

Nanotechnology solutions for the climate crisis

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Climate change is one of humankind's biggest challenges, leading to more frequent and intense climate extremes, including heatwaves, wildfires, hurricanes, ocean acidification, and increased extinction rates. Nanotechnology already plays an important role in decarbonizing critical processes. Still, despite the technical advances seen in the last decades, the International Energy Agency has identified many sectors that are not on track to achieve the global climate mitigation goals by 2030. Here, a multi-stakeholder group of nanoscientists from the public, private, and philanthropic sectors discuss four high-potential application spaces where nanotechnologies could accelerate progress: batteries and energy storage; catalysis; coatings, lubricants, membranes, and other interface technology; and capture of greenhouse gases. This Comment highlights opportunities and current gaps for those working to minimize the climate crisis and provides a framework for the nanotechnology community to answer the call to action on this global issue.

The severity of the climate crisis and the short timeline to dangerous tipping points require step-change solutions¹ in industrial processes. Nanotechnologies can help achieve these step-changes precisely because nanostructures are orders of magnitude smaller than bulk systems. It's at the nanoscale that the inherent behaviour of energy and matter at the scale of atoms, molecules, and interfaces manifests itself. Nanotechnologies have already delivered disruptive step-changes to the status-quo in other sectors: exponential reduction in power consumption and miniaturization in the semiconductor industry; increasing efficiency in photovoltaic devices; and record-time development of COVID-19 vaccines using lipid nanoparticles.

Given the crucial role of nanotechnology in modern society, the White House Office of Science and Technology Policy and the National Nanotechnology Initiative (NNI) launched Nano4EARTH (www.nano.gov/Nano4EARTH), the National Nanotechnology Challenge on climate change. Nano4EARTH aims to mobilize the nanotechnology community to accelerate the responsible development of climate change solutions, which promote innovation while safeguarding the well-being of workers, consumers, and the environment.

Studies have charted plausible paths to net zero emissions^{2,3}, providing blueprints and priority areas for nanoscientists addressing climate change. Nano4EARTH activities have identified four priority areas as examples of high-potential and high-impact opportunities for addressing the climate crisis: 1) batteries and energy storage for electrification, 2) nanocatalysts to decarbonize industries, 3) nanotechnology-enabled solutions for friction reduction at interfaces, and 4) greenhouse gas (GHG) capture and storage⁴ (Fig. 1).

Energy storage: electrifying the world with nanotechnology

The variable power output of solar and wind energy requires batteries and other energy storage technologies to maintain the balance between supply and demand. Likewise, as the transportation sector transitions to battery electric vehicles (BEVs), demand for light, safe, durable, and efficient batteries will increase, with concomitant mining of critical minerals and associated environmental and national security concerns. Using nanomaterials in traditional battery electrode configurations enhances power density and reduces recharge time. New electrode designs based on nanomaterials require less material volume due to increased electrode surface area.

In high-rate batteries typically used in BEVs and high-performance electronics, nanomaterials are less likely to undergo phase transformations upon cation insertion and de-insertion, as compared to larger particles⁵. Phase transformation is associated with mechanical failure, poor rate performance, and shorter cycle life⁵. Longer-lasting batteries in turn lead to reduced manufacturing, mining, and GHG emissions.

Novel materials, chemistries, and architectures can leverage nanomaterial properties to create alternative battery chemistries to Li-ion. Researchers are investigating nanomaterials for sodium-sulfur batteries or air-sulfur batteries to improve battery lifetime and enable electrification in shipping and the grid. These types of batteries have several advantages (for example, safety, cost, and supply chain security), but the larger size of the cations (Na^+ , Mg^{2+} , Ca^{2+} , Al^{3+}) require diffusion pathways with larger diffusion entry points. Nanoparticulate electrodes can better accommodate the stress and strain of inserting larger cations. For example, MXenes can deliver more than 17% higher Na-storage capacity than conventional electrodes made with polyvinylidene fluoride (PVDF)⁶.

