McKinsey & Company

McKinsey Technology Trends Outlook 2022

Research overview

August 2022

McKinsey & Company

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Introduction

Technology continues to be a primary catalyst for change in the world. Technology advances give businesses, governments, and social-sector institutions more possibilities to lift their productivity, invent or reinvent offerings, and contribute to humanity's well-being. And while it remains difficult to predict how technology trends will play out, executives can plan ahead better by tracking the development of new technologies, anticipating how companies might use them, and understanding the factors that affect innovation and adoption.

To that end, we have worked with the internal and external experts on the McKinsey Technology Council to identify and interpret 14 of the most significant technology trends unfolding today (see sidebar "About the McKinsey Technology Council"). This study builds on the trend research we shared last year, adding fresh data and deeper analysis to provide a more granular assessment of trends in two thematic groups: Silicon Age, which encompasses digital and IT technologies, and Engineering Tomorrow, which encompasses physical technologies in domains such as energy and mobility.

Our analysis examines such tangible, quantitative factors as investment, research activity, and news coverage to gauge the momentum of each trend. We also conducted dozens of interviews and performed hundreds of hours of research to learn which industries are apt to benefit most as they absorb these technologies. And, recognizing that trends can speed up, slow down, or change course, we examined the uncertainties and questions surrounding each trend.

This research overview, an accompanying online interactive, and a set of 14 in-depth trend profiles lay out these considerations in more detail so that executives can better comprehend how the individual trends are developing and interacting, and what these developments might mean for their organizations. Looking across the trends, we also arrived at some general observations that leaders might find instructive.

About the McKinsey Technology Council

Technology is changing everything in our work and home lives. We launched the McKinsey Technology Council to help understand what is coming and how it will affect us all—taking a "look around the corner" toward the futures that technology change can unlock as well as the tough questions it raises.

We will look at a spectrum of technologies, from computing to biology, and their applications across all sectors, from mining to entertainment. We look at the science, how it translates into engineering, and when it will accelerate to impact—at scale, and around the world. We are doing this with a diverse group of more than 50 senior leaders in McKinsey, who come from a wide range of science and technology backgrounds, and orchestrating exchanges between them and dozens of leading scientists, entrepreneurs, founders, and researchers who are leading pathbreaking work in their fields.

—Lareina Yee, senior partner, McKinsey; chair, McKinsey Technology Council

New dynamics

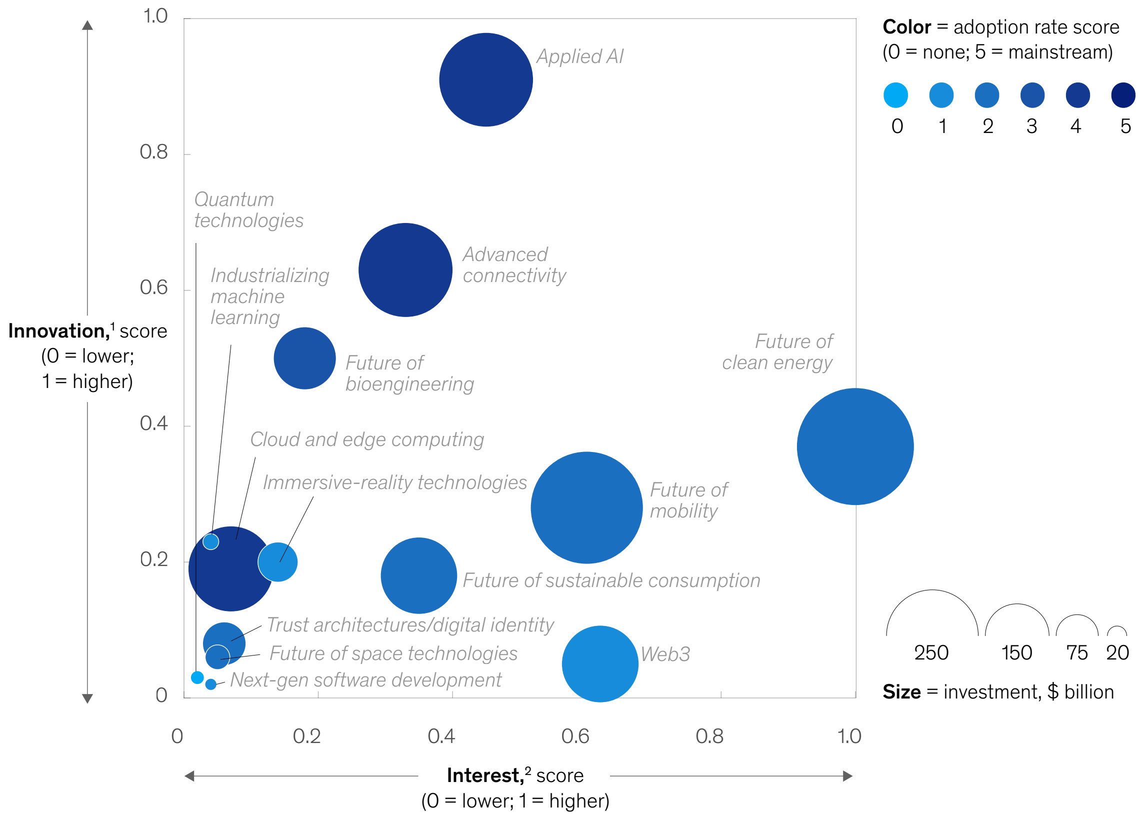
First, several trends that are based on proven and mature technologies—namely applied AI, advanced connectivity, future of bioengineering, and cloud and edge computing—score more highly on quantitative measures of innovation, interest, and investment than trends based on technologies that are still in the early stages of development. These trends also tend to have viable applications in more industries, which places them closer to a state of mainstream adoption than other trends (Exhibit 1). The next noteworthy group consists of trends that are closely aligned with sustainability priorities. These trends—which we call future of clean energy, future of sustainable consumption, and future of mobility—display increasing levels of innovation, interest, and investment. Indeed, of all the 14 trends we studied, the clean-energy and mobility trends attracted the most investment. They have also emerged as significant across multiple industries.

