STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW 2025

A Report on Ten Key Technologies and Their Policy Implications

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TECHNOLOGY APPLICATIONS BY POLICY AREA

This chapter explores applications from each technology field described in the report as they relate to five important policy themes: economic growth, national security, environmental and energy sustainability, health and medicine, and civil society. For each area, we extract from the technology discussions of chapters 1 through 10 applications or consequences that speak to it. Readers are invited to refer to the relevant technology chapter for more information about an application or consequence mentioned as well as for discussions of technical and other terms that may be unfamiliar.

Economic Growth

Artificial intelligence (AI) AI may significantly boost productivity across many sectors of the economy. Large language models such as ChatGPT have already demonstrated how they can be used in a variety of diverse fields, including law, customer support, computer programming, and journalism. Generative AI, a form of AI that creates new text, images, and other content, is expected to raise global GDP by $7 trillion and lift productivity growth by 1.5 percent over a ten-year period, if adopted widely.

Biotechnology and synthetic biology Biotechnology is poised to emerge as a general-purpose technology that can be applied broadly, with the capacity to revolutionize areas such as healthcare and manufacturing. Biological processes could ultimately produce as much as 60 percent of the physical inputs to the global economy. Already, biotechnology and synthetic biology are enablers for advances in medicine and healthcare (e.g., vaccines and cancer treatments), agriculture (e.g., drought-resistant crops), food (e.g., nutritionally enriched vegetables), and energy production (e.g., biofuels). Potential applications also include biotic semiconductors, magnets, fiber optics, and data storage.

Cryptography Blockchain technologies can effectively provide provenance in supply chains as well as personal identity management that curbs fraud and identity theft, leading to more secure and efficient transactions. Blockchain technology also underpins cryptocurrencies. A US central bank digital currency (CBDC), a form of digital currency that does not necessarily use blockchains, could help reduce inefficiencies in US deposit markets, promoting broader participation in the financial system.

Lasers Lasers are a key component for a variety of economically significant applications across manufacturing, communications, high-end chip production, defense, and medicine. For example, in precision manufacturing, lasers play an important role in cutting and shaping materials. Another application is in long-distance fiber-optic communications, where they are the providers of the light pulses that carry very high volumes of data.

Materials science Lighter and stronger materials will increase the energy efficiency of vehicles used to transport people and cargo. New semiconductor materials enable new types of chips and other information processing hardware. Technological innovations are also offering new ways to produce low-carbon steel and cement.

Neuroscience Interventions for those with neural disorders include pharmaceuticals that curb, treat, or reverse neurodegenerative conditions; diagnostics to identify early onset of such conditions; and rehabilitation therapies that help those suffering from them engage in the activities of daily living. By helping to address neurogenerative diseases more effectively, research in the field could allow people to remain in the workforce longer and be more productive, as well as reduce the burden on caregivers, who often need to take time off work to look after relatives and friends.

Robotics Robots are used widely today, including in manufacturing; on-demand delivery services; surgery; science and exploration; food production; disaster assistance; security and military services; and transportation. Innovations in robotics have enormous potential to increase productivity in many fields and perhaps to create new types of jobs. But robots involving physical labor and presence may also eliminate some jobs and change others, creating the need for retraining and other measures to address short-term impacts.

Semiconductors Semiconductors are an enabling technology for any application that can be improved through the use of information. They provide the computing capabilities that many sectors of the economy rely on. As such, they are key drivers of economic activity and growth. However, reductions in the cost of semiconductors and increases in processing power are likely to become less frequent or regular in the future—and predictions about economic growth in the years ahead attributable to improvements in semiconductor technology may prove to be overly optimistic.

Space Space activities play critical roles in our daily lives and the economy, from enabling global navigation systems to providing precise time information for financial transactions. Expanding commercial activities are expected to drive high growth in the space sector. In the future, space activities could become even bigger drivers of economic growth on Earth, through things such as asteroid mining and space-based power production.

Sustainable energy technologies In 2023, clean energy accounted for 10 percent of global GDP growth. Doubling the share of renewables by 2030 would increase global GDP by over $1 trillion in addition to creating 24 million new jobs in the renewable energy sector. Although up-front expenses remain high, the cost of both wind-generated and solar-generated electricity is now substantially lower than that of fossil fuels. Nuclear-generated electricity is widely considered a necessary part of a net-zero emissions energy mix in the longer-term future. However, economic considerations such as the cost and timelines for constructing reactors and the lack

of an actual long-term US nuclear-waste disposal policy are a substantial impediment to more widespread deployment of nuclear power in the United States.

