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SCIENCE SERIES

Superbreakthroughs: Four vignettes of how AI will transform the way we live

We believe AI is going to usher in a future of energy abundance, but what could that actually look like? Through four vignettes of solar power, geothermal energy, carbon removal, and electrochemical manufacturing, we trace out how cheap, clean energy will power new ways to understand and engineer our planet and to build the materials modern life runs on.

October 2026

Look around: nearly everything around you is likely the product of compounding human innovation in materials production—computers, clothes, buildings, modern foods, medicines. And even where your surroundings may be natural and undisturbed by human intervention, humans have made tremendous progress in understanding the natural world. These are the products of a human tradition of science, inquiry, and innovation—a tradition that AI is likely to greatly accelerate and transform, as we've previously written about.

We use the term *superbreakthrough* to describe something even more ambitious: scientific advances that compound and cascade together through technology, industry, and society to transform how people live. Superbreakthroughs are like the discovery of antibiotics and the subsequent transformation of medicine, or like the invention of the transistor leading to the integrated circuit and the entire universe of digital electronics. We believe that AI will catalyze a new wave of superbreakthroughs—and this means AI for science that isn't only a new model or another arXiv posting, but a unified effort to build real-world technology that matters. And while each individual advance may come in different shapes of AI—specialized scientific predictive models, large language models, world models, robotics, integrated AI co-scientists, or even science that doesn't rely on AI at all—we believe that all of these together compound to expand the feasible future.

In this piece we present four vignettes about the future of energy and climate technology: the first, on solar energy, serves as reminder that transformative technology is possible, humanity has done it several times before. The next three vignettes examine three emerging technologies and walk the reader along the path to superbreakthrough. We look at geothermal energy, carbon removal, and electrochemical manufacturing, painting a picture of what the production and harnessing of energy could look like in the near future. These vignettes present an optimistic vision for the future of technology and society, although the scientific pathway there will remain challenging and certainly not guaranteed.

Vignette 1: Solar Energy

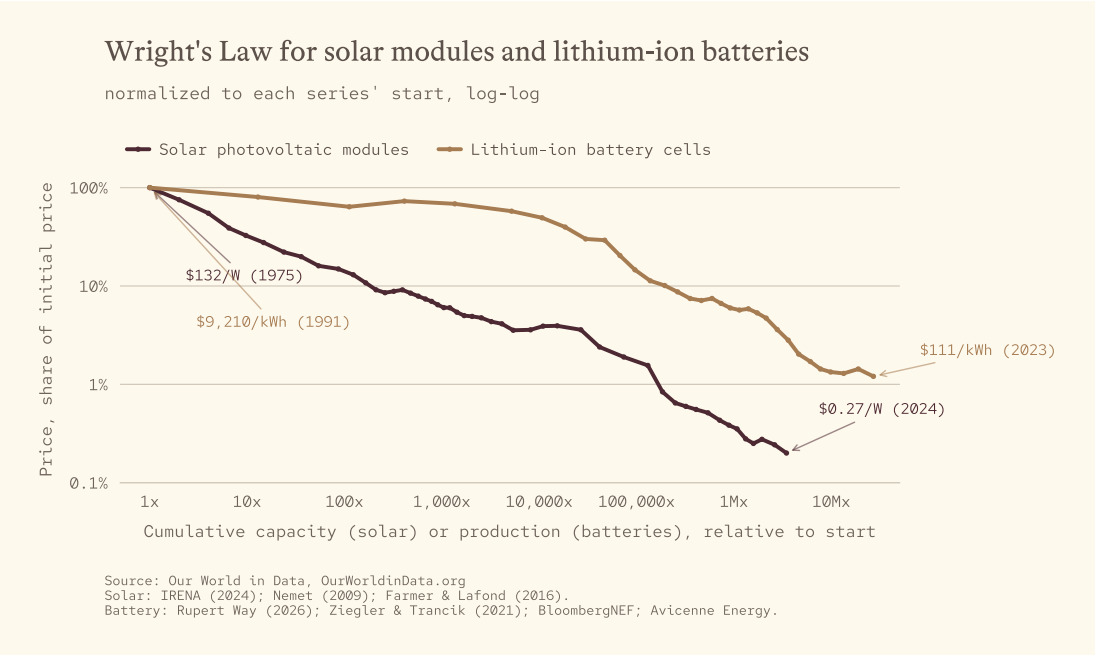
For three billion years, the only way to harness energy directly from the sun was through photosynthesis. It's only in the last century that we've discovered a second way: the photovoltaic cell, which uses layers of semiconductor materials to convert solar energy directly to electricity.