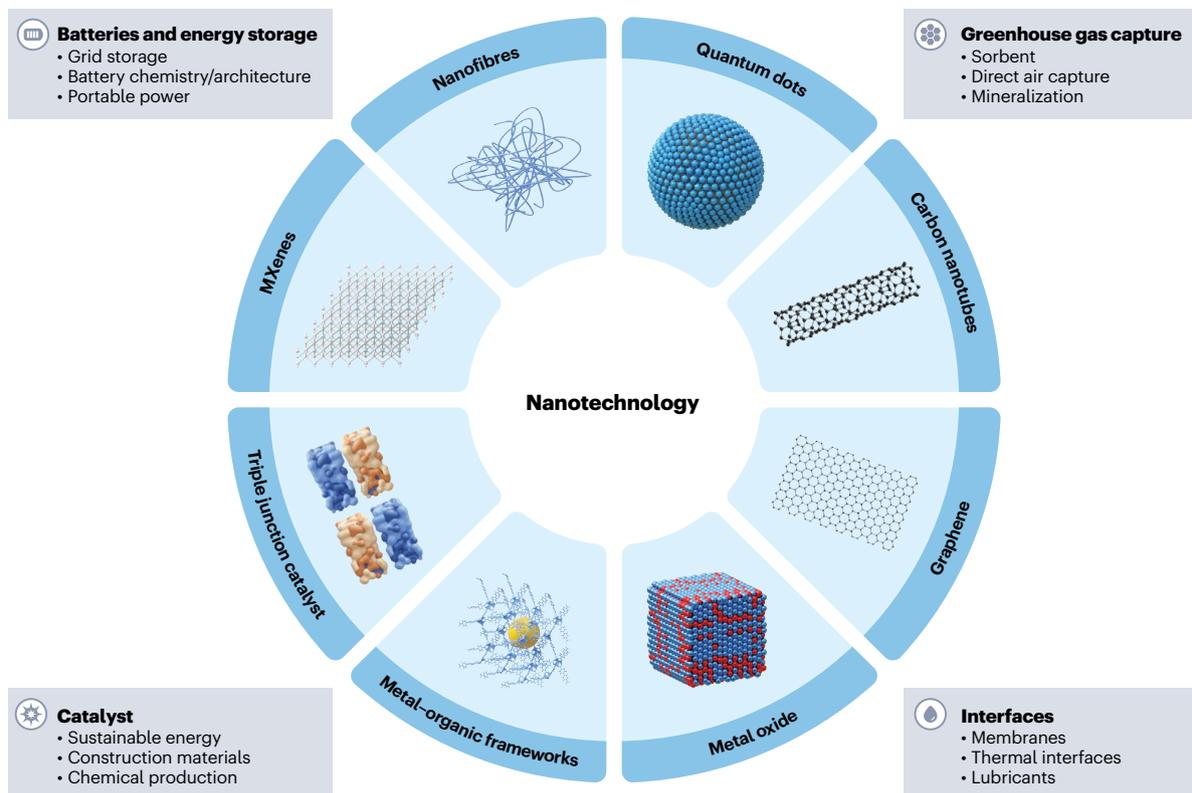


Fig. 1 | Nanotechnologies for climate solutions. Examples of nanotechnology-enabled solutions for climate-intensive processes. The examples shown illustrate nanomaterials and technologies for 1) batteries and energy storage; 2)

greenhouse gas capture; 3) interfaces; and 4) catalysis. The inside of the circle highlights nanomaterials that are being used to enable climate solutions; the outer circle shows examples of specific technologies.

Nanocatalysts: catalysing clean energy and ‘low-carbon’ materials

Nano-sized catalytic materials, such as metals, metal oxides, low-dimensional materials, and structural substrates (for example, zeolites and metal–organic frameworks (MOFs)) possess larger surface area to volume ratios over traditional catalysts, allowing more contact area with reactants. Well-designed nanocatalysts have higher activity, stability, selectivity, and recoverability, making them eco-friendly and cost-efficient.

