Chung-Ang University, South Korea | Membrane-based HP | Building AC and dehumidification (DH) | Ranges from about 2 to 5 |
| Tsinghua University, China | 1: AC using refrigerant blend with optimized temperature glide in evaporator and condenser<br><br>2: hybrid AC; prototype was Global Cooling Prize winner; prototype cost ~2× baseline AC; recent work focusing on reducing cost<br><br>3: integrated design method, GraPHsep, for optimized design of HPs and heat exchanger networks | Room AC for 1 and 2; industrial HPs for 3 | Ranges from about 7 to 8<br><br>>7<br><br>~5 |
| City University of Hong Kong, China | Absorption thermal energy storage | Commercial heating, ventilation, and air-conditioning | Ranges from about 3 to 5 |
| Institute for Advanced Energy Technologies, Italy | Adsorption transformation for cooling (thermal compression) | Integration with renewable energy sources; waste heat recovery in industrial processes; integration in combined cooling, heat, and power; mobile AC/refrigeration | ranges from about 3 or 4 to ≥7 |

| R&D institute | Technology description | Initial target market/application | TRL estimate |
|---|---|---|---|
| University of Maryland, USA | 1: Electrochemical compression (ECC): selective fluid pumping via chemical process (no moving parts)<br><br>2: Electrohydrodynamic-enhanced electrochemical DH | Building AC for latent and sensible cooling; evaluating the integration of $NH_3$ ECC with $NH_3$ synthesis to produce and store liquid $NH_3$ for use as internal combustion engine fuel | 1: 3<br>2: 3 |
| Oak Ridge National Laboratory, USA | Rotary pressure exchanger for expansion loss recovery in R-744 VC refrigeration systems and HPs | VC refrigeration and HPs, particularly systems using $CO_2$ as the refrigerant | About 8 |

Table ES-2 Nontraditional technologies

| R&D institute | Technology description | Initial target market/application | TRL estimate |
|---|---|---|---|
| University of Maryland, USA | Elastocaloric (EC) cooling | Initial: small-scale refrigerators (wine coolers, etc.)<br><br>Eventually: residential refrigerators and small Acs | 3 |
| Xi'an Jiao Tong University, China | EC cooling | Initial: portable beverage coolers<br><br>With further development: residential refrigerator or personal cooling device<br><br>Thermal-driven EC: solar-thermal AC or refrigerator; waste heat recovery mobile AC | About 4<br><br><br><br>Ranges from about 2 to 3 |
| Shanghai Jiao Tong University, China | Electrocaloric cooling | Personal cooling devices, electric vehicle battery thermal management or seat coolers, data center on-chip cooling; miniature, portable Acs | Ranges from about 3 to 5 |
| Fraunhofer Institute for Physical Measurement Techniques | Active caloric heat pipe concept | Medical or lab device cooling; mobile AC systems; residential HPs | Ranges from about 3 to 4 |
| Ames National Laboratory, USA | a) High–power density magnetocaloric (MC) systems | Residential refrigerators or AC | Ranges from about 3 to 4 |
| Oak Ridge National Laboratory, USA | Alternative cooling technology using MC materials | Refrigerators; residential or specialty | About 3 |

## 1.1. Annex Significant Accomplishments

- **Tsinghua University (TU)/China:** Prototype hybrid AC system developed under partnership between Tsinghua University and Gree Electric Appliances, Inc. of Zuhai, was named one of the two Grand Winners of the Global Cooling Prize competition (2018–2021).
- **TU/China:** Hybrid AC cost reduction efforts have led to potentially 15%–20% lower cost so far.
- **City University of Hong Kong (CUHK)/China:** R&D investigating absorption thermal energy storage system (ATES) cycles achieved maximum energy storage efficiency,

energy storage density (ESD), and exergy efficiency values of 1.53, 365.4 kWh/$m^3$, and 0.61, by a double-effect ATES cycle, a compression-assisted ATES cycle, and the basic ATES cycle, respectively. This work aims to facilitate the rational development of ATES cycles for high-density and high-efficiency thermal energy storage toward carbon neutrality.