The physics that undergirds solar photovoltaics stretches back to the photoelectric effect, first observed in 1839 and explained by Einstein in 1905. In 1954, scientists at Bell Labs created the first practical solar cell out of silicon. For decades following, solar remained a niche technology found in satellites and calculators. But since 1976, the price per watt of solar modules has fallen a remarkable 99.6%, following a trend known as Wright's Law which describes technologies that get cheaper at a consistent power law learning rate as cumulative production increases—basically the idea that the more you make something, the better you get at making it. The price of solar has so far dropped 20.2% with every doubling of installed capacity.[1] This has been traced to over a hundred different cross-disciplinary innovations that have compounded over the decades, spanning both hardware innovations and non-technical improvements in testing, permitting, and training processes.[2] Now, solar panels line deserts and plateaus and hillsides across continents: China alone added about 315 GW of solar capacity in 2025 or around 2,000 square miles of panels—which is enough to power about a quadrillion calculators.[3]

[1] Roser, M. Learning curves: What does it mean for a technology to follow Wright's Law? Our World in Data. (2023); available at https://ourworldindata.org/learning-curve

[2] Kavlak, G. et al. Nature of innovations affecting photovoltaic system costs. PLoS One 20, e0320676 (2025).

[3] 315 GW × 30% capacity factor / 50 μW per calculator = 1.89×10^{15} calculators



These learning curves exist because we continue to innovate through scientific breakthroughs and improved operational efficiencies, and AI is uniquely positioned to accelerate both. For example, the next generation of solar cells are layered hybrid perovskite/silicon tandem cells already demonstrating a power conversion efficiency of over 31%, exceeding the 29% efficiency maximum of silicon-only cells.[4] However, a challenge to commercialization has been keeping the cells stable in real-world conditions of heat, moisture, and UV exposure.[5] Finding a stable composition of perovskites, as well as finding materials for protective layers or coatings, will require searching through an enormous space of possible materials, including some which don't yet exist. As discussed in our earlier AI for Science essay, this is nearly impossible with traditional methods but AI-driven screening makes this a tractable problem. Additionally, AI-driven simulation and experimentation will accelerate the validation process. AI will likely catalyze a data flywheel here, and the Perovskite Database Project[6] is a strong example of how FAIR (findable, accessible, interoperable, and reusable)