National Security

Artificial intelligence Because AI enables more rapid processing of an expanded range of data inputs, all aspects of military operations potentially benefit from it. Possible applications include managing military logistics; improving the effectiveness and efficiency of maintaining equipment; managing electronic medical records; navigating autonomous vehicles; operating drone swarms; recognizing targets; performing intelligence analysis; developing options for command decisions; and enhancing war gaming to develop and refine plans. However, the US Department of Defense's ethical considerations for the development and deployment of AI capabilities (especially in nuclear command and control) may not be shared by adversaries.

Biotechnology and synthetic biology With synthetic biology becoming increasingly available to state and nonstate actors, there are concerns that a malicious actor could create or deploy weaponized organisms or threaten the provision of biologically developed foods, medicines, fuels, or other products to coerce others. Conversely, the prospect of distributed biomanufacturing offers possibilities for localized biodefense and a larger degree of independence from foreign suppliers of many raw materials. China is investing considerably more resources in biotechnology than the United States, creating the potential for a Sputnik-like strategic surprise.

Cryptography Adversaries are likely to have been storing encrypted data, hoping that future advances in quantum computing and other digital capabilities will allow them to crack the encryption protecting the information. Efforts are already underway to create new encryption methods that would be quantum resistant. Separately, zero-knowledge proof methodology to cooperatively track and verify numbers of tactical nuclear warheads may benefit future arms control agreements.

Lasers Operational laser weapons systems are starting to be fielded for military applications such as short-range air defense against drones and to counter artillery, missiles, and other threats. But they have not yet been deployed widely, and their battlefield effectiveness in the face of countermeasures has not yet been tested fully.

Materials science Improvements in materials science and nanotechnology can advance capabilities in stealth technology, camouflage, and body armor and can increase the energy content in explosives. Quantum dots—materials that are smaller than about 100 nanometers in all dimensions—can be used in sensors for detecting agents associated with chemical and biological warfare.

Neuroscience Neuroscience may help illuminate the nature of traumatic brain injuries and post-traumatic stress disorder, thereby leading to better treatments for these conditions. Brain-machine interfaces could also enable new prostheses for wounded combatants.

Robotics Advances in robotics can assist military forces with transporting equipment and supplies, urban warfare, autonomous vehicle deployment, and search-and-rescue efforts. Additionally, robotics can assist with mine clearance, disaster recovery, and firefighting. Some military robots, such as lethal autonomous weapons systems, also raise questions of roboethics on the battlefield. Given the pressure for militaries to act more rapidly, many observers believe that decisions of lethal force will be turned over to computers, while others insist that life-and-death decisions must remain with humans.

Semiconductors Modern military hardware is critically dependent on semiconductor technology

for information processing. The primary fabricator of semiconductor chips globally is Taiwan, which houses two of the three leading manufacturers, the Taiwan Semiconductor Manufacturing Company and the United Microelectronics Corporation. China's long-held interest in reunification with Taiwan and its rising military capabilities and assertiveness toward Taiwan are raising deep concerns about the potential for a Chinese blockade or other actions that could disrupt the global semiconductor supply chain and raise the risk of military conflict between the United States and China. The Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act of 2022 is intended to reduce that risk, but major initiatives called for in the legislation have not been fully funded.

Space Communications, surveillance, and navigation in denied areas are essential functions for military forces. In the future, nonnuclear weapons may be based in space and used to attack terrestrial and/or space targets. Satellites are also essential for the detection of launched ballistic missiles, nuclear weapons explosions, and electromagnetic emissions from other nations. The emergence of low-cost, high-quality information from space-based assets (almost entirely commercial) is a driver of open-source (unclassified) intelligence (OSINT), which has the potential to upend traditional intelligence processes built on classified information collection and analysis. The net effect of OSINT could be a declining US intelligence advantage, as more countries, organizations, and individuals can collect, analyze, and disseminate high-quality intelligence without expensive, space-based government satellite capabilities. The commercialization of space also puts powerful capabilities in the hands of individuals and organizations who are not accountable to voters and whose interests may not be aligned with those of the US government.