- **CUHK/China:** A prototype of a two-stage ATES was successfully developed. Experimental results showed that it can operate under extremely low charging temperatures (~50°C). The two-stage ATES has the advantages of higher ESD and lower charging temperature than the conventional ATES, providing a great option for low-grade renewable energy use.
- **ITAE/Italy:** The team at ITAE showed that employing plastic material could achieve an adsorber mass reduction in the range of 50% to 65% compared to aluminum while still maintaining similar performance.
- **Chung-Ang University (CAU)/South Korea:** To realize active membrane dehumidification, a highly water-selective membrane material will be required.
- **University of Maryland (UoMD)/USA:** Electrochemical $NH_3$ compressors were shown to have isentropic efficiency that monotonically increases with pressure ratio in contrast with positive displacement mechanical screw compressors, which show a peak in efficiency and then a decrease as pressure ratio continues to rise. Elastocaloric (EC) compressors may, thus, have an advantage for high suction-to-discharge pressure applications.
- **UoMD/USA:** Lab test EC dehumidification prototype achieved dehumidification 175% higher than shown by previous lab systems.
- **UoMD/USA:** A 260 W EC cooling prototype has been developed. This prototype is the largest power caloric system outside of reported magnetocaloric systems and indicates that the EC technology is rapidly maturing.
- **Oak Ridge National Laboratory (ORNL)/USA:** Field tests of a pressure exchanger (PEx) component integrated into the $CO_2$ transcritical refrigeration system of a supermarket in northern Italy demonstrated coefficient of performance (COP) improvements up to 27% under high–ambient temperature operation.
- **ORNL/USA:** Analytical projections for PEx-equipped HP systems show up to 30% efficiency boost.
- **Xi'an Jiao Tong University (XJTU)/China:** A Ni–Ti EC wine refrigerator design was developed with 100 W cooling power and a projected cost (at volume production) of $270.
- **XJTU/China:** A solar heat–driven EC system design was projected (by simulation) to have a COP >1.0 with a 120°C driving temperature. This COP exceeds that of both a state-of-the-art single-effect LiBr–$H_2O$ absorption chiller and a photovoltaic-driven electric AC unit.
- **Shanghai Jiao Tong University (SJTU)/China:** A proposed electrocaloric HP device operating with a high-entropy polymer achieved a maximum COP of 11.4 (~80% of Carnot) compared with a COP of 1 when operating with a baseline terpolymer.
- **SJTU/China:** The conflict between high thermal conductivity and high electrocaloric effect (ECE) has been demonstrated on the molecular level. Click chemistry has been applied to expand the ordered and disordered structure to achieve both high ECE and large thermal conductivity.
- **SJTU/China:** An interface-regulated nanocomposite exhibited an electrocaloric entropy change of 30.94 J/(kg·K) under 100 MV/m and tripled thermal conductivity of 0.72 W/(m·K). Using a nanocomposite material, the standard model of an electrocaloric refrigerator achieved a 5.23 W/g cooling power density, 6.8× higher than the one operating with a simple material.
- **SJTU/China:** A figure of merit for electrocaloric nanocomposites has been proposed to assess their overall capability in heat-pumping applications.

- **Fraunhofer Institute for Physical Measurement Techniques (IPM)/Germany:** Three heat pipe–coupled caloric technologies—magneto-, elasto-, and electrocalorics—were successfully demonstrated. High cooling power densities of 12.5, 6.25, and 1.50 W/g of MC material were attained for magnetocaloric (MC), EC, and electrocaloric systems, respectively. At this point, an increase in system frequency, and thereby in maximum cooling power density, was hindered by the structure size of the caloric material (MC and EC) or the self-heating owing to dissipative losses in the material (electrocaloric). These aspects will be addressed in future work, as well as an increase in the temperature lift of the systems by cascading several segments.
- **Ames National Laboratory (ANL)/USA:** An MC device was demonstrated and projected to have approximately 10 W/kg power density at 50 W cooling power (based on total mass of all magnetic material in the device), which is higher than almost all MC devices in similar cooling power ranges.
- **ANL/USA:** Estimates show that power density of similar MC devices can match that of commercially available mechanical compressors up to approximately 500 W. Meeting or exceeding the power density of compressors in given power ranges demonstrates that there is a viable path to cost parity and commercial adoption of the technology.
- **ANL/USA:** The highest estimated power density for MC devices using first-order materials was 162 W/kg at approximately 10 kW.
- **ORNL/USA:** Model results indicate the potential for an MC refrigeration cycle with a 16-stage regenerator to reach 84% of Carnot COP.

