The

Electrifying the Energy System

FROM COLUMBIA ENGINEERING

Lever

The Lever

Welcome

The Lever is a new series featuring analysis from researchers at Columbia Engineering. In the first edition, we're exploring the technology that underlies the global effort to electrify our energy system.

Our experts will explain some of the technical challenges and offer promising solutions in this urgent undertaking.

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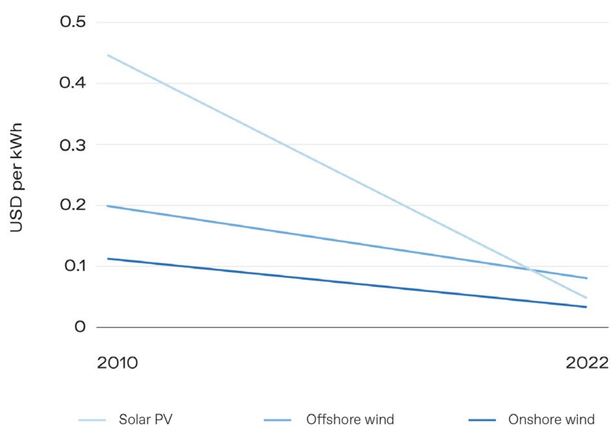
Setting the Stage for Transformation

We are in the middle of a sprint to replace old technologies that burn fossil fuels with new ones that run on electricity.

Engineers across the world have spent decades perfecting technologies to produce electricity from renewable sources and put it to use. Those efforts have paid off. Today, solar energy is cheap, consumers are buying electric vehicles faster than expected, and we're on a viable path to decarbonizing the energy system.

Costs

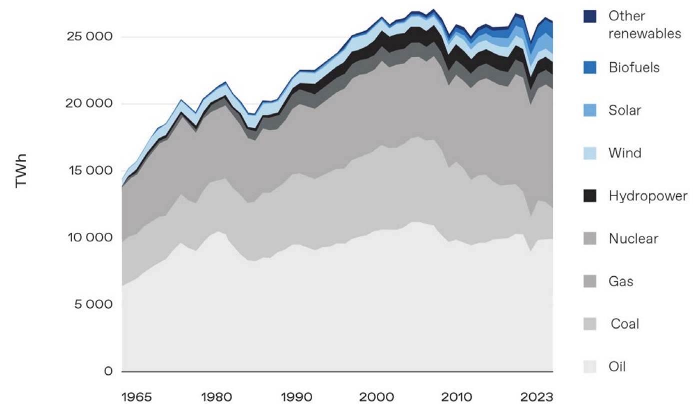


THE AVERAGE LEVELIZED COST OF ELECTRICITY FOR NEW RENEWABLE ENERGY PROJECTS FELL BY 89% FOR SOLAR PV AND 69% FOR ONSHORE WIND BETWEEN 2010 AND 2022. SOURCE: IEA

Realizing that vision lies in our ability to store and harness electrical energy at tremendously large scales. The basic concepts necessary to accomplish this — the fundamentals of electrochemistry — aren't new, but we have been slow to put that knowledge into practice across our energy system.

One of the main reasons that electrochemistry has lagged behind combustion is also the technology's fundamental advantage: circularity.

Energy Consumption by Source, U.S.



ROUGHLY 9% OF TOTAL U.S. ENERGY CURRENTLY COMES FROM RENEWABLE SOURCES. SOURCES: ENERGY INSTITUTE AND OUR WORLD IN DATA

With combustion, you take fuel, blow it up, spit it out, and let that waste become someone else's problem. Electrochemistry is much harder because we have to account for the entire circuit and manage the flow of energy and mass throughout the system.

In solving the problems of electrochemistry, we're solving the most crucial challenges of sustainability.