Sustainable energy technologies The United States is no longer the world leader in energy manufacturing at scale. For instance, China and other countries with lower operating costs control most of the manufacturing, supply chain, and critical minerals for battery and solar cell production. US energy security will require expansion of domestic production and manufacturing, as well as collaboration with allies and partners to better protect energy supply chains. Moreover, there are concerns that a global increase in fission reactors will result in a greater risk of nuclear proliferation (i.e., the spread of nuclear weapons), especially to nonnuclear states or nonstate actors, while some believe that the emissions-free potential of fission reactors is worth the risk of proliferation, which can be minimized through carefully implemented safeguards. Fuel security for nuclear power remains an issue as well—America currently imports more than 90 percent of its uranium, with about half coming from Kazakhstan and Russia.

Environmental and Energy Sustainability

Artificial intelligence AI capabilities can greatly improve global sustainability efforts, from helping farmers identify which produce or livestock are appropriate to harvest to helping analyze weather patterns to prepare populations and infrastructure for extreme or unusual conditions. At the same time, training and using AI models requires a large amount of energy, and demand for power to support these activities is expected to grow significantly in the future.

Biotechnology and synthetic biology Synthetic biology can contribute to new methods for energy production and environmental cleanup. Electrobiosynthesis is a biotechnology that enables plant-free bioproduction in places where soils are poor, water is scarce, or climate and weather are too variable to support traditional agriculture.

Cryptography Blockchain technologies can provide a transparent and secure way to track the movement

of goods, including their origin, quantity, and other relevant information, thereby improving efficiency in global supply chains and limiting illegal extractions of certain materials. Although some established cryptocurrencies such as Bitcoin require massive amounts of energy, newer ones require far less.

Lasers Lasers can help monitor the environment. For example, when integrated into appropriate instruments, they can help measure levels of toxins or biological agents and enhance the study of microbes in soil or algae in water. In all these cases, laser light stimulates responses in the targets it illuminates that help other instruments to make more accurate measurements of the state of the environment.

Materials science Innovations in materials science and engineering are creating new and sustainable plastics that are easier to recycle. New materials can also advance the electrification of transportation and industry, which is integral to decarbonization strategies, and can support the design of relatively cheap batteries that last a long time and can be quickly recharged. Nanomaterials such as quantum dots can further improve the efficiency of solar cells and biodegradable plastics. However, some innovations in the field have potential downsides, too. For instance, the long-term dangers of nanoparticles released into the environment at the end of their life cycle are unknown.

Neuroscience Sustainability on a planet with finite resources requires that decision makers and the people they represent are able to make trade-offs between immediate rewards and future gains. Neuroscientists have found evidence for cognitive predisposition favoring short-term gains over long-term rewards, based on functional resonance magnetic imaging (fMRI) brain scans of people making choices between immediate and delayed reward.[1] (This example is not further discussed in chapter 6.)

Robotics The deployment of robots primarily for the Three Ds—dull, dirty, or dangerous jobs—enables robotic cleanup of environmentally hazardous materials and their operation in environments that can be dangerous for humans, such as nuclear reactors. Robots are also valuable in the construction, maintenance, and management of solar and wind farms.

Semiconductors Transitioning to renewable energy sources will require vast amounts of semiconductors. Advanced chips are integral to electric vehicles, solar arrays, and wind turbines. Design innovations will continue to improve the energy efficiency of chips.

Space Remote sensing data can create a "digital twin" of Earth to track and model environmental change and the movement of humans and animals, informing disaster response and sustainable development policies. In the future, the development of space technologies will help to address food security, greenhouse gas emissions, renewable energy, and supply chain optimization. Satellite imagery, combined with weather data and powered by predictive optimization algorithms, could increase crop yields and also detect greenhouse gas emissions to identify natural-gas leaks and verify compliance with regulations. Advancing space technologies could also enable mining from the Moon and asteroids of minerals that are hard to find on Earth, as well as transmission of sustainable solar energy directly to Earth from space.

Sustainable energy technologies New investments in energy research and development are enabling advances in clean electricity generation, long-distance transmission lines, lighting based on light-emitting diodes (LEDs), and electric car batteries. Long-duration energy storage is a critical field for climate and sustainability goals. The development of batteries for electric grids that can store energy for weeks or months is needed to support the use of solar and other intermittent renewable energy sources. Renewable fuels, especially hydrogen, can replace hydrocarbons in transportation and industry. However, new hydrogen production and storage methods are needed to make its use cost-effective at scale. Nuclear power could help the United States reach sustainability goals, too, but it is unclear

whether enough reactors can become operational in time to meet commitments to triple nuclear generation of electricity by 2050 compared to the 2020 baseline. Moreover, nuclear waste remains an environmental policy issue, and the United States has no enduring plan for a long-term solution to storing it.

