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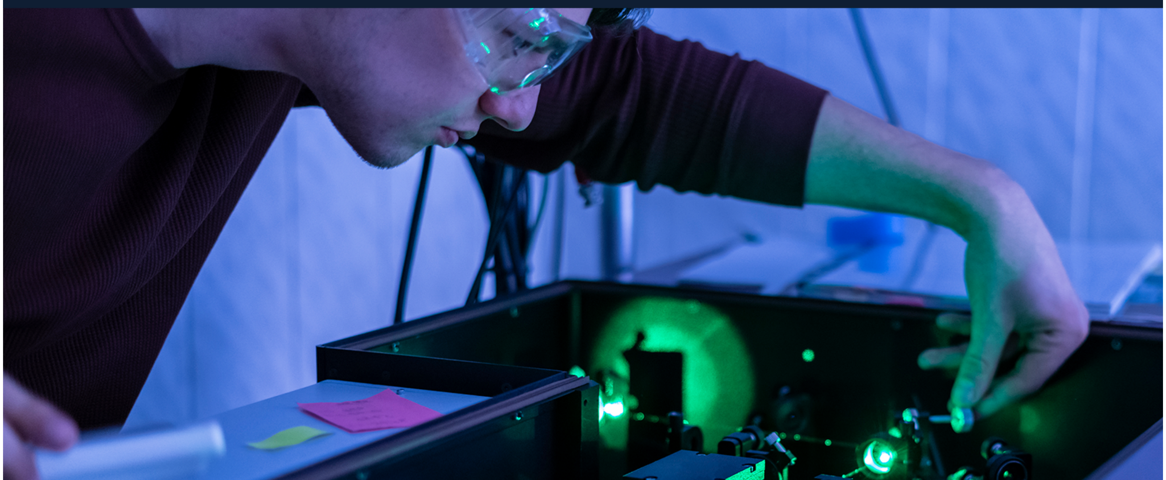


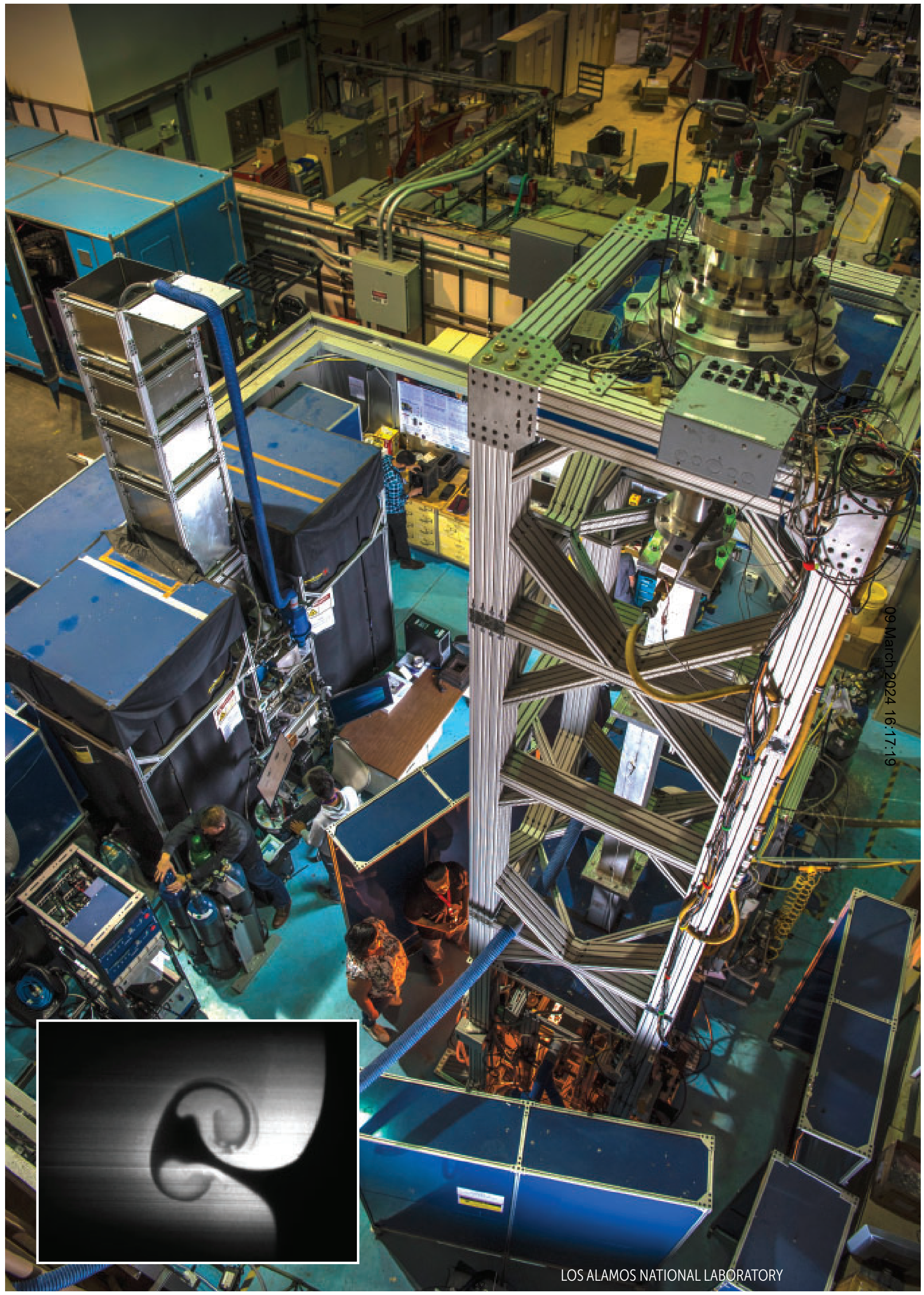
Scientists take steps in the lab toward climate sustainability