DAN STEINGART IS THE STANLEY-THOMPSON PROFESSOR OF CHEMICAL METALLURGY IN THE DEPARTMENT OF EARTH AND ENVIRONMENTAL ENGINEERING, PROFESSOR OF CHEMICAL ENGINEERING, AND CHAIR, DEPARTMENT OF EARTH AND ENVIRONMENTAL ENGINEERING.

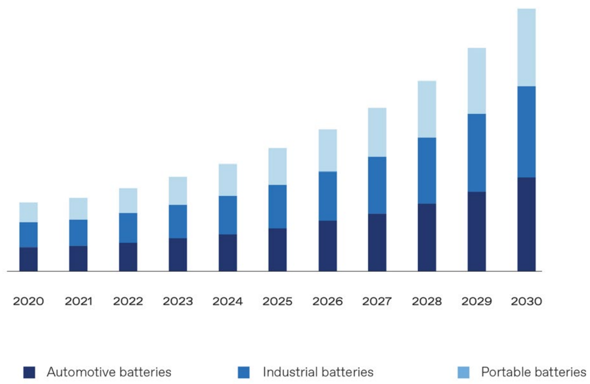
Clean Energy When You Need It: Designing Safer, Cheaper Batteries

Storage has presented a major hurdle in the transition to renewable energy. Find out about efforts to improve leading battery technologies and to develop new approaches.

Most sources of renewable energy share a fundamental challenge: variability. Wind and solar are cheap and abundant — but only when (and where) the wind blows or the sun shines.

For our research teams and the larger research community, this basic fact motivates our urgent efforts to improve existing battery technology while simultaneously developing new designs and manufacturing techniques for safe, inexpensive, and long-lasting energy storage.

Global Battery Market Size



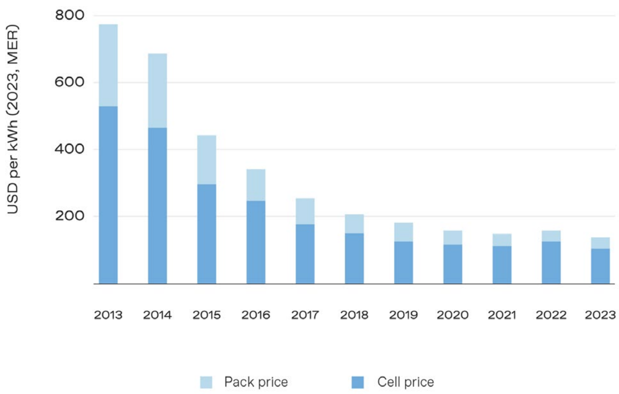
THE GLOBAL BATTERY MARKET IS PROJECTED TO GROW BY MORE THAN 15% PER YEAR THROUGH 2030. SOURCE: GRAND VIEW RESEARCH

We are reimagining current battery technologies and developing new approaches. Along with our colleagues at the Columbia Electrochemical Energy Center (CEEC), we are developing new innovations to improve everything from the atomic structure of electrolytes to the architectures of battery cells and packs to the management of grid-scale storage.

LITHIUM DOMINATES TODAY'S BATTERY INDUSTRY

Lithium's chemical properties make it an ideal component for batteries. Over the past few decades, lithium batteries have gained an additional advantage: economies of scale. Since the rise of lithium-ion batteries 30 years ago, manufacturing techniques have continuously improved, causing the cost of these batteries to drop by 90% since 2010. Today, lithium-ion batteries dominate the market, powering nearly all smartphones and electric vehicles (EVs) and most grid-level energy storage facilities.

Lithium-Ion Battery Pack and Cell Prices 2013 – 2023



THE PRICE OF LI-ION BATTERIES HAS STEADILY DECLINED FOR MORE THAN A DECADE. SOURCE: IEA

However, there are limitations. As more lithium-ion batteries have entered the market, there have been more instances of battery-related fires. In the first eight months of 2024, lithium-ion batteries caused over 170 fires in New York City alone, resulting in three deaths. The supply chain for materials and batteries presents another challenge. Lithium sources — along with other raw inputs, such as cobalt — are concentrated in a few regions, making the global battery industry vulnerable to geopolitical tensions.

