comment

Five thermal energy grand challenges for decarbonization

Roughly 90% of the world's energy use today involves generation or manipulation of heat over a wide range of temperatures. Here, we note five key applications of research in thermal energy that could help make significant progress towards mitigating climate change at the necessary scale and urgency.

Asegun Henry, Ravi Prasher and Arun Majumdar

Advancing our ability to transport, store, convert and efficiently utilize thermal energy will play an indispensable role in avoiding a greater than 2 °C rise in global average temperature. Even though this critical need exists, there is a significant disconnect between current research in thermal sciences and what is needed for deep decarbonization.

Here, we highlight five thermal science and engineering grand challenges that we believe could have a meaningful impact on global emissions. These were identified based on estimations of the size of their potential impact (that is, by assessing the fraction of global greenhouse gas (GHG) emissions that could be abated if the technology was maximally successful), as well as our own opinions and qualitative assessments of the magnitude of the opportunities for scientific advancement and technological breakthroughs. For example, improving the efficiency of heat engines in the stationary power sector is not highlighted here, despite the fact that it could be impactful, because current heat engines already operate very close to their thermodynamic limits.

Thermal storage systems

As solar and wind electricity penetration has increased, its intermittency has hastened the need for low-cost storage over a wide range of time scales, from seconds to days, and even seasonal storage. Current technologies, such as pumped hydroelectricity, are geographically limited and lithium-ion batteries (~US\$80–100 kWh^{-1} capital cost) are too expensive for the multi-day storage targets (~US\$3–30 kWh^{-1}) needed to fully decarbonize the grid[1,2]. Solving this problem could enable full decarbonization of the grid, thereby reducing global GHG emissions by ~25%[3,4]. Thus, the storage problem is one of the single most impactful problems to be solved.

Several new thermal energy storage (TES) concepts have been proposed[5,6]. While it is relatively easy to convert electricity to heat at a variety of temperatures, the key challenge for TES is the large efficiency penalty associated with the second law of thermodynamics when converting heat back to electricity.

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However, the key advantage for TES is its potential for low cost (<US\$20 kWh^{-1}) at the gigawatt scale[5,6]. This is because, unlike batteries, where only a small fraction of the atoms that make up the device are actually active species carrying energy, with TES virtually every atom is participating, albeit with much less energy (that is, meV versus eV for batteries). Nonetheless, since the specific heat of virtually all materials is the same on a molar basis, at high temperatures, TES can make use of extremely abundant and low-cost materials that are impure or even recycled.

Although several embodiments of TES have been put forth, they are still early stage and have not yet reached commercial deployment. Thus, there is a need to continue developing more competing embodiments that exploit other thermal storage materials and mechanisms. In particular, it is of utmost importance to develop full-system concepts that carefully consider all of the practical issues (for example, materials degradation and compatibility over time, safety, system integration, transients and so on) that might stifle or prevent commercial deployment. For example, systems that utilize a liquid medium typically have to deal with issues of corrosion and how the liquid will be pumped, which can be very challenging at high temperatures. However, a recent demonstration of pumping at 1400 °C suggests it is nonetheless possible[7]. For systems that utilize a solid TES medium, the intrinsically transient output as conductive resistance builds up is inevitable and it is important to consider how this might affect the heat engine. For example, power generating turbines are usually optimized for a specific inlet temperature, and if the TES medium's output decreases during the discharge, it can have a major impact on efficiency.

Low-cost, high-gravimetric and high-volumetric energy density TES systems can also significantly extend the range of electric vehicles (EVs), because as much as 40% of the electrical battery capacity in EVs is used for cabin heating/cooling[8]. TES could also play a major role in offsetting heating/cooling loads in buildings as heating/cooling is expected to be more than 50% of the load in buildings[9,10]. First, buffering heat in the walls of a building could reduce its net energy consumption, by enabling time-shifted matching of internal thermal demand with the diurnal temperature swings of the external natural environment. Second, TES has the ability to make use of inexpensive renewable electricity during its peak production (often oversupply), by storing it in the form most conducive to its final usage — namely as thermal energy for space heating/cooling, instead of electricity.