They are working to lower greenhouse gas emissions without compromising research.

Reducing air travel, improving energy efficiency in infrastructure, and installing solar panels are among the obvious actions that individual researchers and their institutions can implement to reduce their carbon footprint. But they can take many other small and large steps, too, from reducing use of single-use plastics and other consumables and turning off unused instruments to exploiting waste heat and siting computing facilities where they are powered by renewable energy. On a systemic level, measures can encourage behaviors to reduce carbon emissions; for example, valuing in-person invited job talks and remote ones equally could lead to less air travel by scientists.

So far, the steps that scientists are taking to reduce their carbon footprint are largely grassroots, notes Hannah Johnson, a technician in the imaging group at the Princess Máxima Center for Pediatric Oncology in Utrecht and a member of Green Labs Netherlands, a volunteer organization that promotes sustainable science practices. The same goes for the time and effort that they are putting in for the cause. One of the challenges, she says, is to get top-down support from institutions, funding agencies, and other national and international scientific bodies.

At some point, governments are likely to make laws that support climate sustainability, says Astrid Eichhorn, a professor at the University of Southern Denmark whose research is in quantum gravity and who is active on the European Federation of Academies of Sciences and Humanities' committee for climate sustainability. "We are in a situation to be proactive and change in ways that do not compromise the quality of our research or our collaborations," she says. "We should take that opportunity now and not wait for external regulations."



A VERTICAL SHOCK TUBE at Los Alamos National Laboratory is used for studies of turbulence. Sulfur hexafluoride is injected at the top of the 5.3-meter tube and allowed to mix with air. The waste is ejected into the environment through the blue hose at the tube tower's lower left; in fiscal year 2021, such emissions made up some 16% of the lab's total greenhouse gas emissions. The inset shows a snapshot of the mixing after a shock has crossed the gas interface; the darker gas is SF_6 and the lighter one is air. The intensities yield density values.

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PLASTIC CONSUMABLES PILE UP as waste in many wet labs. An exhibition last winter at the Lakenhal Museum in Leiden, the Netherlands, aimed to motivate scientists and the public to find ways to make science more sustainable.

If humanity manages to limit emissions worldwide to 300 gigatons of carbon dioxide equivalent (CO_2e), then there is an 83% chance of not exceeding the 1.5 °C temperature rise above preindustrial levels set in the 2015 Paris Agreement, according to a 2021 Intergovernmental Panel on Climate Change special report. That emissions cap translates to a budget of 1.2 tons of CO_2e per person per year through 2050. Estimates for the average emissions by researchers across scientific fields are much higher and range widely in part because of differing and incomplete accounting approaches, says Eichhorn. She cites values from 7 to 18 tons a year for scientists in Europe.

To be sure, the greenhouse gas contributions of the scientific community are small in the grand scheme of global emissions. Still, the community has a "moral responsibility," says Thomas Roser, an emeritus senior scientist at Brookhaven National Laboratory (BNL) and author of a white paper on sustainability for future accelerators written for the recent Snowmass exercise. (See Physics Today, October 2022, page 22.) That's especially true for a "luxury field" like high-energy physics, he says, "which doesn't have a societal benefit other than knowledge and some spinoffs." Science and academia can serve as examples for the rest of society, he says, "and the development of energy-efficient technologies could be an important bonus."

