Nano4EARTH Roundtable Discussion on Coatings, Lubricants, Membranes, and Other Interface Technologies

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Overview

The National Nanotechnology Initiative (NNI) launched the National Nanotechnology Challenge on climate change (Nano4EARTH) to convene and mobilize the broad nanotechnology community to accelerate solutions for climate change. The NNI, with support from the National Nanotechnology Coordination Office (NNCO), has organized a series of roundtable discussions on promising areas that could have near-term impacts (four years or less) on climate change. These promising areas were identified at the Nano4EARTH kick-off workshop. Among them was *coatings, lubricants, membranes, and other interface technologies*, which was the focus of the first roundtable discussion.

The U.S. economy loses more than $1 trillion to friction and wear every year, which is equivalent to 5% of the GDP[1]. With that in mind, NNCO assembled 10 subject-matter experts from different sectors, including academia, national laboratories, small and large businesses, and technology development and finance, to discuss and identify the most pressing near-term needs, opportunities, and challenges to utilize interfacial innovations to increase energy and emissions efficiency. The agenda and list of invited participants can be found here.

Identifying Nanotechnology Opportunities

Given the surface-dominant nature of nanotechnologies, potential solutions at interfaces exist that can increase energy and emissions efficiency, while being economically beneficial. Participants brainstormed 15 nanotechnology opportunities related to coatings, lubricants, membranes, and other interfacial technologies and identified opportunities that could have the biggest impact to achieve climate goals in a short amount of time (Table 1).

Table 1. Nanotechnology Opportunities

Categories Identified	Description
Carbon and 2D materials	Carbon nanotubes (aligned and not), functional coatings, graphene, MXenes, superwood, nano electro mechanical systems

[1] https://www.ornl.gov/news/superlubricity-coating-could-reduce-economic-losses-friction-wear

Nanoporous materials	Metal organic frameworks, covalent organic frameworks, polymers of intrinsic microporosity, membrane gas separation and capture, and nanoporous membranes
Reclamation of materials	Reworkable interfaces, upcycling of plastic waste, reclamation of precious materials, and hydrometallurgy
Surface modifications and lubricants	Atomic-layer-deposition coatings, high thermal or electrical conductivity polymers, superlubricity materials, green lubricants, hydrophobic coatings, sustainable polymers, and ionic liquids

Other areas that were identified, but received less attention, included: hydrogen; thermoelectrics; synthetic food; energy storage (e.g., solid-state batteries, fuel cells); nuclear energy; water harvesting and separations; alternative cementitious materials; batteries and energy storage (another roundtable was dedicated to this topic); and optical properties of nanomaterials.

The discussions highlighted different areas in which nanotechnology holds promise due to its tunability, selectivity, and precision. For example, nanoporous materials, such as metal-organic frameworks, are highly tunable and can be used in climate-related applications, such as gas separation and capture. (Note that these materials were covered more significantly during the greenhouse gas capture, storage, and use roundtable.) Nanomaterials also have an advantage in surface science, because they can cover microscopic grooves and cracks in materials. For example, nanoparticle additives in lubricants can help decrease the coefficient of friction, achieving superlubricity properties, reducing friction and wear, and increasing energy efficiency and lifetime of machinery, when compared to traditional lubricants.

The discussions addressed the importance of systems thinking, as well as material and product circularity. Also, many potential nanotechnology solutions already exist but need to be economically and sustainably scaled. Circularity, end-of-life plans, and life-cycle assessments were highlighted as key analyses needed to avoid unintended environmental, health, and safety implications of emerging technology during design and scale-up. For example, on-demand decomposition could be a useful component of future engineered surface solutions.

Matching Climate Needs with Nanotechnology Opportunities

The roundtable participants were also tasked to brainstorm climate change-related needs. The needs identified were grouped into categories, prioritized by the participants based on what categories they thought could have the biggest impact and then matched (Table 2) with nanotechnology opportunities identified in Table 1.