Outside the first two major categories, newer and less-proven digital tools power a set of emergingtrends: industrializing machine learning, immersive-reality technologies, trust architectures and digital identity, next-generation software development, and quantum technologies. These trends could have major benefits for businesses. For example, industrializing machine learning (ML) can shorten the production time frame for ML applications by 90 percent. But much work must be done to develop, refine, and commercialize the

Exhibit 1

Applied AI recorded the highest innovation score of all 14 trends, while clean energy drew the most interest and investment.

Innovation, interest, investment, and adoption, by technology trend, 2021



Note: Innovation and interest scores for the 14 trends are relative to one another. All 14 trends exhibit high levels of innovation and interest compared with other topics and are also attracting significant investment ($2 billion minimum in 2021).
[1]The innovation score combines the 0–1 scores for patents and research, which are relative to the trends studied. The patents score is based on a measure of patent filings, and the research score is based on a measure of research publications.
[2]The interest score combines the 0–1 scores for news and searches, which are relative to the trends studied. The news score is based on a measure of news publications, and the searches score is based on a measure of search engine queries.

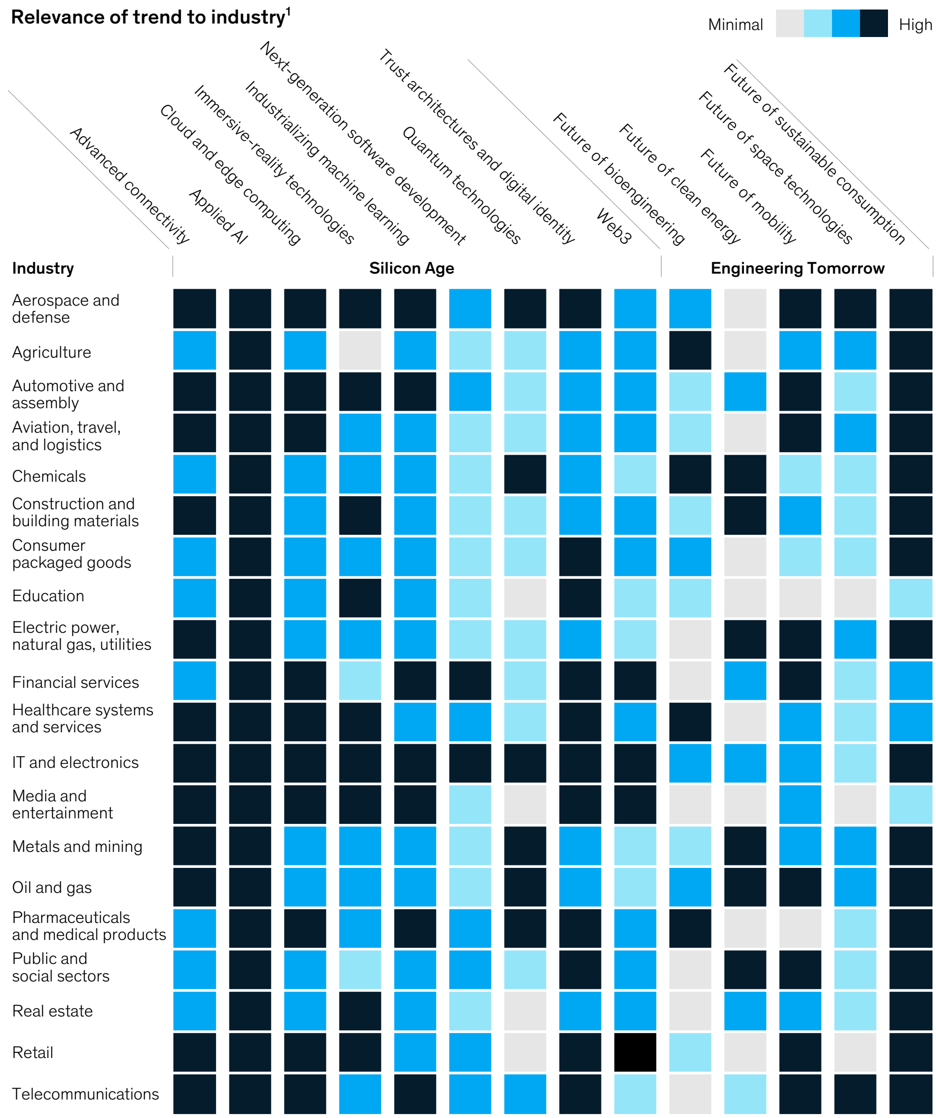
technologies that underpin these trends. As a result, it's unclear how long it will take for these trends to be adopted in multiple sectors, let alone to realize the potential seen by proponents.