"Carbon-neutral for everything"

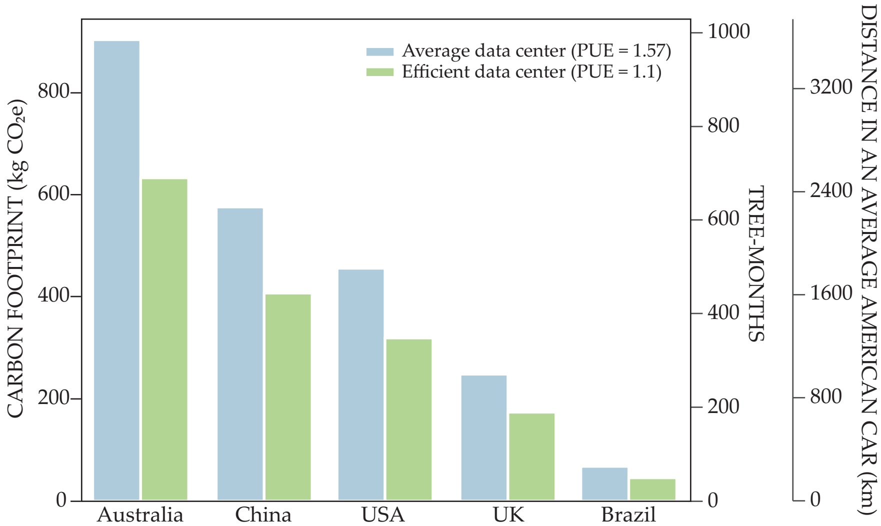
Scientific facilities often include renewable energy as part of their sustainability plans. "I'm leery about that," says Roser. "If a scientific facility switches to renewable energy, it takes that energy source away from other parts of society." The focus should be carbon-neutral for everything, he says, but until that happens, "scientific facilities should strive for energy efficiency and energy recovery."

As an example of increasing energy efficiency in experimental particle physics, Roser suggests using permanent magnets rather than power-hungry electromagnets where feasible. Advances have made it possible to make precise permanent magnets, he says, pointing to the Cornell University facility CBETA, the Cornell–BNL ERL (Energy Recovery Linear) Test Accelerator. Multiple permanent magnets are glued together and fine-tuned with wire shims to create a field accurate to 10^{-4} in strength and direction. Permanent magnets are a "big opportunity for synchrotron light sources," with their static storage rings and fixed fields, says Roser. They have also been patented for use in cancer radiation therapy. Another sustainable aspect of CBETA is energy recovery, whereby the energy the electrons collect while accelerated is removed when they are decelerated and then reused. CBETA "substantially reduces energy consumption and still maintains performance," says Roser. "Nobody wants to compromise performance."

Across the sciences and beyond, computation is a growing area of energy consumption and carbon emissions. Scientists tend to think that computing is free because the financial cost is low and a lot of supercomputer time is available, says Loïc Lannelongue, a postdoc in computational biology at the University of Cambridge. "Very rarely does someone decide not to run a calculation because it's too expensive."

In 2020 Lannelongue took what he thought would be a two-week detour from his PhD studies to create a calculator of carbon footprints. That detour has become an ongoing side project, as he refines the calculator (see https://green-algorithms.org) for broad use and writes papers and gives talks on the topic. "If people realize there is a carbon cost, they will be more mindful," he says. "I no longer do a computation just because I can."

Other carbon-footprint-reducing measures that individuals can take, Lannelongue says, include optimizing code and updating software. In one case, a particular calculation done with the latest version of a genomic analysis software package created only a quarter of the carbon emissions of the first commercial version, he says. "The team behind the tool is making it more efficient. As a side effect, it's better in terms of carbon emissions. It doesn't have to be a trade-off. It can be win-win."



GREENHOUSE GAS EMISSIONS from computing vary widely by location, depending on the energy source, and also on cooling and other design features. For a test calculation quantifying radiation damage to DNA, the blue bars show the values for an average data center for a given country and the green bars are for energy-efficient data centers in the same country. The power usage effectiveness (PUE) is a measure of the energy efficiency of the data center. At near right, the time it would take a tree to sequester the emitted carbon dioxide is shown. At far right is the distance that a car in the US would drive on average to emit the same amount of CO_2 as the computation. (Courtesy of Loïc Lannelongue; data and details at https://www.carbonfootprint.com/international_electricity_factors.html and https://doi.org/10.1002/advs.202100707.)