One fundamental challenge in TES adoption is that there is limited tunability in the usage temperature. For example, if the required temperature is 25 °C and the ambient temperature swings above and below 25°C, two different TES materials and systems are needed, which dramatically reduces the utilization of each system, leading to a higher cost.

Since the levelized cost of storage (LCOS) is inversely proportional to its utilization factor, tunable TES has the potential to dramatically decrease the LCOS. Advances will require revisiting the thermodynamics of phase transitions to look for ways that such transitions can be manipulated using external fields, for example an electric field or pressure[11]. There are already promising examples of research in this direction. Li et al. for instance demonstrated a large effect (~10–20 °C) on the transition temperature in plastic crystals by applying pressure[11].

Decarbonizing industrial processes

GHG emissions in the industrial sector comprise more than 15% of global emissions, the majority of which are associated with providing heat at temperatures of 100–1000 °C. Aside from providing heat, there are many cases where one must also compensate for the thermodynamic driving force associated with forming CO_2. This can only happen electrochemically (for example, electrolysis)[12], thermally (for example, pyrolysis)[13], with a reducing agent such as H_2 that is synthesized without CO_2 emissions, or through some combination of the previous three. Although each industry poses its own unique challenges, the most significant industries are: cement, iron/steel, aluminium and hydrogen (H_2), which are each responsible for approximately 10%, 4%, 1%, and 1% of global GHG emissions, respectively.

With the rapidly decreasing cost of renewable electricity and potentially GHG free H_2[13], it's now feasible to decarbonize the industrial sector by using either resistive heaters or H_2 combustors[14]. The industrial processes can be redesigned so that they use low-cost intermittent renewable energy to provide the required heat. The heat can also be localized only where needed[15]. There is also an opportunity to invent or develop new processes that use one of the aforementioned approaches for thermodynamic compensation[12,13].

Significant science and engineering challenges, however, still remain. For intermittent renewable electricity, either cheap high temperature storage needs to be developed (see section on storage) or low capacity factor furnaces need to be developed. Heat from electricity can also be added volumetrically (for example, via microwaves, joule heating or by induction), which has a major advantage over convection since heat can also be delivered locally, but the cost and durability needs to be improved. GHG free H_2 can be used as a fuel to provide heat, although there are still significant issues associated with the design of and dynamics within H_2 combustors that have not been completely solved[14]. Promising combustor designs[14], such as the low swirl burner, have emerged in the past few years as a potential solution, but their scalability needs further development.

Initial demonstrations of alternative approaches for steel using high-temperature electrochemical systems and H_2 as a reductant have been achieved[12], but more work is needed. For cement, no chemistry has been identified yet that does not generate CO_2. Therefore, research to find GHG free alternatives is needed, otherwise CO_2 capture will be required. Finally, one option for H_2 that is currently being explored is methane pyrolysis, which could produce H_2 at competitive costs along with solid carbon, which could be used as construction material[13]. However, carbon deposition in reactors has been a major challenge, and although some exciting progress such as using a liquid metal[16] to solve this problem has been made, further research is needed.

Cooling and heat pumping systems

The global warming potential of hydrofluorocarbons (HFCs), which are used as refrigerants, is more than 2000 times that of CO_2. With the growing demand for air-conditioning in developing economies and the electrification of heating using heat pumps in developed economies, it is expected that the seemingly unavoidable leakage of HFCs alone could single-handedly become a notable fraction (10–40%) of the planet's global warming by 2050[17]. Therefore, affordable and scalable high energy efficiency cooling systems using refrigerants that are non-toxic, non-flammable and that have a warming potential not worse than CO_2 are needed. However, currently there are no viable solutions that meet all of these requirements.

Research is needed to either identify and characterize new refrigerants or to develop higher coefficient of performance low-cost systems that use an alternative to HFCs for mechanical vapour compression (MVC), a new approach to preventing refrigerant leakage, or a completely new type of refrigeration system (non-MVC). There is also a need to develop alternatives that decouple dehumidification from cooling, as the dehumidification load (that is, a latent heat load) can add significant inefficiency to the system[18]. For example, this could involve compression by electrochemical, instead of mechanical means, or by making use of a different form of entropy change, for example, via a redox couple, thermoelectricity, thermoacoustics or barocaloric materials[11], combined with membrane-based dehumidification processes. Recently, evaporative cooling has been proposed to provide an additional efficiency boost to MVC based systems (https://globalcoolingprize.org), however, it's important to consider how much extra water will be needed, as access to clean water is another global challenge.