Health and Medicine

Artificial intelligence AI data analytics are already improving the accuracy of healthcare assessments and procedures. Continued advancement could place AI-monitored cameras and sensors in the homes of elderly or at-risk patients to provide prompt attention in case of emergency while protecting patient privacy. AI-operated mobile robots can potentially replace basic nursing care.

Biotechnology and synthetic biology Synthetic biology has remarkable potential to contribute to the creation of new drugs as well as to pathogen detection and neutralization. Synthetic biology can also help to reduce disease transmission, personalize medicine through genetic modifications, improve cancer treatment, and offer custom lab-grown human tissue for medical testing. DNA sequencers and synthesizers using the internet allow researchers around the world to obtain information on viruses—and potentially vaccines or cures—even faster than a pandemic spreads. However, that same speed and accessibility raise concerns about potential misuse of the technology by bad actors. It is also unclear how some new biological organisms will interact with the natural and human environments.

Cryptography Blockchain technology can securely store all data from a person's important documents, including medical records, in encrypted form while facilitating selective data retrieval that protects a patient's privacy. This approach enables data analytics to be performed on aggregated and anonymized datasets, thus enabling researchers and internal auditors to access information without violating patients' privacy rights.

Lasers Lasers have a host of applications in medicine. Laser-based measurements of biological tissue can yield information about tissue composition and structure without the need for invasive biopsies. Lasers can also replace surgical scalpels in many instances, making cleaner and more precise incisions with less collateral damage to surrounding tissue.

Materials science Materials science and nanotechnology are improving the capabilities and effectiveness of medical devices and the delivery of treatments. For example, wearable electronic devices made from flexible materials can conform to skin or tissues to provide specific sensing or actuating functions; devices like "electronic skin," or e-skin, can sense external stimuli such as temperature or pressure; and "smart bandages" with integrated sensors and simulators can significantly accelerate healing of chronic wounds. Injectable hydrogels can fine-tune long-term delivery of medications, which can lead to improvements in the administration and efficacy of essential medicines such as insulin. Nanomaterials like quantum dots are being used as fluorescent markers in biological systems to improve the contrast of biomedical images. Finally, biosensors allow the rapid testing of blood for bacterial pathogens.

Neuroscience Advances in neuroscience may help address neurodegeneration and related diseases, such as chronic pain, depression, opioid dependency, and Alzheimer's disease, dramatically improving the quality of life of patients (and their families) and potentially reversing the anticipated rising costs associated with care. However, too many fundamental gaps still remain in our understanding of the brain to be confident of rapid progress in treating such illnesses.

Robotics Some robotics are already deployed in the healthcare industry, such as assisted laparoscopic surgical units and equipment. Improvements in haptic technology, which provides doctors using

robots to operate on patients remotely with the tactile sensation of actually holding surgical tools, can increase the effectiveness and safety of these robots. Robotics will also be increasingly useful to support aging populations. Assistive robots could help people move around, while other robots can help nursing and homecare workers provide essential functions such as bathing or cleaning.

Semiconductors Semiconductor chips are ubiquitous in modern medical equipment. Imaging devices such as magnetic resonance imaging (MRI), computed tomography (CT), and ultrasound use embedded computers to generate images from electromagnetic radiation and sound waves penetrating or emanating from the human body.

Space The potential for space manufacturing can improve development of specialized pharmaceuticals, which can be made in a microgravity environment with minimal contaminants.

Sustainable energy technologies A transition from fossil fuel energy to a renewable energy–based world economy would reduce greenhouse gas emissions and prevent thousands of premature deaths from pollution and extreme weather events. Eliminating energy-related air pollution in the United States alone could prevent more than fifty thousand deaths annually and save hundreds of billions of dollars a year from avoided illness. Reducing carbon dioxide emissions will result in less extreme climates, which in turn will lead to fewer health problems from extreme heat.