Nanocatalysts can enable low-carbon emission processes to prepare GHG-intensive materials and fuels such as ammonia, cement, hydrogen, iron, petrochemicals, plastics, and steel, that currently rely heavily on hydrocarbons throughout their production chain. For example, rare-earth metals are currently the most efficient way to split water molecules to create green hydrogen, but limited supply and high cost prohibit scalability. However, a catalyst made of atomically dispersed Ir on top of MnO_2 uses 95% less Ir but achieves the same results as Ir by itself⁷, providing a path to move away from current hydrogen processes that rely on hydrocarbons (grey hydrogen). Triple junction catalysts, which couple three different materials – only possible at the nanoscale – provide greater activity, durability, and stability in different media. Engineered triple junction nanocatalysts can achieve precise selectivity that takes advantage of the controlled distribution of the active components, minimizing unwanted reactivity⁸. Nanocatalytic pyrolysis of captured methane offers a sustainable method to produce carbon nanomaterials and hydrogen, which could have the

potential to substitute a percentage of hard-to-abate (hard to mitigate CO_2 release) technologies for the production of materials such as steel, aluminium, and cement⁹.

Nanocatalysts can also help expand utilization of captured GHGs. Photocatalysts such as metal sulfides¹⁰ and TiO_2 (ref. 11) can reduce CO_2 and other GHG captured from the atmosphere and transform them into value-added fuels or other products¹¹. Commercial production of synthetic fuels from captured CO_2 is already available, but in modest quantities. Scaling up carbon capturing and production of net-zero replacement fuels that do not require significant changes in existing infrastructure or production processes has the potential to drastically reduce the carbon footprint of the aviation and shipping industries, which cannot be easily electrified.

Waste can also be transformed into value-added products. The transesterification reaction, which converts free fatty acids with alcohol to biodiesel, can be improved by incorporating CaO nanocatalysts synthesized from eggshells waste. Biofuel development may lead to increased use in international shipping. Nanocatalysts that enable the distributed and cost-efficient production of fuels or products can facilitate adoption of sustainable solutions.

Energy transfer efficiency: nanotechnology at interfaces

Interfacial inefficiencies related to coatings, lubricants, and membranes affect many industrial processes. It is estimated that tribological advances across the transportation, industrial, and utilities sectors could save nearly 11% of total energy use in the United States¹². In the last