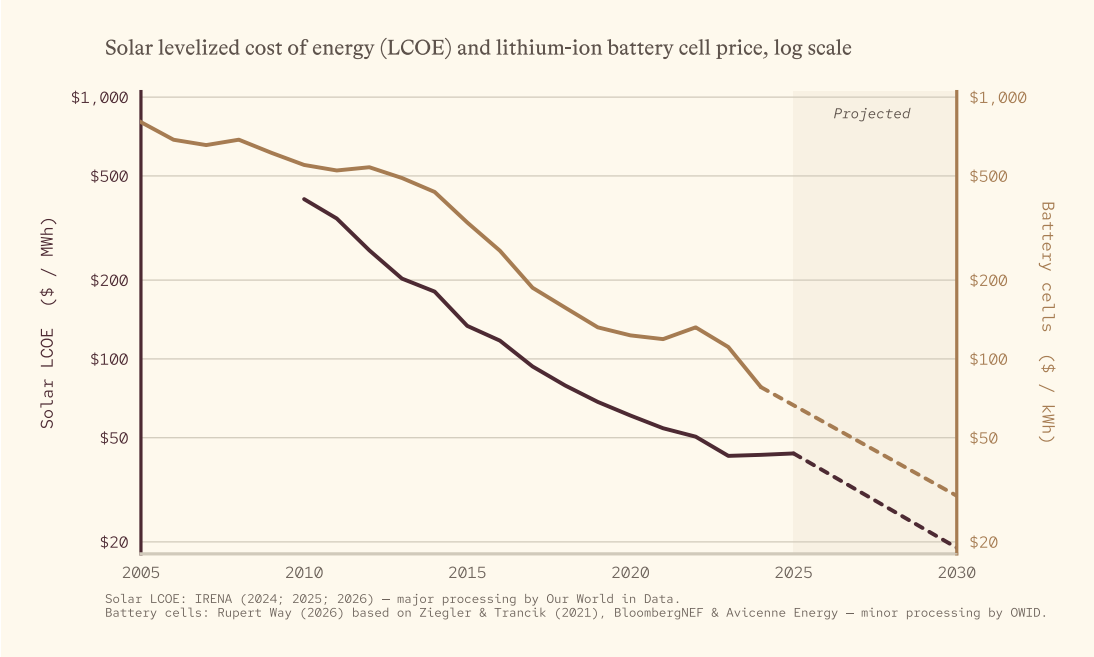
[4] Chin, X. Y. et al. Interface passivation for 31.25%-efficient perovskite/silicon tandem solar cells. Science 381, 59–63 (2023).

[5] Seyisi, T. et al. Major challenges for commercialization of perovskite solar cells: A critical review. Energy Reports 13, 1400–1415 (2025).

[6] Jacobsson, T. J. et al. An open-access database and analysis tool for perovskite solar cells based on the FAIR data principles. Nat Energy 7, 107–115 (2021).

digital assets can be brought together across fields and papers to build AI models for both scientific discovery and operational optimization of new technologies.

For energy storage as well, AI materials design generation will surface new candidates for more effective anodes, cathodes, and electrolytes to build batteries with higher capacity, better safety, and fewer critical minerals.[7] Predictive models will help simulate battery chemistry and battery cyclability over thousands of charge-discharge cycles. Autonomous labs will synthesize and test battery materials around the clock. And this is just for lithium-ion batteries—there exists an entirely open space for next-generation storage technologies which rely on different chemistries to explore, including sodium-ion, iron-air, and thermal batteries.



Solar is already the cheapest form of new utility electricity in history at a levelized cost of ~$44/MWh[8], and lithium batteries are 99% cheaper than they were 30

[7] Chen, C. et al. Accelerating Computational Materials Discovery with Machine Learning and Cloud High-Performance Computing: from Large-Scale Screening to Experimental Validation. J. Am. Chem. Soc. 146, 20009–20018 (2024).

[8] IRENA. Renewable power generation costs in 2025. International Renewable Energy Agency. (2026).

years ago and continuing to drop.[9] In a matter of years—still within a single human lifetime since the invention of the solar cell—we'll likely reach <$20/MWh of solar, with overnight storage costing a few dollars more, meaning cheap, clean, and nearly universal energy harnessed directly from the sun.

Vignette 2: Geothermal Energy

While solar energy comes from up above, geothermal energy comes from below our feet: at a few kilometers deep, the rock becomes hot enough to boil or superheat water to spin a turbine. Natural geothermal power systems exist in the form of hot springs like in Iceland and in The Geysers in California, but they are generally rare around the world. Man-made geothermal systems, called Enhanced Geothermal Systems (EGS), seek to engineer these types of reservoirs anywhere on Earth, tapping into a 24/7 source of fossil-free power generation. EGS involves drilling deep into the earth and then circulating water either through a closed loop circuit or through fractures in the hot rock that are created through hydraulic fracturing (fracking).