### 1.2. Potential Follow-On Annex Topics

Currently, the main focus in the field of heat pumping technologies is the expedient, effective, and efficient implementation of systems in the field in large numbers. Advancing the technology itself, in the form of more efficient, compact, and lower-cost vapor compression (VC) systems or the development of entirely new technologies that may potentially supplement or replace VC altogether, is taking a back seat. It may be appropriate, therefore, to undertake a follow-up annex or annex-like effort to foster collaboration and the exchange of information among researchers worldwide to expand the cost-effective efficiency envelop of future heat pumping technologies. The objective of such an effort is to promote, enhance, and strengthen research initiatives that help to bring next-generation technologies and approaches for heat pumping to the market, fulfilling a core mission of the IEA Technology Collaboration Programme on Heat Pumping Technologies.

The goal is to enable revolutionary progress of all heat pumping technologies, not incremental advances. All heat pumping (heating, cooling, refrigeration, and dehumidification) technologies would be included in the scope as long as the focus of the work is to go significantly beyond current state-of-the-art approaches and foster novel ideas and concepts. This objective is similar to those of efforts now underway by the International Institute of Refrigeration (IIR) particularly the IIR working group Solid-State Cooling and Heating (https://iifiir.org/en/news/new-iir-working-group-on-solid-state-cooling-and-heating). Therefore, a strong collaboration with the IIR in this proposed follow-up to Annex 53 is strongly encouraged.

This proposed effort is envisioned as a very long-term effort (beyond the duration of typical annexes) and has only one major task: the regular exchange of information among participating researchers to mutually enhance motivation, progress, and creativity. One potential output/deliverable of the work would be to have an annual webinar series where brief updates on specific projects are presented for the wider heat pumping community. These webinars could perhaps be held in conjunction with the ongoing IIR THERMAG events (https://iifiir.org/en/events/11th-iir-conference-on-caloric-cooling-and-applications-of-caloric-materials) or other related conferences when appropriate.

## 1.3. Specific Future RD&D Topic Suggestions from Annex 53 Participants

- **CAU/South Korea:** Technology development on vacuum membrane dehumidification should be developed further experimentally. Also, the influence by selectivity should be discussed to enhance the system performance. The priority should be set for the development of a high-permeance, high-selectivity membrane.

- **CUHK/China:** Advanced HP technologies for heating should be further investigated. In Annex 53, this work focused on advanced HP technologies for cooling. Because space heating and process heating are also energy-intensive, it is also necessary to investigate some advanced heating technologies. This work is significant for addressing the energy crisis and achieving carbon neutrality.
- **ORNL/USA:** Investigate the application of PEx to high-temperature HPs using CO2 refrigerant.
- **UoMD/USA:** Develop higher-power EC systems. Explore new materials to develop smaller-footprint actuators for implementation as EC system drivers.
- **XJTU/China:** Rate not-in-kind cooling prototypes at target applications' standard rating conditions.
- **SJTU/China:** Continue work on high-entropy ceramics and their multilayer ceramic capacitor (MLCC). If successful, the MLCC would exhibit extended cooling capacity, which is an essential step for fabricating an electrocaloric cooling machine with large cooling power.
- **SJTU/China:** Develop multilayer polymeric capacitors for the wide Tspan of an electrocaloric device.
- **IPM/Germany:** Standardize caloric measurements (e.g., adiabatic temperature change, isothermal entropy change, hysteretic losses of materials, cooling power, temperature lift and efficiency of systems), as well as establishing a standardized nomenclature.
- **ANL/USA:** Demonstrate first-order MC materials and advanced regenerators to achieve power density parity with compressors above approximately 10 kW.
- **ANL/USA:** Investigate additional materials and device concepts that can meet the temperature spans and power (heating or cooling) of additional end-use applications.
- **ANL/USA:** Investigate the potential for both cooling and heating in a single caloric (magneto-, elasto-, electro-, multicaloric) HP.

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