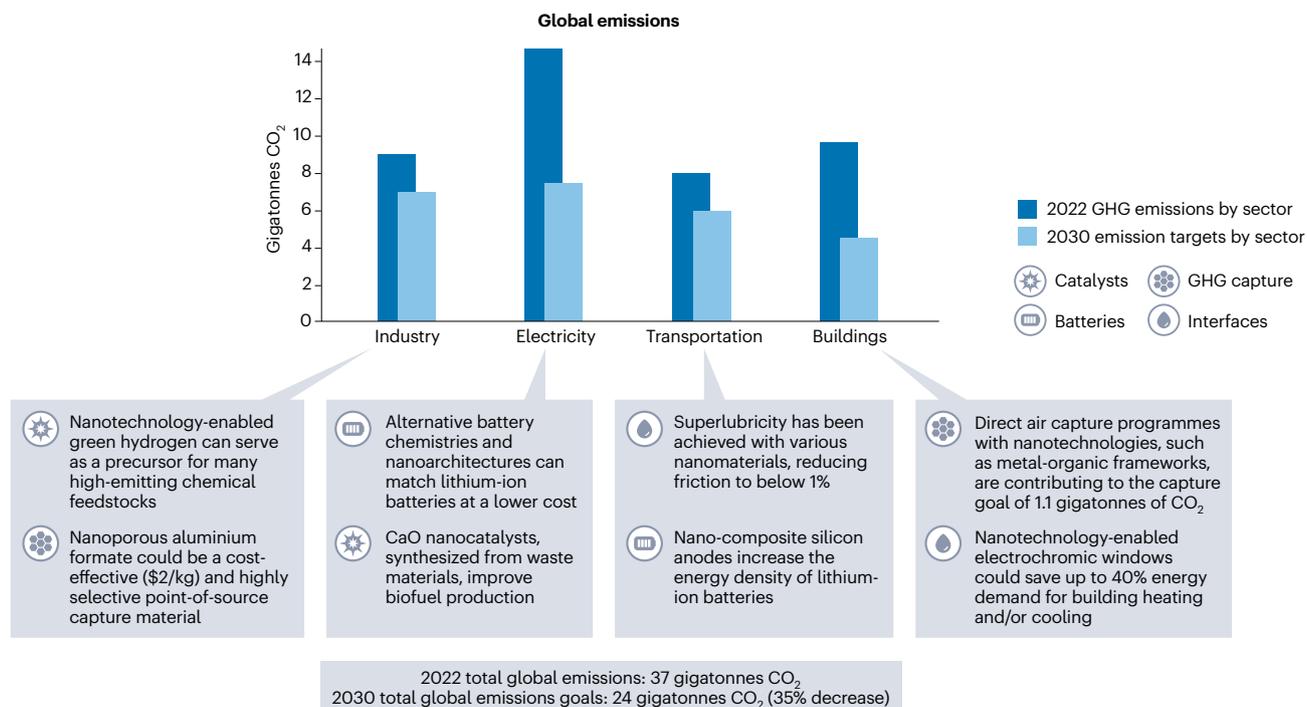


Fig. 2 | Greenhouse gas emission reduction by sector and potential nanotechnologies to meet 2030 targets. High-emission sectors, industry, electricity, transportation, and building are high-opportunity areas for

nanotechnology-enabled innovations to make a step-change impact to meet global climate goals. For more information on 2022 global emissions and 2030 targets please refer to ref. 25.

25 years, advances in nanomaterials have helped push the limit of tribology from coefficients of friction of around 0.08 to levels lower than 0.0005 (ref. 13). Several nanomaterials, including graphene, MXenes, and diamond-like carbon, have achieved superlubricity (coefficients of friction below 0.01) (ref. 14). Other nanolubricants include ‘intelligent’ oils that incorporate nanomaterials that release supplemental additives as a function of various physicochemical forces, which could increase fuel economy savings of up to 6% (ref. 12).

Additionally, the energy required to meet the cooling demands of today’s modern electronic systems accounts for 1–2% of global energy consumption. Nanotechnology-based thermal interface materials leverage a unique combination of thermal and mechanical properties, due to nanoscale confinement. For example, aligned carbon nanotubes can provide high through-plane thermal conductivity, while their elasticity allows reliable thermal contact during thermal cycling. This results in a >10 times reduction in thermal resistance compared to the thermal greases and pads typically used today in electronics¹⁵. These technologies have already demonstrated lower manufacturing costs (>60% reduction¹⁶), less waste production, and reduced time from design to commercial launch.

The chemical industry in the US accounts for at least 25% of industrial energy usage, over half of which is needed for chemical separations, which uses heating and cooling. Nanotechnology-based membranes or nanoporous adsorbents can enable more efficient and sustainable separation than conventional thermal or auxiliary phase processes. Effective membrane design requires a difficult balance between permeability and selectivity to allow the desired component to flow freely without other chemicals passing through. The membrane must also be produced at a large scale and be durable enough

for sustained economic use. Advances in nanoscale manufacturing aim to address these issues through increased replicability and scalability. Zeolites and nanofiltration membranes made of graphene oxide, metal oxides, MOFs, nanofibres, or carbon nanotubes could be used as alternatives to thermal distillation. For example, through adsorption, ion-exchange, or catalysis zeolites can perform chemical separations based on their micro- and nanopores, minimizing the need for energy-intensive thermal changes, and are already being used in many fields including hydrocarbon separation¹⁷. Nanotechnology has strongly impacted the separations processes, as illustrated by reverse osmosis. Industrial-scale desalination (developed around 1981) is nowadays carried out using polymer nanoscale membranes. The cost of desalination is sensitive to energy cost, but improvements in membranes since the 1990s have reduced the current cost by a factor of ~3. Novel nanofiltration membranes are nowadays competing with reverse osmosis membranes, achieving energy savings of up to 29% (ref. 18).