Progress in enhanced geothermal systems has been steady, though still in early stages. Recent pilots are at the few-MW scale but have proven that vertical and horizontal drilling techniques plus hydraulic fracking—largely developed earlier through the U.S. shale revolution and for oil and gas extraction—can be translated to the hot and crystalline rock conditions needed for EGS.[10] Scaling this up further to become a significant proportion of global power generation will require building both on existing science, innovation, and infrastructure in geological engineering, as well as a slate of breakthroughs in advanced materials, simulations

[9] Ritchie, H. & Rosado, P. Battery costs have declined by 99% in the last three decades, making electrified transport a reality. Our World in Data. (2026); available at https://ourworldindata.org/battery-price-decline

[10] Norbeck, J. & Latimer, T. Commercial-Scale Demonstration of a First-of-a-Kind Enhanced Geothermal System. Preprint at https://doi.org/10.31223/X52X0B (2023).

of extreme conditions, geological monitoring, and more—and we expect that AI will help advance each of these dimensions.[11]

For example, a significant challenge in scaling up will be identifying appropriate sites, which requires understanding how far down the heat reservoir is and the type of rock and faults that surround it. Drilling a well which ends up not producing is extremely costly and is a significant source of risk for EGS developers and financers. But geological remote sensing tools try to make sense of the underground world using only clues from the surface: like electromagnetic, resistivity, and acoustic signals that are sensitive to different types and densities of rock and fluid reservoirs. AI tools will be very effective at making sense of and combining these signals to construct a fine-meshed digital twin of the local subsurface that directs developers to the best well formations.[12]

An additional challenge is that all materials involved, including pipes, walls, drills, and sensors, must withstand the extreme heat and pressure of the geothermal reservoir (>200 °C, 20 MPa) for the lifetime of the well. AI for materials science would help propose new material combinations to achieve that strength and durability, and AI simulations of tests under extreme conditions would be important for evaluating the operational capacity.

Managing the potential risks of enhanced geothermal systems is also a key aspect that takes this from individual innovations to a superbreakthrough that is widely adopted and widely transformative. There are known challenges related to hydraulic fracking, such as groundwater contamination and induced earthquakes. Better subsurface mapping and stronger materials would both help prevent groundwater contamination, and a network of advanced geophysical sensors could continuously monitor for predictive maintenance, to detect issues before they become catastrophic. And while earthquakes cannot easily be predicted, a strong network of seismic sensors plus algorithmic triangulation would provide early warning systems that allow for rapid response, such as pausing operations if seismic activity grows too quickly. These tools would also deepen knowledge of

[11] Dou, Y. et al. Artificial Intelligence for Subsurface Imaging Understanding: A Decade Review of Challenges, Methods, Benchmarks, and Outlook. Preprint at https://doi.org/10.48550/arXiv.2606.09094 (2026).

[12] Zhao, T. et al. Artificial intelligence for geoscience: Progress, challenges, and perspectives. The Innovation 5, 100691 (2024).

controlled microearthquakes that could relieve geological tension while minimizing seismic risk and human impact.[13]

Geothermal energy is clean and available around the clock, in every season, and in every latitude, and in these ways serve as an excellent complement to the previous vignette of solar superbreakthrough. Historical lessons from solar foster an optimism that geothermal energy will follow learning curves—through a spectrum of innovations on every part, process, and parcel—to bring down costs exponentially quickly, and that challenges related to manufacturing, permitting, or land use may be worked through. A superbreakthrough here would look like firm energy that is more decoupled from access to natural reservoirs or resources than other forms of energy, bringing an equalizer to energy independence and energy abundance.

Vignette 3: Understanding carbon removal

Next, we explore a superbreakthrough in Earth systems modeling that is already unfolding. Already, there has been incredible progress in AI atmospheric modeling and weather forecasting, translating decades of complex physics-based calculations into fast, data-based AI inference. The Aurora foundation model generates 10-day weather forecasts in seconds, at an estimated 5,000x speedup over traditional supercomputing techniques. It also predicts tropical storm trajectories and ocean wave heights.[14] Aurora also does extremely well at predicting air quality and pollution at speed, which requires modeling complex atmospheric chemistry on top of fluid dynamics. Aurora 1.5 extends this further by covering 22 additional variables, including humidity, precipitation, and radiation fields. This longer-horizon forecasting and understanding has profound

[13] Chung, J., Manga, M., Kneafsey, T., Mukerji, T. & Hu, M. Deep learning forecasts the spatiotemporal evolution of fluid-induced microearthquakes. Commun Earth Environ 6, 643 (2025).