At the institutional level, the carbon emissions of computing can be reduced by modifying cooling designs and locating computing centers where renewable energy is available. For example, CERN has upgraded the efficiency of an existing data center by cooling corridors of computers rather than the whole room, among other measures. "The upgrades brought the PUE down from 1.7 to 1.5," says Bob Jones, deputy head of the lab's information technology department. (The PUE, or power usage effectiveness, is the ratio of the total energy used by the facility to the energy delivered to its computing equipment.) A new data center due to open at CERN later this year will have a PUE of 1.1, he adds. CERN plans to recuperate the heat generated by the new center; similarly, some of the hot water currently generated from cooling the Large Hadron Collider (LHC) is diverted for use in a neighboring town.

Fluorinated gases

Because CERN is powered mostly by nuclear energy from France, its enormous energy consumption is not the main contributor to its greenhouse gas emissions. Instead, roughly 80% comes from fluorinated gases used for particle detection and detector cooling in the LHC experiments and for electrical insulation in power supplies, according to the lab's 2021 environmental report. Fluorinated gases have a warming potential that is thousands of times greater than that of CO_2.

Some 20 detector systems in the LHC experiments use various gas mixtures as the active medium to detect particles generated in collisions. The gases, which include hydrofluorocarbons and perfluorocarbons, as well as CO_2, neon, argon, and oxygen, are chosen to "fulfill the requirements of the particular experiment—the time resolution, efficiency, rate capability, and so on," says Beatrice Mandelli, a particle physicist who is on the team that oversees CERN's gas detector systems. Harm to the environment occurs through leakage.

One type of gaseous detector contains mostly tetrafluoroethane with small amounts of isobutane and sulfur hexafluoride (SF_6). The mixture allows for primary ionization and an avalanche, and suppresses the development of sparks, Mandelli explains. Carbon tetrafluoride, which is used in a different type of gaseous detector, provides high time resolution and mitigates detector aging. Tetrafluoroethane is common in refrigeration, in automobile air conditioners, and more. Industry has found replacements, says Mandelli, but they are not suitable for particle detectors.

"Our needs are very specific," Mandelli says. The geometry and electronics are customized, and the detectors have to be able to run for many years. When the detectors were designed decades ago, she adds, "there was not awareness of the emissions of greenhouse gases."

CERN has decreased emissions by closing detector systems so gas mixtures can recirculate, recuperating fluorinated gases, and fixing leaks when the accelerator is off. Pointing to ongoing research on eco-friendly alternatives, Mandelli says that future detectors will not use greenhouse gases. Aside from polluting the environment, they are likely to become harder to obtain, she notes, because of industry shifting away from fluorinated gases and the Kyoto Protocol having called for their phaseout.

Researchers at Los Alamos National Laboratory (LANL) in New Mexico likewise are stymied in finding replacements for fluorinated gases. In fiscal year 2021, fluorinated gases were responsible for 20% of the lab's greenhouse gas emissions; LANL did not say how much those total emissions amounted to.

John Charonko leads a group at LANL that studies mixing of heavy and light gases. In one setup (see the photo on page 20), SF_6 is pushed down a 5.3-meter vertical tube to mix with air, and the researchers take pictures of the mixing. The group uses SF_6 because it's heavy, nontoxic, and cheap. The experiments are analogous to part of the inertial confinement fusion process studied at the National Ignition Facility, Charonko says. (See "National Ignition Facility surpasses long-awaited fusion milestone," Physics Today online, 13 December 2022.) They also are relevant for understanding astrophysical processes, such as the evolution of white dwarfs and supernova explosions.

Per an executive order signed by President Biden in December 2021, LANL is working to achieve a carbon-pollution-free electricity supply by 2035 and net-zero emissions by 2050. LANL plans a 50-acre photovoltaic farm and is considering a nuclear microreactor for on-site power generation. For now, the lab is focusing on renovating buildings to be more energy efficient and procuring carbon-free power. Transportation is also in their sights: Ideas being floated to encourage employees to cut emissions include providing electric bikes for campus transportation, offering parking only to carpoolers, and switching the lab's vehicles to electric cars, says Shannon Blair, who is on the lab's sustainability team. "Our government fleet is 1500 vehicles. It's 2% of our total emissions. That's tiny, but it's visible."