Carbon management: capturing carbon with nanotechnology

Carbon management – including point-source carbon capture and storage (CCS), direct air capture (DAC), and land sink approaches – is another key enabler for GHG reduction targets². The US Department of Energy Carbon Negative Shot initiative set the goal of US\$100 per metric tonne of removed carbon dioxide by 2030. Major hurdles remain, however, that span technological and economic barriers¹⁹, though some governments including the United States, are making investments to drive market development.

Nano-enabled capture solutions include nanoporous polymers, low-dimensional nanomaterials, nanocatalytic CO₂ conversion,

nanostructured ionic liquids, and nanoengineered filtration membranes. For example, engineered nanoparticles can enable land and ocean sequestration of GHG through nanoparticle-directed mineralization and nanoparticle-enhanced algae or phytoplankton growth.

MOFs can be designed to act as solid ‘nano-sponges’ that selectively absorb CO₂ through both physisorption and chemisorption mechanisms. The goal is to create water-stable and highly selective CO₂ capture systems targeted to DAC or flue-gas applications. For example, the small-pore MOF CALF-20 (ref. 20) is already used in a metric tonne per day capture at a first-of-its-kind demonstration project at a cement plant in Richmond, British Columbia²¹. Bottlenecks to globally scaling such technologies include chemical stability in humid atmospheres, material synthesis cost, and access to sufficient raw materials. Yet, for relatively dry flue gas applications, the highly CO₂-selective nanoporous aluminium formate²² could be cost-effective (US\$2 per kg) even if the uptake capacities are more modest than with other MOFs. When combined with an efficient CO₂-to-formate catalytic conversion of the captured gas, an almost circular economy in producing one of the starting components of the MOF is possible, hence reducing the demands for a scale-up process.

Outlook

Reaching net-zero emissions by 2050, as well as substantial near-term emission reductions by 2030, are needed to avoid the worst impacts of climate change globally. There is a unique opportunity for nanotechnology to contribute to this goal (Fig. 2) by focusing on high-emission sectors such as buildings, electricity, industry, and transportation. Urgent action is needed to rapidly scale-up and implement new climate solutions, drawing insights from successful nanotechnology applications.

Globally, buildings account for almost 9.8 gigatonnes of CO₂ released into the environment each year. According to the IEA, overall building-related emissions, which are mainly from heating and cooling, must decrease to 4.4 gigatonnes CO₂ yr⁻¹ to reach net-zero globally². Chromic nanocoatings (for example, thermochromic, electrochromic, and photochromic) can change a window's optical properties based on external stimuli and thereby decrease solar thermal impact and hence the need for cooling. Electrochromic windows alone have the potential to save up to 40% of energy demand for building heating and/or cooling²³.

Decarbonization of the electricity sector will heavily depend on advances in batteries and energy storage to tie intermittent renewable energy to the grid. According to the IEA, the electricity sector will need to abate 7 gigatonnes of CO₂ yr⁻¹ globally by 2030². Nanotechnologies are already helping achieve higher energy and power densities in traditional Li-ion batteries and new approaches are being added to the market. Nanotechnology-enabled iron–air batteries for grid storage are currently under commercial development, with claims that they can achieve 100 hours storage, at one tenth of the cost of traditional lithium-ion batteries (<https://formenergy.com/technology/battery-technology/>). Improved nanoarchitectures could also allow for other emerging battery chemistries with optimized characteristics to match Li-ion batteries at a lower cost²⁴; but access to advanced processing and manufacturing techniques currently represent a bottleneck to accelerate the scaling-up of these solutions²⁴. Researchers and entrepreneurs in the United States have voiced the need for a Manufacturing USA institute focused on advanced battery manufacturing to help reduce cost and risk of new materials and manufacturing techniques.