[14] Bodnar, C. et al. A foundation model for the Earth system. Nature 641, 1180–1187 (2025); Beatty, S. From sea to sky: Microsoft's Aurora AI foundation model goes beyond weather forecasting. Microsoft. (2025); available at https://news.microsoft.com/source/features/ai/microsofts-aurora-ai-foundation-model-goes-beyond-weather-forecasting/

implications for extreme weather safety, agriculture, air/sea transportation, and even for uses like forecasting local solar energy generation.[15] Sophisticated foundation models like Aurora will soon build up into a unified model of the Earth System.

One breakthrough out of a unified model of the Earth System would be a transformation in our understanding of atmospheric and oceanic carbon cycles—that is, how carbon moves between air (mostly as carbon dioxide), oceans, living matter in plants and animals, rocks, and more, through photosynthesis, respiration, consumption, decomposition, and dissolution. Understanding and mapping the carbon cycle is critical to controlling and mitigating climate change: according to the Intergovernmental Panel on Climate Change (IPCC), lowering carbon emissions is not enough; active carbon dioxide removal is now required to limit global warming to below 1.5 °C—and on a massive scale of several gigatons each year.[16] A calculation of available land surface shows that there simply isn't enough land on the planet to plant our way to 10 gigaton/year of carbon dioxide removal[17]—we need bold, innovative solutions which can remove carbon from the air at scale, and we also need the carbon monitoring and measurement systems that support this.

For carbon dioxide removal at scale, one direction to look is toward the ocean: our biggest natural carbon sink, which already holds 50x more carbon than the atmosphere and absorbs over a quarter of all carbon dioxide emissions. Some carbon dioxide removal techniques propose to engineer the ocean to be an even bigger absorber of carbon, but these must come at a balance between the ocean's immense potential for carbon storage and its sensitivity and importance to life of all forms, not exclusively humans. Marine carbon dioxide removal comprises

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[15] Takeda, K, et al. Aurora 1.5: Extending open foundation models for weather and Earth-system applications. Microsoft Research Blog. (2026); available at https://www.microsoft.com/en-us/research/blog/aurora-1-5-extending-open-foundation-models-for-weather-and-earth-system-applications/

[16] Calvin, K. et al. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland. https://www.ipcc.ch/report/ar6/syr/ (2023).

[17] Bastin, J.-F. et al. The global tree restoration potential. Science 365, 76–79 (2019); National Academies of Sciences, Engineering, and Medicine. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. (National Academies Press, Washington, D.C., 2019).

several classes of techniques, for example: ocean alkalinity enhancement involves adding alkaline rocks or other chemicals to raise the pH of the ocean, which turns CO_2 in the ocean into stable carbonate ions, which then allows the ocean to absorb more CO_2 from the atmosphere. Nutrient fertilization is a technique to add iron or macronutrients to the upper ocean to stimulate the growth of phytoplankton like algae, which would then absorb more CO_2 through increased photosynthesis. Electrochemical direct ocean capture techniques use electricity to separate gaseous CO_2 out of water so it can be captured and stored elsewhere, freeing the ocean to absorb more CO_2 from the atmosphere. These techniques have been explored by the National Academies of Science and other scientists for several decades and feasibly could remove >1 gigaton/year.[18] However, common among these techniques is a huge gap in understanding of the rate and durability of carbon removal, the impact on wildlife and ecosystems, and the long-term or financial viability. The impact of any of these proposed techniques depends on a sensitive balance between atmospheric and oceanic carbon transfer, as well as downstream effects that may actually reverse the net climate effects—for example, if the phytoplankton release even more potent greenhouse gases when they die and decompose.