Table 2. Matching Climate Change Needs with Nanotechnology Solutions		
Climate Change Needs Identified	**Description**	**Nanotechnologies with Untapped Potential**
Industrial decarbonization	Hard-to-abate industries, such as cement, steel, petrochemical industry, mining, refining, and water purification	• Nanoporous materials • Hydrogen • Surface modifications and lubricants
Low energy computing	Material innovation (materials beyond silicon) and heat energy management	• Carbon and 2D materials • Thermoelectrics • Reclamation of materials
Green transportation	Long-haul transportation, production of advanced long-duration batteries, electrofuels, alternative aviation fuels, and vehicle-to-grid technologies	• Hydrogen • Carbon and 2D materials • Surface modifications and lubricants

Categories that were identified, but not thoroughly discussed, included: heating and cooling of buildings/HVACs; circularity; sustainable agriculture; greenhouse gas removal/avoidance; sustainable, long-lasting lubricants and coatings; power; and labor efficiency.

Industrial decarbonization is a goal in most climate change conversations. The group argued that nanotechnology-enabled solutions at interfaces could provide solutions across industries. For example, clean hydrogen could serve as a precursor for many hard-to-abate industries, such as steel. In addition to the production of “green” hydrogen, which could be achieved through the use of nanocatalysts, an entire infrastructure will need to be built. For example, the retrofitting of pipes could be addressed with coatings made from nanocomposites and novel membranes (i.e., powered by surface modification using nanoscience and creating new nanotechnology-enabled membranes with unique surface properties). The creation of liquid fuels using captured CO_2 and H_2 is another area where nanocatalysts could play a role. (Note that nanocatalysts are the subject of another Nano4EARTH roundtable.)

There are many opportunity areas in the field of computing. For example, scaled silicon-based transistors have significant leakage currents and generate considerable waste heat. A replacement material is needed. Carbon, 2D materials, and spintronic materials could provide an alternative to silicon, but those technologies are not yet mature. Thermal management issues for computing also need to be addressed. There is an opportunity to minimize or harvest the heat generated by data centers. It is estimated – if current technologies are still used in the future – that in 20 years, the energy demand for global computation activities could be equal to the amount of energy the world can produce. Carbon nanotubes could be used for heat management, and thermoelectric nanomaterials could harvest the heat. This discussion was also part of a broader conversation on the importance of improved heat transfer and optimized electricity transmission and distribution.

Expansion of transportation electrification is already increasing energy and carbon emission efficiency due to nanotechnology-enabled advancements in batteries. In addition to electrification, lubricants and coatings (i.e., surface modification) can provide significant energy savings in different transportation sectors. For example, shipping vessels suffer from biofouling, and airplanes suffer from energy inefficiencies caused by insects sticking to their surfaces. Nanotechnology-enabled hydrophobic coatings can help different transportation systems shed external objects that create drag.

The conversation led to the identification of inefficiencies in current industrial processes and opportunities for optimization that are not nanotechnology-specific but still worth considering. Participants emphasized the importance of optimizing existing processes in the short term and focusing on solutions that could be "dropped in" without affecting existing supply chains and manufacturing infrastructure. At least a 10-times improvement is needed to justify a change in existing industrial systems and supply chains.

Techno-economic analyses are crucial to understand the cost, feasibility, and impact of a potential technical solution. For example, green lubricants can be made using recycled plastics and can offer as good a performance as traditional lubricants (or even a better performance), but they are not produced at the scale needed. Currently, 4 million tons of lubricants are used, while green lubricants are produced at orders of magnitude less than that amount. To make solutions widely available, climate change solutions should provide a "green saving" instead of a "green premium."

The roundtable discussion helped identify promising areas in which nanotechnology could optimize existing industries and provide new solutions for emerging problems. The nanotechnology-enabled solutions discussed have the potential to provide significant impact in the short term, but only if scalability, cost, circularity and environmental, health, and safety concerns are addressed.