One set of solutions is to move away from lithium entirely. As we develop these options, we should also be improving the design of this established technology.

> To make lithium batteries safer, we must come up with innovative ways to visualize what is going on inside the batteries during degradation, prior to them becoming potential hazards.

For instance, one of our labs (Marbella's) is developing new imaging techniques that remove hurdles that have prevented us from using lithium metal (rather than graphite) for the anode in lithium batteries.

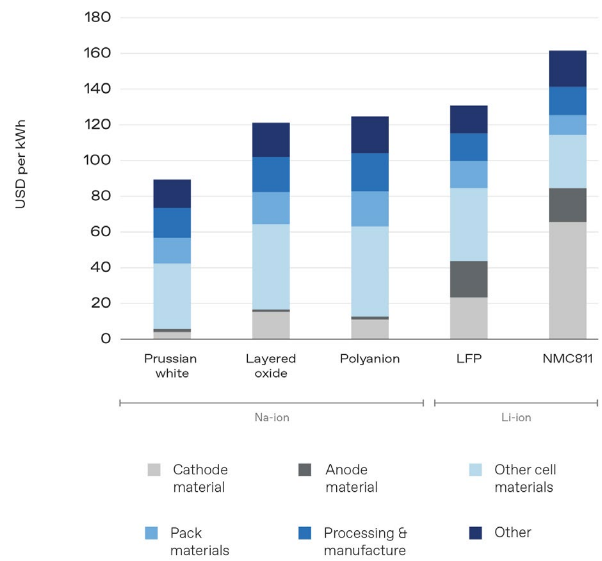
The technique, called nuclear magnetic resonance spectroscopy, makes it possible to measure both how quickly lithium ions are moving and determine the exact chemical and physical structure of the problem-causing defects. Once these structural changes come into focus, researchers can design lithium metal batteries that meet the performance metrics required for commercializing these higher energy-density batteries.

BATTERIES BEYOND LITHIUM

In parallel with work to improve lithium batteries, researchers across the world are developing designs for batteries with other chemistries.

One of the most promising alternatives is sodium-ion batteries. Sodium is far more abundant than lithium, and it's found in deposits spread across the world. While sodium-ion batteries generally weigh more, they are cheaper and less prone to catching fire, making them especially attractive for grid applications. Zinc-based chemistries share many of these advantages.

2022 Battery Pack Costs by Chemistry



SODIUM-ION (NA-ION) BATTERIES PRESENT A LOWER COST OPERATION THAN LITHIUM-BASED COUNTERPARTS. SOURCE: WOOD MACKENZIE

Sodium-sulfur batteries are capable of storing large amounts of energy for extended periods of time. These relatively inexpensive batteries are appealing for grid storage but with a catch — they operate at dangerously high temperatures. One of our labs (Yang's) is developing electrolytes that operate safely enough for widescale commercialization.

THE FUTURE OF BATTERY INNOVATION

The global effort to turn away from fossil fuels and electrify the energy system depends on continual advancement in battery designs and manufacturing processes. Fortunately, many such advancements are coming down the pike.

For example, several research groups and companies are racing to develop processes to transition from wet processing to dry coatings, potentially cutting 50% of the energy required in the entire battery manufacturing process. Other researchers are working to answer the question of why lithium batteries catch fire so easily — and how it could be prevented entirely.

Our work at CEEC is paving the way for a future where energy storage is safer, cheaper, and more efficient. In addition to bringing Columbia Engineering researchers together with experts from across the world, CEEC's industry partnerships enable the realization of breakthroughs in electrochemical energy storage and conversion.

LAUREN MARBELLA IS AN ASSOCIATE PROFESSOR OF CHEMICAL ENGINEERING.

YUAN YANG IS AN ASSOCIATE PROFESSOR OF MATERIALS SCIENCE AND ENGINEERING.

