STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW 2026

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.

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 and computer security 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, or 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.

Energy technologies The Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy (ADVANCE) Act of 2024 sought to strengthen US global leadership on nuclear energy by directing the Nuclear Regulatory Commission (NRC) to coordinate international nuclear export licensing and to establish an International Nuclear Reactor Export and Innovation Branch of the NRC's International Programs office. With growing demand around the world for nuclear power, there are many opportunities expected for the US reactor industry to export its products.

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 people 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.

Quantum technologies Quantum computing can address problems in portfolio optimization, modeling for drug discovery, and the improvement of delivery routes. Quantum sensing may be important for subsurface exploration for oil and minerals and quality control in semiconductor manufacture.

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 that involve physical labor and presence may also eliminate some jobs and change others, creating the need for retraining people 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 future economic growth 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, through things such as asteroid mining and space-based power production, space activities could become even bigger drivers of economic growth on Earth.

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, and 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 and computer security 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.

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. However, 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.

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.

Quantum technologies Quantum inertial sensing can provide precise timing and position information in GPS-denied environments (i.e., places where global positioning systems are not available). Quantum magnetometers can enable detection and tracking of submarines, camouflaged weapons, and mines by sensing small magnetic anomalies from long distances. Quantum imaging technologies like quantum LIDAR (light detection and ranging) may enable better vision through obscurants such as smoke, fog, or foliage and enhance detection of hidden targets with high resolution.

Robotics Advances in robotics can assist military forces with the transportation of 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, raise questions of robo-ethics 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. Taiwan is home to 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 in regard to semiconductors. Many are concerned 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 the risk of supply chain disruption, 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 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 that are largely commercial has been a driver of open-source intelligence (OSINT). Unclassified intelligence like OSINT 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.

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 the energy demand 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 and computer security Blockchain technologies can provide a transparent and secure way to track the movement of goods. This includes tracking 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 cryptocurrencies require far less.

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. However, 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 storage solution.

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. They can also 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 tradeoffs between immediate rewards and future gains. Neuroscientists have found evidence for cognitive predisposition favoring short-term gains over long-term rewards, based on functional magnetic resonance imaging (fMRI) brain scans of people making choices between immediate and delayed reward.

Quantum technologies Because of their improved sensitivity, quantum sensors can provide more precise real-time monitoring of air, water, and soil pollution. Important use cases include detecting trace pollutants, greenhouse gases, and microplastics with high specificity.

Robotics The deployment of robots primarily for the "three D's"—jobs considered dull, dirty, or dangerous—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. 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. It could also detect greenhouse gas emissions to identify natural-gas leaks and verify compliance with regulations. Advancing space technologies could enable mining from the Moon and asteroids of minerals that are hard to find on Earth. It could also enable the transmission of sustainable solar energy directly to Earth from space.

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. It 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—faster than a pandemic can spread. 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 and computer security 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 the performance of data analytics on aggregated and anonymized datasets, enabling researchers and internal auditors to access information without violating patients' privacy rights.

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.

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 can significantly accelerate the 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. These advances could dramatically improve the quality of life of patients (and their families) and potentially reverse the anticipated rising costs associated with care. However, too many fundamental gaps still remain in our understanding of the brain for confidence in the rapid progress of treating such illnesses.

Quantum technologies Quantum sensors can provide sensitive detection of the small magnetic fields generated by neural activity. This enables the development of noninvasive, wearable systems that can perform three-dimensional mapping of brain activity in real time, with high spatial and temporal resolution, while subjects move naturally. The capability contributes to brain–computer interfaces, neurological disease diagnosis, and the understanding of complex brain functions.

Robotics Some robots are already being deployed in the healthcare industry. These include assisted laparoscopic surgical units and equipment. Improvements in haptic technology can increase the effectiveness and safety of these robots by providing doctors using them to remotely operate on patients with the tactile sensation of actually holding surgical tools. 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.

Civil Society

Artificial intelligence Because AI models are trained on existing datasets, they are likely to encode any biases present in these datasets. This affects 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—are 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 and computer security The nature of cryptography and encrypted communications raises questions about exceptional access regulations. These would require communications carriers and technology vendors to provide access to encrypted information to law enforcement agents or other bodies under specific legal conditions. Such information would be shared 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 of law enforcement's increased ability to catch and prosecute bad actors.

Energy technologies Continued creation of sustainable energy infrastructure requires new acquisitions of land to build generating stations and storage facilities. These 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.

Materials science There are many uncertainties about the long-term dangers and health concerns of nanoparticles released into the environment. Given this, there are important questions about how and to what extent regulations should be adopted to mitigate the risks potentially accompanying such releases. To resolve these questions, a consensus must be reached on the magnitude and severity of these risks and 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: For example, a basic aspect of criminal law is the nature and extent of an individual's responsibility for a criminal act. Currently, minors under eighteen years of age cannot be subject to the death penalty for crimes they have committed because adolescent brains are not considered fully developed; this puts minors at higher risk of impulsive, irrational thoughts and behaviors. As neuroscience advances, it could find evidence that reinforces or contradicts this principle and others.

Quantum technologies As quantum computers evolve, they may become capable of breaking the public-key encryption algorithms that protect data. Governments may have first access to such computers, but others may use them thereafter. Sensitive information belonging to ordinary citizens is already in the hands of malefactors, though in encrypted form, currently protected by today's public-key encryption algorithms. However, should quantum computers become able to break public-key encryption algorithms, this data will no longer be protected. Because that information is already in the hands of people who could exploit it in unencrypted form, there would be no recourse against their doing so.

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 (e.g., Should the requirement be that a robot's performance is comparable to an average human's, 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, given the current rates at which students with relevant degrees are graduating in the United States, 60 to 80 percent of jobs in semiconductor manufacturing will be unfilled by 2030.

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—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.

This publication reflects updates through December 2025

32 31 30 29 28 27 26 7 6 5 4 3 2 1

Designer: Howie Severson
Typesetter: Maureen Forys

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