Civil Society

Artificial intelligence Because AI models are trained on existing datasets, they are likely to encode any biases present in these datasets, affecting model-based outcomes and decision-making. Many facial recognition algorithms are better at identifying lighter-skinned faces than darker-skinned ones, leading to discrimination against people with the latter. Indiscriminate data collection can violate privacy and copyrights. Deepfakes used for misinformation and disinformation have personal, legal, and political impacts. The long-term nature and extent of AI's impact on employment—in terms of displacing some jobs and improving productivity in others—is still unknown.

Biotechnology and synthetic biology Different religious traditions may have different stances toward life or living systems, as well as different opinions as to whether the engineering of new lifeforms violates any of their basic precepts. Another deliberation will be over who should have access to the benefits from synthetic biology given the risks to human and environmental safety from both malicious and unintentional acts.

Cryptography The nature of cryptography and encrypted communications raises questions about exceptional access regulations, which would require communications carriers and technology vendors to provide access to encrypted information to law enforcement agents or other bodies under specific legal conditions on the basis that encryption technology is also accessible to criminals and other malefactors. Opponents of exceptional access argue that implementing this capability weakens the security provided by encryption. Its supporters argue that the reduction in personal encryption security is worth the benefits to law enforcement of being able to catch and prosecute bad actors.

Lasers Lasers per se do not particularly raise issues of relevance to civil society. Instead, such issues often arise for specific applications in which lasers play a central role. Different ones arise if lasers are being used in a military context, a medical context, a manufacturing context, and so on. And even within each of these domains, concerns can vary. For example, certain types of laser can produce a toxic exhaust, which obviously raises environmental concerns, while others do not produce noxious outputs.

Materials science Given the many uncertainties about the long-term dangers and health concerns of nanoparticles released into the environment, important questions arise about how and to what extent regulations should be adopted to mitigate risks that might accompany such releases. Resolving them will require seeking consensus on the magnitude and severity of these risks, as well as on appropriate remedies.

Neuroscience Neuroscience development is influenced by existing legal frameworks. The Controlled Substances Act, for instance, limits medical research on some substances that may have therapeutic effects. Meanwhile, cognitive and behavioral neuroscience have broad implications for public policy because a basic aspect of criminal law is the nature and extent of an individual's responsibility for a criminal act. Minors under eighteen years of age, for example, cannot be subject to the death penalty for crimes they committed because adolescent brains are not considered fully developed, putting minors at higher risk of impulsive, irrational thoughts and behaviors. As neuroscience advances, it could find evidence that reinforces or contradicts this and other principles.

Robotics Greater adoption of robotics will require moving workers to new roles as well as setting standards for human safety around robots. As robots assume more tasks, human workers will need education and training programs to undertake new roles and to benefit from robotics. Standards will also be needed to clarify limits to robotic applications. Ethical considerations warranting policy development include how to ensure data acquisition for training robots respects privacy and inclusiveness and how to set safety standards (i.e., Should the requirement be that a robot's performance is comparable to that of an average human, or should it be near perfect?). Safety considerations for human-robot interactions will be an ongoing challenge.

Semiconductors Student interest in hardware design has dropped precipitously in favor of software-oriented jobs. Some estimates suggest that by 2030, 60 to 80 percent of jobs in semiconductor manufacturing will be unfilled given current rates at which students with relevant degrees are graduating in the United States.

Space In space, the rapid expansion of commercial assets and applications is raising important new policy considerations not covered by current norms. The increasing dependence of government on the private sector to provide space-based capabilities—including launch, vehicles, and space-based communications and internet access—that are vital to national security and economic growth raises questions about how to align public and private interests. Attempts at improvement have often stagnated due to nations' differing geopolitical aims. Dual-use space technologies and the challenge of getting private and government actors to cooperate will complicate crisis response.

Sustainable energy technologies Continued creation of sustainable energy infrastructure requires new acquisitions of land to build generating stations and storage facilities, which can displace residents from private property and impact local property values, encouraging some to adopt a position of supporting windmills but "not in my backyard." The construction of nuclear power plants and facilities for storing radioactive waste is often met with opposition from those concerned about exposure to radiation in the environment.

NOTES

1. Emmanuel Guizar Rosales, Thomas Baumgartner, and Daria Knoch, "Interindividual Differences in Intergenerational Sustainable Behavior Are Associated with Cortical Thickness of the Dorsomedial and Dorsolateral Prefrontal Cortex," *NeuroImage* 264, no. 119664 (2022), https://doi.org/10.1016/j.neuroimage.2022.119664.