Integrating Batteries into the Grid

Most U.S. energy infrastructure wasn’t built with renewables in mind. Learn how machine learning algorithms are helping batteries plug into the grid.

Utility companies across the world have begun replacing coal- and gas-fueled power plants with large batteries that store solar and wind energy. In the United States, California and Texas are leaders in deploying this technology, with states including New York developing a nascent capacity for grid-scale storage.

Total U.S. Grid-Scale Battery Capacity

IN JULY 2024, MORE THAN 20.7 GIGAWATTS OF BATTERY ENERGY STORAGE CAPACITY WAS AVAILABLE IN THE U.S. SOURCE: IEA

This significant advancement brings new challenges. With traditional grids, a utility could easily adjust its generators to meet consumer demand. Managing a grid that relies on batteries requires a more strategic approach. Increasingly, grid managers will make decisions (or oversee algorithms that make decisions) based on the type of predictive models that my colleagues and I are developing.

We’re all accustomed to thinking of energy infrastructure in terms of power plants, electrical lines, and other physical aspects of the grid, but AI systems are quickly becoming an indispensable part of the energy system. With smart research and investment, it is possible to keep electricity cheap and reliable while drastically reducing the amount of fossil fuels we burn.

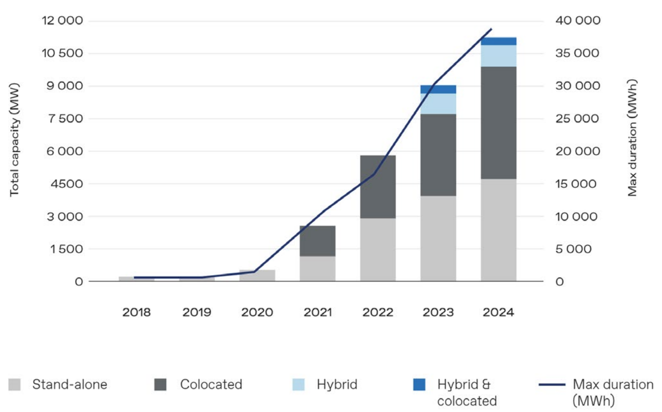
THE CHALLENGE OF MANAGING GRID-SCALE BATTERIES

In theory, these batteries should be charged when renewable sources are producing more energy than consumers need, and they should send that extra energy onto the grid when demand exceeds supply.

In reality, it’s not so easy. To ensure that power is always available, grid operators have to predict the production and consumption of energy hours or even days in advance. They use algorithms to analyze large and diverse datasets — including weather data, historical consumption data, and market prices — to make these predictions.

The systems that make these forecasts are rapidly becoming an essential piece of the electrical infrastructure. In California, where battery capacity now accounts for nearly 30% of the state’s power capacity, decisions about when to charge and discharge batteries have become critical to maintaining grid reliability.

Active Battery Capacity in CAISO Balancing Area 2018 – 2024



AS OF JUNE 2024, GRID-SCALE BATTERIES ACCOUNT FOR MORE THAN 10% OF CALIFORNIA’S BULK ENERGY CAPACITY. SOURCE: CALIFORNIA INDEPENDENT SYSTEM OPERATOR

THE PROMISE – AND COMPLEXITY – OF INTEGRATING AI

These large batteries and the electrical grids they serve are usually owned by different companies. These companies interact by continually setting and updating the price at which they're willing to buy and sell energy.

Using an approach called predictive control, the battery owners and grid operators use historical data and real-time inputs to forecast future conditions. These systems, which are very similar to the algorithms used in automated stock trading, ultimately inform decisions about when to charge and discharge the batteries.

> In a well-designed market, this application of AI will ensure that stored energy is available when it's most needed while offering investors the incentives to fund new storage products and extend the reach of renewable energy.