The industrial sector – made up of aluminium, cement, chemicals, light industry (for example, food processing, textiles, and consumer

goods), paper, and steel – needs to reduce emissions by 2 gigatonnes of CO₂ yr⁻¹ globally by 2030². Here, nanocatalysts have an enormous role to play. A promising approach is the development of green hydrogen; but the process is currently two to three times more expensive than producing hydrogen from natural gas. Cheap and abundant green hydrogen can serve as a precursor for many high-emitting chemical feedstocks, such as ammonia, methanol, ethylene, propylene, benzene, toluene, and xylenes, which account for around 75% of GHG emissions in the chemical industry globally. Several companies are working on novel ways to produce and utilize green hydrogen. For example, a company developed heterogeneous nanocatalysts to produce green hydrogen (<https://www.aircompany.com/technology/>) that is then used to transform captured CO₂ from industrial plants into value-added chemicals using a nanocatalyst. Optimized electrolyzers, Earth-abundant nanocatalysts, and improving nanocatalysts' lifetime and reliability could decrease costs and scale-up circular economy solutions. To date, there are 40 GHG capture and utilization commercial facilities accounting for a modest 0.05 gigatonnes CO₂ captured annually worldwide². Increased commercial and government support has propelled over 500 new pilot plants, demonstration projects, and commercial plants in various stages of development².

The transportation sector currently emits nearly 8 gigatonnes CO₂ yr⁻¹ globally. By 2030, a reduction of almost 2 gigatonnes CO₂ yr⁻¹ globally is targeted through enhanced efficiency and technology adoption. Multiwall carbon nanotube additives and carbon coatings on silicon particles in Li-ion battery electrodes are already being used in commercial electric vehicle batteries²⁴. One company, whose batteries are being deployed by a major automobile company, claims that its nano-composite silicon anode lithium-ion batteries can currently achieve 20% more energy density than traditional Li-ion batteries (<https://www.silanano.com/our-solutions/titan-silicon-anode>) while diminishing the use of critical materials. Nanotechnology could also hold the key for mobile energy delivery beyond batteries, including hydrogen-storage and fuel cell solutions.

Across a variety of critical technology sectors, nanoengineering can enable the kind of performance leaps needed to mitigate climate change. However, the severity and urgency of the issue demands that we consider not just technical potential, but also the economic, manufacturing, workforce, and adoption hurdles that could impede the realization of nanotechnology's potential before irreversible harm is done. Given the urgency, it is important to prioritize drop-in technologies that can be incorporated into existing infrastructure and supply chains, and to use Earth-abundant materials to remove barriers for adoption. There are many federal resources available in the United States (for example, I-Corps, Small Business Innovation Research grants, ARPA-E SCALEUP) to help scientists advance the technology readiness level of their inventions. Federally funded user facilities (<https://www.nano.gov/userfacilities>) can also serve as a resource for business and researchers to characterize and further develop their climate solutions. Public–private facilities, such as Manufacturing USA, can provide advanced manufacturing capabilities for climate solutions, but need to be expanded to streamline production. Artificial intelligence (AI) tools are being developed to help move low technology readiness innovations toward commercial deployment. Nanotechnology-enabled step changes in semiconductors are powering the AI revolution, which can help accelerate climate change solutions by rapidly marrying capabilities with technical demands. AI-enabled nanomaterials design may eventually enable long sought-after technologies such as high-temperature superconductors,

a virtuous cycle enabling yet another step-change in computational energy efficiency.

Nanomaterials' size-dependent properties and the ability to tailor materials to desired physicochemical properties can drive, and already are driving, technical solutions in the realms of energy storage, catalysis, interfaces, and GHG capture. These are environmentally and economically valuable opportunities, many of which have shown real climate impact and economic viability. For its part, Nano4EARTH is mobilizing the entire nanotechnology community: researchers, entrepreneurs, government, industry, investors, and philanthropists to combat climate change on all fronts.

