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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 may 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 each application or consequence mentioned.

Economic Growth

Artificial intelligence 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 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 As much as 60 percent of the physical inputs to the global economy could be affected by biological processes. Biotechnology and synthetic biology are enablers for advances in medicine and health care, such as new vaccines and treatments for diseases including Alzheimer's, diabetes, and cancer. Synthetic biology also underlies advances in agriculture (e.g., drought-resistant crops), food (e.g., plant-based proteins), and energy production (e.g., biofuels). These advances could improve crop yields and boost energy production, lowering costs for consumers and solidifying US leadership in the field.

Cryptography Blockchain technologies can effectively provide provenance in supply chains and personal identity management that curbs fraud and identity theft, leading to more secure transactions and increases in seller efficiency. A US central bank digital currency could help reduce inefficiencies in US deposit markets, promoting broader participation in the financial system.

Materials science Lighter and stronger materials will increase the energy efficiency of vehicles used to transport people and cargo, leading to increased distribution of goods. New semiconductor materials are enablers for new types of chips and other information processing hardware. Technological advancements are also offering new ways to achieve low-carbon steel and cement production, which will help to reduce CO_2 emissions.

Neuroscience Neurodegenerative diseases—including chronic pain and subsequent opioid dependencies—currently lack effective treatments. Neuroscience is the best hope we have today for science-based interventions to reduce the symptoms and treat underlying conditions. While such interventions may be able to improve quality of life, they will also become increasingly important as the average age of citizens rises.

Nuclear technologies Nuclear-generated electricity is widely considered to be a necessary part of a net zero-emissions energy mix in the future. However, the lack of a US waste disposal policy is a substantial impediment to more widespread deployment of nuclear power in the United States.

Robotics Robots are used widely today, including in manufacturing, warehouse logistics, surgery, science and exploration, food production, disaster assistance, security and military services, and transportation. Advancements in robotics have enormous potential to affect jobs involving physical labor and presence.

Semiconductors Taiwan controls most of the world's production of semiconductors. To promote the US domestic semiconductor manufacturing industry, the White House signed into law the CHIPS Act in 2022. The act was also intended to incentivize companies to invest in American fabs. One year after the law was enacted, companies had announced $166 billion in investments, though many of those projects are contingent on the approval of federal aid.

Space Growth in the space sector is primarily driven by commercial and private activities and is expected to continue. Already, commercial space activities play critical roles in our daily lives and the economy. Satellites enable global navigation systems, guiding everything from autonomous cars to drones. Satellites also facilitate financial transactions, allow for more accurate weather predictions, and can even provide internet connectivity to people in remote, war-torn, or censored areas without broadband access.

Sustainable energy technologies Significant growth in the US renewable energy market is expected in the next several years as costs decline. In some local markets, renewable energy may become less expensive than fossil fuels. Widespread renewable energy deployment also has large macroeconomic effects. 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.

National Security

Artificial intelligence Because AI enables more rapid processing of more data inputs, all aspects of military operations potentially benefit. Possible applications include managing military logistics, improving equipment maintenance effectiveness and efficiency, managing electronic medical records, navigating autonomous vehicles, operating drone swarms, recognizing targets, performing intelligence analysis, developing options for command decisions, and red teaming and war gaming to develop and refine plans.

Biotechnology and synthetic biology With synthetic biology becoming increasingly available to state and nonstate actors, many concerns arise 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.

Cryptography Adversaries are likely to have been storing encrypted data, and even though they were unable to read them at the time of storage, they hope future advances will allow them to crack the encryption. That future is the quantum future, and managing potential fallout from this scenario is a policy problem that will need to be faced when quantum computers come online.

Materials science Improvements in materials science and nanotechnology can improve capabilities in stealth, camouflage, and body armor, and can increase the energy content in explosives. Quantum dots, or materials that are smaller than about 100 nanometers in all directions, 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 posttraumatic stress disorder, thereby leading to better treatments for these conditions.

Nuclear technologies There are concerns that a global increase in fission reactors will result in a greater risk of nuclear proliferation, especially to current nonnuclear states or nonstate actors, while some believe that the emissions-free potential of fission reactors can minimize the risk of proliferation. The United States does not offer competitive exports of nuclear power plants; Russia, the United Arab Emirates, and South Korea lead this global market. The United States currently imports more than 90 percent of its uranium—about half from Kazakhstan and Russia and some 30 percent from Canada and Australia. Uranium extracted from seawater may decrease foreign dependence.

Robotics Advancements in robotics can assist US forces with load carrying, 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 for semiconductor chips globally is Taiwan, which houses two of the three leading manufacturers (TMSC and UMC). 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 semiconductor supply chain for the United States and raise the risk of military conflict between the United States and China.