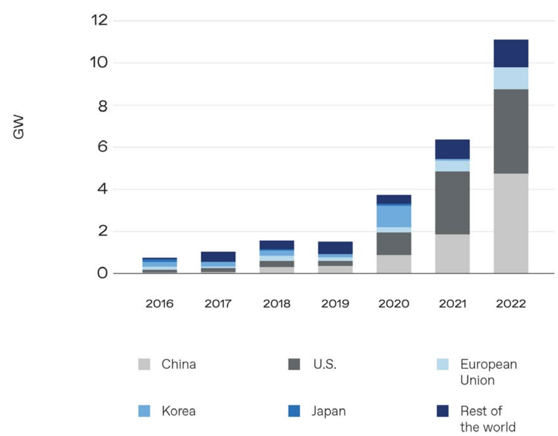
The use of AI in energy markets raises questions about fairness and transparency. As more decisions are driven by algorithms, there is a risk that the complexities of AI could obscure the decision-making process, making it difficult for regulators and consumers (and even the battery owners and grid operators themselves) to understand how energy prices are set or why certain decisions are made.

Furthermore, while fossil fuel prices are usually public, prices for electricity from grid-scale batteries usually aren't. This opacity could lead to perceptions of unfairness, particularly if AI-driven decisions result in price spikes that leave consumers with sky-high utility bills and increased risk of outages.

CHARTING THE PATH FORWARD

Addressing these challenges requires a better understanding of the dynamics, incentives, and technical systems that underlie these new markets. By investing in this research, governments and private companies can better position themselves to foresee potential issues and quickly address problems as they arise.

Annual Grid-Scale Battery Storage Additions 2017 – 2022



GLOBAL GRID-SCALE BATTERY CAPACITY HAS GROWN EXPONENTIALLY SINCE 2019. SOURCE: IEA

My research group and I are working on several lines of research to address these issues related to integrating batteries into power systems. With support from the National Science Foundation and Columbia University's Data Science Institute, we are doing the theoretical heavy-lifting to develop new algorithms that analyze and facilitate storage operation in the power system. The U.S. Department of Energy is funding a more practical project, in association with Lawrence Berkeley National Lab, aimed at developing frameworks to improve power system operation in California.

We are also working on an industry-sponsored project using AI to improve the market offerings of a battery company in Texas. Along with colleagues at Columbia Engineering, members of my group are analyzing the life cycle of in-home batteries and scoping out the use of sodium-sulfur batteries for long-term storage.

BOLUN XU IS AN ASSISTANT PROFESSOR OF EARTH AND ENVIRONMENTAL ENGINEERING.

Safely Refining Critical Materials

The U.S. isn't on track to produce and import enough raw inputs for the energy transition. Read about a new process for refining metals that could transform the supply chain.

A global energy system powered by renewable electricity won't require the constant supply of new material the way it requires fossil fuels today. The raw materials that go into equipment like batteries, solar panels, and wind turbines aren't destroyed — those minerals will be reused again and again.

In fact, there will eventually be enough material circulating through the economy that recycled minerals will satisfy most of the demand for nickel, lithium, and other important metals.

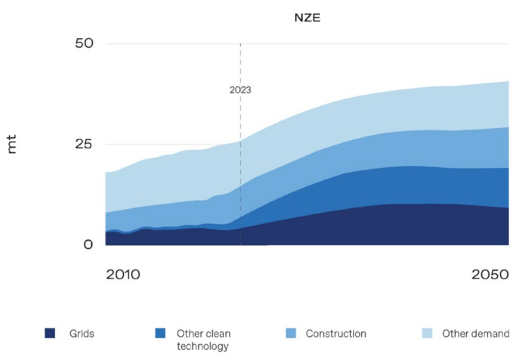
But we're not there yet. Over the next several decades, the U.S. and global economies will need an enormous pulse of newly mined materials to electrify the existing energy system and stock the circular supply chains of the future.

Existing mining and processing technologies aren't up to this challenge. That's why we and our colleagues are urgently pursuing advances in metallurgy that will increase the efficiency, safety, and sustainability of refining these materials at industrial scale.