These carbon dioxide removal techniques are nascent and unproven at large-scale, but have the potential to be transformative if properly executed. Earth systems AI catalyzes the capabilities to simulate these large, complex, and long-time-horizon systems in order to understand where the carbon goes, and where it stays. This understanding will help us build the engineering systems and necessary guardrails to carrying this out safely and at scale. Earth systems AI will also be critical for selecting optimal sites for geoengineering, as that can be a complicated and delicate balance of ocean currents, temperature, coastline topography, and more. Additionally, predictive models for carbon paired with AI-enhanced ocean sensors will play a large role in the monitoring, reporting, and verification (MRV) of carbon removal at a local scale. Quantifiable MRV is critical for creating a sustained, global carbon market where buyers and sellers have confidence in the removal, and this allows for commercialization, market incentives, and enforceable policies that can really drive carbon removal to scale.

[18] National Academies of Sciences, Engineering, and Medicine. A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration. (National Academies Press, Washington, D.C., 2022).

Combating climate change is one of the most important global challenges today, and many angles of this will be as much about social and economic systems as they are about technological systems. The incredible pace of improvement in modeling and predicting atmospheric and oceanic systems with AI in just the last handful of years gives optimism that we can make breakthroughs in carbon removal in line with IPCC targets.

Vignette 4: Electrochemical manufacturing

Energy generation is an essential part of how we live—how we travel, cook, stay warm, manufacture goods, grow food, and pretty much everything else. But to extend the imagination a bit more to the simplest building blocks of matter, in this vignette we discuss how we use energy to control and rearrange atoms and make molecules—and how AI-driven materials discovery changes what's been traditionally possible. The simplest non-AI example is electrolysis: by passing an electrical current through water, we can split water (H_2O) into hydrogen (H_2) and oxygen (O_2) gas. We've known how to do this for over two centuries, but in the recent decades we've learned how to build better membranes and catalysts—like proton-exchange membranes and iridium- and platinum-based catalysts—that speed up this process and make it feasible to produce hydrogen at an industrial scale.[19] These improvements have made green hydrogen an increasingly popular choice for energy storage for renewables and for portable fuel like in vehicles.

But actually, hydrogen's most important use is to make ammonia, the key component in synthetic fertilizer for agriculture. Primarily, ammonia production is through the Haber-Bosch process, which since the 1910s has been credited with feeding half of humanity.[20] However, Haber-Bosch is incredibly energy and carbon intensive: it burns natural gas to isolate hydrogen, then combines it with air with an iron catalyst at 400–500 °C and extremely high pressures. A scientific

[19] Carmo, M., Fritz, D. L., Mergel, J. & Stolten, D. A comprehensive review on PEM water electrolysis. International Journal of Hydrogen Energy 38, 4901-4934 (2013).

[20] Ritter, S. K. The Haber-Bosch reaction: An early chemical impact on sustainability. Chemical & Engineering News. (2008); available at https://cen.acs.org/articles/86/i33/Haber-Bosch-Reaction-Early-Chemical.html

breakthrough here (with or without AI) would be huge: nitrogen fertilizer production consumes 1–2% of the world's energy[21] and accounts for 1.8% of global carbon dioxide emissions.[22] Using green hydrogen as both a chemical feedstock for nitrogen fixation and a fuel source to reach the temperatures and pressures needed for production would make up a huge dent in decarbonization. Green hydrogen or green ammonia could also be a drop-in replacement for fossil fuel heating in other industrial chemical production processes and steel production which are difficult to electrify and decarbonize because of the high temperatures and pressures required. Those together add up to around another 10% of global greenhouse gas emissions.[23]

Haber-Bosch evolved at a time when fossil fuel use was not a concern. But conditions have changed, and we can go bolder: the atomic ingredients for ammonia (NH_3) are already all around us. With the right catalysts (and AI is very good at searching for catalysts[24]), we should be able to build ammonia directly from air (which is 78% nitrogen), water, and electricity as a direct electrochemical process. Recent work in lithium-mediated nitrogen reduction in ambient conditions has demonstrated high current-to-ammonia efficiencies, continuous operation, and strong progress in exploring new alloyed catalysts and solvents.[25]

And ammonia is just one of many small molecules that are essential for modern human society and also comprised of light and abundant elements like hydrogen, nitrogen, carbon, and oxygen found in air and water. Other examples include ethylene (C_2H_4) which is a huge part of making plastics (and also sometimes called the "World's Most Important Chemical"),[26] methanol (CH_3OH) which is a

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[21] Smith, C., Hill, A. K. & Torrente-Murciano, L. Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape. Energy Environ. Sci. 13, 331–344 (2020).