Space Communications, surveillance, and navigation in denied areas are essential functions for military forces. In the future, nonnuclear weapons may be based in space, for attack on terrestrial and/or space targets. Satellites are also essential for 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 is a driver of open-source (unclassified) intelligence, which has the potential to upend traditional intelligence processes built on classified information collection and analysis. The net effect of open-source intelligence 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; China and other countries with lower operating costs control most of the manufacturing, supply chain, and critical minerals for battery and solar cell production. Since these technologies will be directly tied to US energy security, it will be important to promote domestic production as well as collaboration with allies and partners to better protect energy supply chains.

Environmental and Energy Sustainability

Artificial intelligence AI capabilities can greatly improve global sustainability efforts, from helping farmers and hunters identify which produce or livestock are appropriate to harvest to helping analyze weather patterns to prepare populations and infrastructure for extreme or unusual conditions.

Biotechnology and synthetic biology Synthetic biology can contribute to new methods for energy production and environmental cleanup. It can also create more efficient fuel production, construction materials, and chemical processing; stabilize agriculture and aquaculture systems to address food scarcity; and improve food safety.

Cryptography Blockchain technologies can provide a transparent and secure way to track the movement of goods, their origin, quantity, and so forth, thereby improving efficiency in global supply chains and limiting underground or illegal extractions of certain materials.

Materials science Advancements in materials science and engineering are creating new and sustainable plastics that are easier to recycle. New materials design is also integral to decarbonization through electrification of transportation and industry. New materials will support the design of batteries capable of quick recharging, long stability, and cost reduction. Nanomaterials such as quantum dots can further improve the efficiency of solar cells and biodegradable plastics.

Neuroscience Sustainability on a planet with finite resources requires that decision makers and the people they represent be 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 fMRI brain scans of people making choices between immediate and delayed reward.[1] (This example is not further discussed in chapter 5.)

Nuclear technologies While nuclear power remains essential in the effort to decarbonize the energy industry, the capacity for nuclear reactors to generate electric power has declined in recent years, with new reactors coming online, mainly in Asia, unable to replace capacity loss from aging and decommissioned reactors in the West. It is unclear whether a sufficient number of nuclear reactors will become operational in time to reduce greenhouse gas emissions at a useful scale. Nuclear waste remains an environmental policy issue, and the United States has no enduring plan for a long-term solution to storing nuclear waste.

Robotics The deployment of robotics primarily for the Three Ds—dull, dirty, or dangerous jobs—enables robotic cleanup of environmentally hazardous materials and operation in environments inappropriate for humans, such as nuclear reactors.

Semiconductors Transitioning to renewable energy sources will require vast amounts of semiconductors. Advanced chips are integral to electric vehicles, solar arrays, and wind turbines. They are also used in smart devices and infrastructure that can self-monitor to consume energy more efficiently.

Space Satellite imagery can provide data on urban sprawl and global processes on land and at sea, including drought and ice cap melt, data that can inform sustainable development policies. In the next five years, there is room for development of space technologies 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 regulation compliance. Advancing space technologies can also enable mining of minerals from the moon or asteroids that are rare to find on Earth or transmission of sustainable solar energy directly to Earth from space.

Sustainable energy technologies The US government is investing in research-and-development projects across new energy technologies, enabling advancements in clean electricity generation, long-distance transmission lines, lighting based on light-emitting diodes, and improvements in electric car batteries. Long-duration energy storage is a critical field for climate and sustainability goals. Developing batteries for grid-scale storage across weeks or months are necessary to complement intermittent renewable energy generation. Hydrogen will power fuel-cell automotive vehicles and industrial processes. Currently, hydrogen is sourced from fossil fuels; sustainable hydrogen production methods that are cost-effective at scale are needed.

Health and Medicine

Artificial intelligence AI data analytics are already improving the accuracy of health-care assessments and procedures, and continued advancement in the field 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 new methods for pharmaceutical synthesis as well as pathogen detection and neutralization. Synthetic biology can additionally reduce disease transmission through gene drives, personalize medicine through genetic modifications, cure cancer with mRNA vaccines, and offer custom lab-grown human tissue for medical testing using "organoids." DNA sequencers and synthesizers using the internet allow researchers to move viruses (and potentially vaccines or cures) around the world even faster than a pandemic. However, that same speed and accessibility creates concern for misuse 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. Such data storage can allow data analytics to be performed on aggregated and unassociated datasets, thus enabling researchers and internal auditors to access the needed information without violating patients' privacy rights.