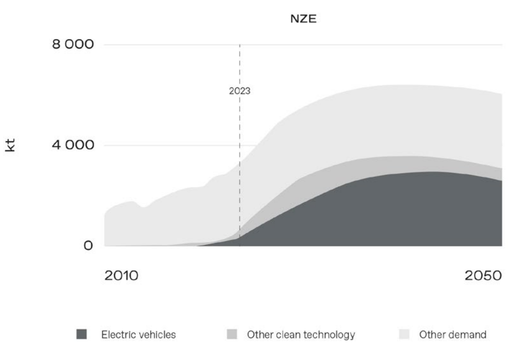
THE COST OF GREEN TECHNOLOGY

Electrifying the energy system will require huge quantities of copper and nickel. While estimates vary widely, the International Energy Association (IEA) predicts the global energy system will require roughly 4 million tons of nickel per year and 20 million tons of copper per year by 2040.

Copper Demand Outlook



Nickel Demand Outlook



DEMAND FOR COPPER AND NICKEL FOR ENERGY-RELATED USE PLATEAUS AND BEGINS TO FALL BY MID-CENTURY UNDER THE NET ZERO EMISSIONS BY 2050 SCENARIO, WHICH ESTIMATES THE RESOURCES NEEDED TO COMPLETELY ELIMINATE NET CO_2 EMISSIONS. SOURCE: IEA

The process of mining and processing nickel and copper already comes at steep human, environmental, and economic costs. The prevailing methods for transforming mined material into usable metals — techniques called pyrometallurgy — require heating ore to 1000 or 2000 degrees Celsius. These smelting processes consume enormous amounts of fossil fuels, pollute the air and water, and leave behind toxic waste that's difficult and expensive to manage safely.

The environmental cost of just one facility is so great that the U.S. government hasn't permitted a new one since environmental regulations were instituted in the 1970s. Instead, nearly all of the copper and nickel supply is processed in low-income countries with lax or nonexistent regulations. A large portion of the copper that is mined in the U.S. is shipped abroad for processing.

Manufacturing nickel and copper in the quantities needed for the energy transition presents another challenge: The highest quality ore has already been mined and smelted. The ore being mined today is a challenge for existing smelters, which were designed to handle higher quality feedstocks.

A NEW APPROACH

Over the past several years, researchers at Columbia Engineering have developed new methods for processing nickel and copper ores more safely. Today, roughly 20% of ore is processed using an approach called hydrometallurgy. In contrast to pyrometallurgy, hydrometallurgy produces manageable waste streams and requires much lower temperatures.

In 2022 and 2023, we published papers detailing how hydrometallurgy can be used to process copper sulfide ore likely to be mined over the next several decades. West's research group has demonstrated in the lab how copper sulfide ores could be processed using these methods. We're pursuing work on similar processes for nickel and othercritical materials.

Importantly, these methods can be employed in smaller facilities that are cheap enough to build beside mines.

> For mining communities that haven't benefited from the higher incomes associated with refined products, hydrometallurgy offers the chance to safely earn a larger share of the value their minerals provide end users.

COMMERCIALIZING THE TECHNOLOGY

Still Bright, a startup founded by a PhD student from West's group, is currently working to validate this technology for industrial-scale copper production. The company has established a business model and obtained investments to support scaling the process to a size that will overcome many deployment barriers.

We are also leveraging our work on copper to develop a process for the production of feedstock for battery-grade nickel refineries. The process is being developed with minerals from a significant minable resource in northern Minnesota.

In the lab, we have developed a process capable of producing roughly one kilogram of nickel per day. While our ultimate goal is to scale the process to match the output of existing nickel smelters, which produce roughly 100 tonnes of nickel per day, our intermediate goal is a process that produces 20 kilograms per day. At this scale, we will be able to overcome the major deployment barrier by reassuring potential customers that we have identified and addressed any "unknown unknowns."