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References

1. Ritchie, P. D. L., Clarke, J. J., Cox, P. M. & Huntingford, C. *Nature* **592**, 517–523 (2021).
2. *Net Zero by 2050* (International Energy Agency, 2021); <https://www.iea.org/reports/net-zero-by-2050>
3. *US Innovation to Meet 2050 Climate Goals* (The White House, 2022); <https://www.whitehouse.gov/wp-content/uploads/2022/11/U.S.-Innovation-to-Meet-2050-Climate-Goals.pdf>
4. Readout of Nano4EARTH kick-off workshop. *The White House* (26 January 2023); <https://www.whitehouse.gov/ostp/news-updates/2023/01/26/readout-of-nano4earth-kick-off-workshop/>

5. Santos, D. A. et al. *Chem. Sci.* **14**, 458–484 (2023).
6. Sun, N. et al. *Adv. Funct. Mater.* **29**, 1906282 (2019).
7. Li, A. et al. *Science* **384**, 666–670 (2024).
8. Chu, Y. et al. *Nano Energy* **86**, 106046 (2021).
9. Pasquali, M. & Mesters, C. *Proc. Natl Acad. Sci.* **118**, e2112089118 (2021).
10. Wang, J. et al. *Adv. Funct. Mater.* **31**, 2008008 (2021).
11. de Richter, R., Ming, T., Davies, P., Liu, W. & Caillo, S. *Prog. Energy Combust. Sci.* **60**, 68–96 (2017).
12. Carpick, R. et al. *Tribology Opportunities for Enhancing America's Energy Efficiency: A Report to the Advanced Research Projects Agency-Energy at the U.S. Department of Energy* (US Department of Energy, 2017); https://www.stle.org/images/PDF/STLE_ORG/whitepaper/Opportunities_for_Enhancing_Energy.pdf
13. Holmberg, K. & Erdemir, A. *Tribol. Int.* **135**, 389–396 (2019).
14. Ayyagari, A., Alam, K. I., Berman, D. & Erdemir, A. *Front. Mech. Eng.* **8**, 908497 (2022).
15. Bar-Cohen, A., Matin, K. & Narumanchi, S. *J. Electron. Packag.* **137**, 040803 (2015).
16. Green, C. et al. Cost savings & predictable performance benefits of carbon nanotube satellite thermal interface solutions. In *2023 IEEE Aerospace Conference* <https://doi.org/10.1109/AERO55745.2023.10115993> (IEEE, 2023).
17. Pérez-Botella, E., Valencia, S. & Rey, F. *Chem. Rev.* **122**, 17647–17695 (2022).
18. Wafi, M. K. et al. *SN Appl. Sci.* **1**, 751 (2019).
19. Hepburn, C. et al. *Nature* **575**, 87–97 (2019).
20. Lin, J.-B. et al. *Science* **374**, 1464–1469 (2021).
21. Ghaffari Nik, O. et al. Rapid cycle temperature swing adsorption using CALF-20 MOF structured adsorbent for cement carbon capture. *SSRN* <https://papers.ssrn.com/abstract=4349347> (2023).
22. Evans, H. A. et al. *Sci. Adv.* **8**, eade1473 (2022).
23. Tällberg, R., Jelle, B. P., Loonen, R., Gao, T. & Hamdy, M. *Sol. Energy Mater. Sol. Cells* **200**, 109828 (2019).
24. Pomerantseva, E., Bonaccorso, F., Feng, X., Cui, Y. & Gogotsi, Y. *Science* **366**, eaan8285 (2019).
25. *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach* (International Energy Agency, 2023); <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach>

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Competing interests

C.G. has a financial interest in Carbice Corporation, a provider of aligned carbon nanotube thermal interface solutions for electronic, energy, and industrial products.