At Johnson's workplace in Utrecht, the ultralow-temperature freezers consume the equivalent energy of 60 average Dutch households. "We are facing a huge energy crisis in Europe, so the sustainability community is using that to get attention and to get institutions on board," she says. Increasing a freezer's temperature to –70 °C from the typical –80 °C uses about 30% less energy. "Through an ongoing in-house challenge, some groups have combined the contents of freezers and turned some off altogether."

Efficiency in cost and carbon

A few years ago, the Gemini Observatory telescopes got solar panels and energy-efficient equipment, including transformers, cooling systems, LED lights, and motion sensors. Solar panels provide 20% of the energy needed at Gemini South on Cerro Pachón in Chile, 12% at Gemini North on Mauna Kea in Hawaii, and 20% at the observatory's Hawaii offices. The upgrades were intended to lower operating costs, but they also reduced the facilities' carbon footprint, says Inger Jorgensen, associate director of operations at NOIRLab, NSF's National Optical–Infrared Astronomy Research Laboratory, which comprises several telescopes and other facilities. "By next year they will have paid for themselves," she adds.

In its 2021 request to NSF for a five-year renewal grant, NOIRLab proposed to reduce staff travel by half compared with pre-COVID-19 levels and to use the consequently freed-up $4.7 million on additional energy-efficient equipment. NSF agreed, and the changes, Jorgensen says, will reduce NOIRLab CO_2e emissions by 30%, from the estimated 8700 tons of CO_2e in 2019 to a target of 6200 tons by late 2027. That reduction "is equivalent to what 500 average US houses emit in a year," she says. "Every little piece makes a difference. And it shows it can be done."

Funding agencies have agency

Eichhorn and others want funding agencies to step in and use their leverage to nudge researchers and institutions to reduce their greenhouse gas emissions. A first step would be for the agencies to require applicants to estimate the carbon footprint of their proposed work. Eichhorn notes that while a growing number of universities and research institutions globally are doing so, the lack of standardization makes it difficult to compare them. "The day funding bodies say you have to estimate your carbon footprint, everyone will do it," says Lannelongue. "I haven't seen compulsory estimates yet, but things are moving in that direction."

Funding agencies could also reward proposals that include ways to reduce emissions. One incentive, suggests Johnson, could be to recognize institutions that behave sustainably—along the lines of the UK's Athena SWAN (Scientific Women's Academic Network) program, which recognizes good practices in advancing gender equality in higher education.

Limiting scientists to listing only one invited in-person talk on grant applications would be an incentive to travel less, says Eichhorn. And conducting all grant or job interviews virtually would likewise reduce travel. Institutions and funding agencies could ease the requirement of taking the cheapest form of transportation to meetings and instead include the carbon budget in such decisions.

Remote conferences reduce emissions by up to 98%, Eichhorn notes. Even selecting a conference location based on where attendees will travel from can reduce a conference's carbon footprint by 20%, she notes. (See Physics Today, September 2019, page 29.)

Says Eichhorn, "Reducing emissions in the science community will require creativity and culture change."

Toni Feder

A computing hardware approach aspires to emulate the brain

Neuromorphic computing promises energy savings, a deeper understanding of the human brain, and smarter sensors.

Imagine getting the performance of today's supercomputers but drawing just a few hundred watts instead of megawatts. Or computer hardware that can run models of neurons, synapses, and high-level functions of the human brain. Or a flexible patch that could be worn on the skin that could detect serious health disorders before symptoms develop. Those are a few applications that could be enabled by neuromorphic computing.

Today's high-performance computers have a von Neumann architecture, in which the central processing or graphics processing units (CPUs and GPUs) are separate from memory units, with the data and instructions kept in memory. That separation creates a bottleneck that slows throughput. Accessing data from main memory also consumes a considerable amount of energy.

In so-called neuromorphic systems, units known as neurons and synapses operate as both processors and memory. Just like neurons in the brain, artificial neurons only perform work when there is an input, or spike, to process. Neuromorphic systems are most often associated with machine learning and neural networks, but they can perform a variety of other computing applications.

Just a handful of large-scale neuromorphic computers are in operation today. The Spiking Neural Network Architecture (SpiNNaker) system located at the University of Manchester in the UK has been operating since 2011 and now has 450 registered users, says Stephen Furber, the Manchester computer engineer who led the computer's construction. The UK-government-funded 1-million-core platform was optimized to simulate neural networks.

A next-generation machine, dubbed