ALAN WEST IS THE SAMUEL RUBEN-PETER G. VIELE PROFESSOR OF ELECTROCHEMISTRY AND PROFESSOR OF EARTH AND ENVIRONMENTAL ENGINEERING.

JEFF FITTS IS THE EXECUTIVE DIRECTOR OF THE COLUMBIA ELECTROCHEMICAL ENERGY CENTER.

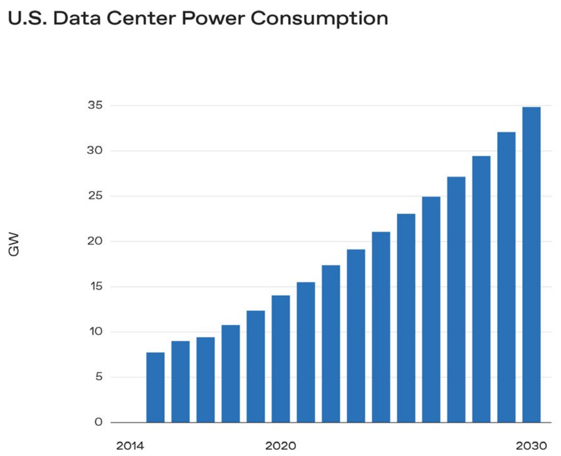
Efficiency Breakthroughs: Optimizing Data Centers

The data centers that run AI systems consume an enormous amount of energy. Learn about the new hardware that could drastically improve performance and efficiency.

Data centers use an enormous amount of energy — and the demand is growing exponentially. From 2022 to 2026, the amount of energy consumed by U.S. data centers is projected to more than double to 1,000 terrawatt-hours per year.

To take one example, the data centers used to train GPT-4 consumed more energy during that four-month process than New York City uses in the heat of the summer. While data centers do everything from hosting streaming videos to managing air traffic, the main drivers of energy consumption are AI and machine learning models.

My colleagues and I have grown increasingly concerned about these trends. With exponentially larger models consuming exponentially larger amounts of energy, data centers are on track to consume more than 10% of the global energy supply within the next 10 years.



THE TOTAL ENERGY USED TO POWER U.S. DATA CENTERS IS GROWING EXPONENTIALLY. SOURCE: MCKINSEY

With today's state-of-the-art technology, energy use and model size increase in lockstep. We desperately need more efficient data centers to bend the curve of energy consumption so that AI applications can continue to grow without consuming an undue share of the global energy supply.

THE INEFFICIENCY OF TODAY'S DATA CENTERS

Data centers contain three essential components: computation, memory, and communication among those subunits. Training very large models requires connecting as many as 10,000 computing elements in complex networks.

In today's data centers, most of that data travels as electrons over wires. Simply moving that data is expensive in terms of energy. Even worse, the physics of electronic communication sharply limits the distance those high data rate signals can travel, meaning computation and memory have to be packaged very closely together on a common interposer substrate and in sockets. This causes a couple of problems. For one, we have to connect many of these sockets in such a way that all components are powered on all of the time. And since many of these sockets have to be relatively far from each other, the communication channels connecting them have low bandwidth.

The elements inside the socket are inefficient. Imagine thousands of powerful computers and memory units wasting a lot of energy as they sit idle waiting for data to travel through the narrow straws that connect them.

Even when conventional fiber-optic cables are used to connect the sockets, it's hugely inefficient for data to travel the relatively short distance from the chip to the connection point at the socket's edge.

THE PROMISE OF INTEGRATED PHOTONICS

We can address these inefficiencies using integrated photonic technologies to transfer data directly from one chip to another. This approach increases bandwidth by more than 100 times, effectively bringing the type of bandwidth currently available within a single chip to an entire data center.

With modern photonics, we can continue to grow AI performance by orders of magnitude while keeping energy consumption essentially flat.