[22] David, B. et al. Ammonia: Zero-Carbon Fertiliser, Fuel and Energy Store. https://royalsociety.org/news-resources/projects/low-carbon-energy-programme/green-ammonia/ (2020).

[23] Ritchie, H. Sector by sector: where do global greenhouse gas emissions come from? Our World in Data. (2020); available at https://ourworldindata.org/ghg-emissions-by-sector

[24] Zhang, D. et al. Accelerating Catalyst Materials Discovery With Large Artificial Intelligence Models. Angewandte Chemie International Edition 65, no. 16 (2026).

[25] Fu, X. et al. Continuous-flow electrosynthesis of ammonia by nitrogen reduction and hydrogen oxidation. Science 379, 707–712 (2023); Li, S. et al. Long-term continuous ammonia electrosynthesis. Nature 629, 92–97 (2024).

[26] AFPM Communications. Ethylene: The "World's Most Important Chemical." American Fuel & Petrochemical Manufacturers. (2017); available at https://www.afpm.org/newsroom/blog/ethylene-worlds-most-important-chemical

precursor to formaldehyde and also a fuel, and acetone (CH_3COCH_3) which is also used in plastics. These are currently manufactured through natural gas or petroleum-based processes.

Decarbonizing chemical manufacturing is an incredibly daunting task. But the hope for electrochemical synthesis lies in creating appropriate catalysts—which are materials which facilitate the movement of electrons from atom to atom—and designing efficient electrolytic cells. Catalyst design is an excellent candidate for end-to-end AI discovery: using models to screen existing libraries of materials for catalyst candidates; using other models to quickly predict electronic structures and chemical dynamics; using autonomous labs to synthesize, test, and characterize these; and then taking the most promising candidates to iterate on.[27] Designing electrolytic cells—which are kind of like reverse batteries—relies on similar considerations for choice of electrodes and electrolytes.

And for this to occur at an industrial-scale, there are also a near-infinite number of process parameter optimizations (like flow rate and operating voltage) and factory design choices (like the type of material for receptacles). The capability to use AI for process simulation and operational control will greatly accelerate how quickly these can move from lab-based demonstrations to fully operational electrochemical factories.

A superbreakthrough in electrochemistry would be a key to decarbonizing our economy, and it would also change the relationship between materials and fossil fuel geopolitics. These electrochemical factories could be clean, small, and local, producing fertilizer, fuel, and other chemicals right where they are needed. And as our final vignette, it is also one that compounds on the previous ones: this is most achievable if energy is clean, cheap, and abundant. But with that energy, we envision a world of using electricity to control chemical synthesis at an atomic scale.

[27] Mok, D. H. et al. Data-driven discovery of electrocatalysts for CO_2 reduction using active motifs-based machine learning. Nat Commun 14, 7303 (2023).

Conclusion: AI that expands the feasible future

AI for science so far has mostly been told through individual innovations, like a novel material structure, or a solved mathematical proof, or a saturated benchmark. But for AI to truly usher in transformative superbreakthroughs, these achievements must compound into new technologies, which also means designing new systems, processes, and behaviors all together. This will take many different forms, but we are optimistic for the ways that AI will support discovery, exploration, and solutions at every stage. This is the thread that runs through our vignettes: solar and geothermal show how AI can accelerate the generation of clean, abundant energy, which then opens opportunities for further innovation and problem solving. Carbon modeling and electrochemical synthesis build on abundant energy to turn clean, cheap power into new ways to monitor our planet and to control molecules which could transform global decarbonization efforts.

AI for science means acquiring better tools for learning how to manipulate energy and matter and for understanding the natural systems in which those interventions occur. It expands the vision for the feasible future and what is in our control to craft it. And while the pathways there are certainly not guaranteed—the science is hard and the institutional work often even harder—the optimism of AI-accelerated discovery appears to at least widen these paths.