Materials science Materials science and nanotechnology are improving the abilities and effectiveness of medical devices and delivery. For example, wearable electronic devices made from flexible materials can conform to skin or tissues to provide specific sensing or actuating functions; devices like "e-skin" can sense external stimuli such as temperature or pressure; and "smart bandages" with integrated sensors and simulators can accelerate healing of chronic wounds by 25 percent. Injectable hydrogels can fine-tune long-term delivery of medications, which can lead to improvements in administration and the efficacy of essential medicines such as insulin. Nanomaterials like quantum dots are using fluorescent markers in biological systems to improve the contrast of biomedical images.

Neuroscience Advancements in neuroscience can address neurodegeneration and related diseases, such as chronic pain, opioid dependency, or Alzheimer's, dramatically improving the quality of life and potentially reversing the anticipated rising costs associated with care. The annual cost of Alzheimer's, for example, is projected to reach $1 trillion by 2050.

Nuclear technologies Medical isotopes, often radioactive, are used to diagnose and treat conditions such as heart disease and cancer.[2] Medical isotopes are often produced in nuclear reactors, although not reactors designed to generate electricity. (This example is not further discussed in chapter 6.)

Robotics Some robotics are already deployed in the health-care industry, such as assisted laparoscopic surgical units and equipment. Improvements in haptic technology (which gives the user a sense of feel—such as a smartwatch vibrating when a text is received) can increase the effectiveness and safety of these tools while providing new capabilities like soft and wearable robotic technologies. Robots can also help nursing and home-care workers provide essential functions such as bathing or cleaning.

Semiconductors Semiconductor chips are ubiquitous in modern medical equipment. Imaging devices such as MRI, CT, and ultrasound use embedded computers to generate images from electromagnetic radiation and sound waves penetrating or emanating from the human body. Tiny wearable health monitors and ingestible micro-robots would not be so small without embedded chips. Precision robotic surgery would not be possible without digital-to-analog converter chips. Across these examples, innovation in chip design, new materials, and integration methods are enablers for the performance, size, and efficiency of medical devices.

Space The potential for space manufacturing can improve development of specialized pharmaceuticals by utilizing the space environment—a very clean 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 could prevent roughly fifty thousand deaths and save billions of dollars per year. Reduction of CO_2 emitted into the atmosphere 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. This leads to inherent bias in AI and large language model systems, which can, in turn, affect decision making or model-based outcomes. For example, research has found that many facial recognition algorithms are better at identifying lighter-skinned faces than darker-skinned faces because of the training data used to develop them. This performance difference has led to cases of wrongful arrest of African Americans. AI models are also poor predictors of discontinuous change.

Biotechnology and synthetic biology Different religious traditions may have different stances toward life or living systems and whether the engineering of new life forms violates any of their basic precepts.

Cryptography The nature of cryptography and encrypted communications leads to some debate on exceptional access. Exceptional access regulations would require communications carriers and technology vendors to provide access to encrypted information under specific legal conditions, because the technology of encryption is accessible to criminals and other malefactors. Opponents of exceptional access argue that implementing this capability weakens the security provided by encryption. Supporters of exceptional access argue that lower personal encryption security is worth the benefits to law enforcement.

Materials science As with regulation in other areas of technology, concerns arise about the appropriate balance between promoting public safety from possible downside risks and the imperatives of innovation to move fast and leapfrog possible competitors. US ability to lead in this field is dependent on pathways for foreign talent to gain permanent residence, especially for PhD and advanced-degree graduates.

Neuroscience Cognitive and behavioral neuroscience also has broad implications for public policy, in that 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 fully developed, putting minors at higher risk of impulsive, irrational thoughts and behaviors.

Nuclear technologies The construction of nuclear power plants or facilities for storing radioactive waste is often met with opposition from those concerned about exposure to radiation in the environment.

Robotics A challenge in designing human-robot interaction (HRI) is unpredictable or unintended physical contact that can cause safety issues for the human. Another challenge is to design HRI in a way that accommodates social norms and that allows robots to exhibit behaviors that are more familiar and comfortable for humans. As robots assume more roles with decision-making components, some concepts of individual accountability may be challenged and need to evolve.

Semiconductors Student interest in hardware design has dropped precipitously in favor of software-oriented jobs. Some estimates suggest that the semiconductor manufacturing employment sector will only be able to fill 30 percent of its needs by 2030.

Space As public entities grow more risk-averse and private companies more risk-tolerant for the sake of financial gain and innovation, collaborative efforts between academia and industry are pivotal for continued leadership and development in this field. In space, rapid expansion driven by increasing commercial assets and applications is exceeding the existing policy context for space activities.

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 (i.e., we support windmills but "not in my backyard"). Additionally, US energy policy is governed by a variety of overlapping federal, state, and local government jurisdictions that can complicate new energy initiatives or incentives.

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.

2. Institute of Medicine, *Isotopes for Medicine and the Life Sciences* (Washington, DC: The National Academies Press, 1995), https://doi.org/10.17226/4818.