The reason for the higher bandwidth lies in the fundamental properties of light. With photonics, it's possible to send multiple streams of data at the same time using different colors. Those signals don't interfere with each other because photons don't interact with one another, unlike electrons, which must be separated. Photonics offers almost unlimited bandwidth density.

BRINGING MODERN PHOTONICS TO REAL-WORLD DATA CENTERS

Developing this technology is one thing — seeing it implemented in data centers is another. Two years ago, Columbia Engineering colleagues Michal Lipson, Alex Gaeta, and I co-founded the startup Xscape Photonics. Our goal is to commercialize these ideas by bringing photonics inside the AI compute socket. If successful, this innovation will revolutionize data centers by providing almost unlimited communication bandwidth, opening the door for scaling while making the entire system significantly more energy efficient.

I also direct the Center for Ubiquitous Connectivity, which we call CUbiC. This systems-level research center unites the efforts of 24 PIs, more than 114 PhD students, and 17 undergraduates across 15 universities. Our outstanding team of researchers strives to flatten the computation-communication gap, delivering seamless edge-to-cloud connectivity with transformative reductions in the global system energy consumption.

The rate of growth in energy consumption by data centers is frightening. With the size of models and datasets growing exponentially and with no end in sight, it is essential that we develop technologies to decouple computation from energy use. Luckily, technologies to flatten the curve of data center energy consumption are on the horizon. As these technologies come to fruition, we must ensure that they are implemented as quickly and widely as possible.

KEREN BERGMAN IS THE CHARLES BATCHELOR PROFESSOR OF ELECTRICAL ENGINEERING; DIRECTOR, CENTER FOR UBIQUITOUS CONNECTIVITY; AND SCIENTIFIC DIRECTOR, CENTER FOR INTEGRATED SCIENCE AND ENGINEERING.

Looking Ahead: Calls to Action

Thanks for Reading The Lever

This is a critical moment for our climate and the energy system. Learn why academic-industry partnerships are essential to making ubiquitous renewable energy a reality.

As it stands today, we have deployed electrochemistry at megawatt scale. Roughly speaking, that's enough to power 10,000 homes, several large hospitals, or a midsized data center.

Our task now is to solve the challenges of deploying electrochemical energy at gigawatt and terawatt scale — without subsidies or higher prices.

When I speak to industry leaders about the progress being made in electrifying the energy system, they answer with a laundry list of open questions. It turns out that doing electrochemistry at scale requires overcoming many challenges. Industry needs de-risked solutions.

Industry researchers can optimize equations, but it's up to academics to figure out what equations at these scales even look like. That's why industrial-academic partnerships, like those we have at CEEC, are so important. We are home to dozens of PhD students and postdocs — and more than a hundred MS and undergraduate students — who work with our core faculty to develop practical solutions to vexing problems.

Our task now is to solve the challenges of deploying electrochemical energy at gigawatt and terawatt scale — without subsidies or higher prices.

Our researchers work on electrochemistry at every scale — from the electron to the power grid — with funding from federal agencies, industry partners, and philanthropic organizations. CEEC recently joined a $62.5 million hub for innovative research on energy storage. Lauren Marbella and I are working with colleagues at MIT to develop new electrolyte designs and generate new chemical states to build novel electrolyte materials that will improve the energy storage of batteries.

This is a crucial moment for the energy system and the planet. There is no time to waste in developing the many technologies necessary for drastically reducing the amount of fossil fuels that we require as a global society.

If you're interested in joining CEEC on our mission, please contact Executive Director Jeff Fitts at j.fitts@columbia.edu.

DAN STEINGART IS THE STANLEY-THOMPSON PROFESSOR OF CHEMICAL METALLURGY IN THE DEPARTMENT OF EARTH AND ENVIRONMENTAL ENGINEERING, PROFESSOR OF CHEMICAL ENGINEERING, AND CHAIR, DEPARTMENT OF EARTH AND ENVIRONMENTAL ENGINEERING.