Long distance transmission of heat

Space and water heating in both residential and commercial buildings are delivered below 60 °C. They comprise ~8% of primary energy consumption in the US (that is, ~7.75 Quads) and they are responsible for more than 6% of US GHG emissions[19]. In principle, this could potentially be provided by waste heat from power plants (~25.4 Quads). However, we cannot transport large amounts of heat over large distances (~10 miles) while incurring only a small (1–5°C) temperature difference or exergy loss. This is an issue of power density, as the goal is to transport large megawatt-scale heat using minimal equipment and materials, so that it is cost effective like an electrical power line. The main difference from transmitting electrical power, however, is that whereas electrical conductivity spans ~30 orders of magnitude (for example, silver versus Teflon), thermal conductivity only spans about 6 orders of magnitude (for example, air versus diamond). There is no fundamental upper bound on thermal conductivity, and thus the discovery of a thermal superconductor[20] would enable long distance transmission of heat, but it is not clear if one can be practically made. Alternatively, one could add enthalpy in an endothermic reaction or phase transition, move the products over long distances and recombine them in an exothermic reaction, which could essentially move heat with potentially small temperature differences.

One approach could use a thermochemical heat transfer fluid and storage medium, such as the ammonia dissociation reaction[21]. However, with the advancements in computational chemistry, which enable ab initio prediction of reaction enthalpies, it may now be possible to discover[22] other pumpable fluids with reversible chemical reactions, that can be used to move enthalpy. Such long-distance heat transmission could also allow much more effective thermal utilization within large chemical plants, which, in general, have not been designed and built to minimize GHG emissions.

Variable conductance building envelopes

In the built environment, the requirements for temperature, humidity and indoor air quality are well known and do not change during the day, but the outdoor temperatures and conditions can vary significantly. However, at times it may be prudent to leverage the external environment for the built environment. One approach is to intelligently trigger the modification of the thermal conductance of building envelopes using non-linear thermal devices[23]. For example, this would allow building walls to be insulating on a hot day to prevent heat from leaking in from the outside, but if the temperature drops at night, the walls could intelligently switch to being conducting to allow heat from the building to escape, thereby enabling free cooling.

A recent study[24] showed that a variable conductance building envelope can lead to energy savings anywhere from 7% to 42% in different cities across the US, which would have a major impact on reducing GHG emissions. This could also enable on-demand control of envelope-based TES. The desired characteristics of a variable conductance envelope are: a high on-state and off-state thermal conductance ratio[25], a very low conductance in the insulating state (off-state), a large number of cycles between on and off states and low power consumption. Enabling a variable conductance envelope will require research in developing cost effective and reliable materials and devices.

Concluding remarks

It seems inconceivable that we can achieve deep decarbonization without technological breakthroughs in thermal science and engineering. Yet, thermal science and engineering has not received as much attention from the research community and funding organizations. Here, we have highlighted five unique challenges in this realm, which, if addressed adequately, can each potentially produce gigatonne-scale reductions in GHG emissions. Given that energy and climate is one of the defining challenges of the 21st century, we hope this will serve as an intellectual appeal and a call to action for the broader research and development community. ❐

Asegun Henry[1✉], **Ravi Prasher**[2,3] and **Arun Majumdar**[4,5,6]

[1]Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA. [2]Lawrence Berkeley National Laboratory, Berkeley, CA, USA. [3]Department of Mechanical Engineering, University of California, Berkeley, CA, USA. [4]Stanford Precourt Institute for Energy, Stanford, CA, USA. [5]Department of Mechanical Engineering, Stanford University, Stanford, CA, USA. [6]Department of Photon Science, SLAC, Menlo Park, CA, USA.

✉*e-mail: ase@mit.edu*

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Competing interests

The authors declare no competing interests.