Despite the uncertainty of these newer trends, it's apparent that industries are broadly exposed to changes resulting from technological innovation and the diffusion of new technology-enabled business practices. When we looked at how frequently news reports mentioned companies in 20 sectors alongside different trends, we found that most of these sectors display a meaningful association with five or more trends. The mature and sustainability-focused trends described above exhibit a close connection with multiple industries. Several nascent trends also show a moderately close connection with many industries. Overall, we see that press coverage connects the automotive, manufacturing, telecommunications, and technology sectors closely to at least one trend and moderately to several others (Exhibit 2). We plan to explore the effects that technology trends are having, and could have, on sectors in more depth over the coming months. (For more about how we performed this work, please see the sidebar "Research methodology.")

Exhibit 2

Most industry sectors display a meaningful association with five or more technology trends.

Relevance of trend to industry[1]



[1]Relevance estimated qualitatively by industry experts based on trend's potential to affect an industry; degree of relevance is scaled at both trend and industry levels.

Looking ahead

We expect changes like these will accelerate and intensify in the years to come, much as they have during the roughly three decades since the start of the internet revolution. The changes will not only alter the competitive landscape but also exert ever-more powerful effects on society: reshaping markets, boosting productivity, spurring economic growth, and enhancing lives and livelihoods.

When we look at these trends, what impresses us more than anything else is the massive effect that technology will have on every sector. The next few decades promise to be a time in which technologies progress ever-more quickly from science to engineering to impact—at scale, and around the world. We also expect to see the multiplying effect of "combinatorial innovation," as different technologies come together in creative ways. For example, this is happening now as organizations combine different technologies to create the metaverse and the many layers that make it up.

Informed by our colleagues and the members of the McKinsey Technology Council, we intend to publish more about the effects of technology trends on particular industries, about the efforts of companies to tap into technology trends, and about the ways that business leaders can manage the implications of technology trends for their strategies, operations, and talent. We invite you to join us in understanding how technology trends evolve and influence the world, and we invite you to share your feedback with us at: techforexecs@mckinsey.com.

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Research methodology

To assess the development of each technology trend, our team collected data on five tangible measures of activity: search engine queries, news publications, patents, research publications, and investment. For each measure, we used a defined set of data sources to find occurrences of keywords associated with each of the 14 trends, screened those occurrences for valid mentions of activity, and indexed the resulting numbers of mentions on a 0–1 scoring scale that is relative to the trends studied. The innovation score combines the patents and research scores; the interest score combines the news and search scores. (While we recognize that an interest score can be inflated by deliberate efforts to stimulate news and search activity, we believe that each score fairly reflects the extent of discussion and debate about a given trend.) Investment measures the flows of funding from the capital markets into companies linked with the trend. Data sources for the scores include the following:

— *Patents*. Data on patent filings are sourced from Google Patents.

— *Research.* Data on research publications are sourced from the Lens (www.lens.org).

— *News.* Data on news publications are sourced from Factiva.

— *Searches.* Data on search engine queries are sourced from Google Trends.

— *Investment.* Data on private-market and public-market capital raises are sourced from PitchBook.

The associations shown on the industry heat map were derived by reviewing the news reports on each trend for references to specific companies within each of the 20 industries.

In addition, we updated the selection and definition of trends from last year's study to reflect the evolution of technology trends:

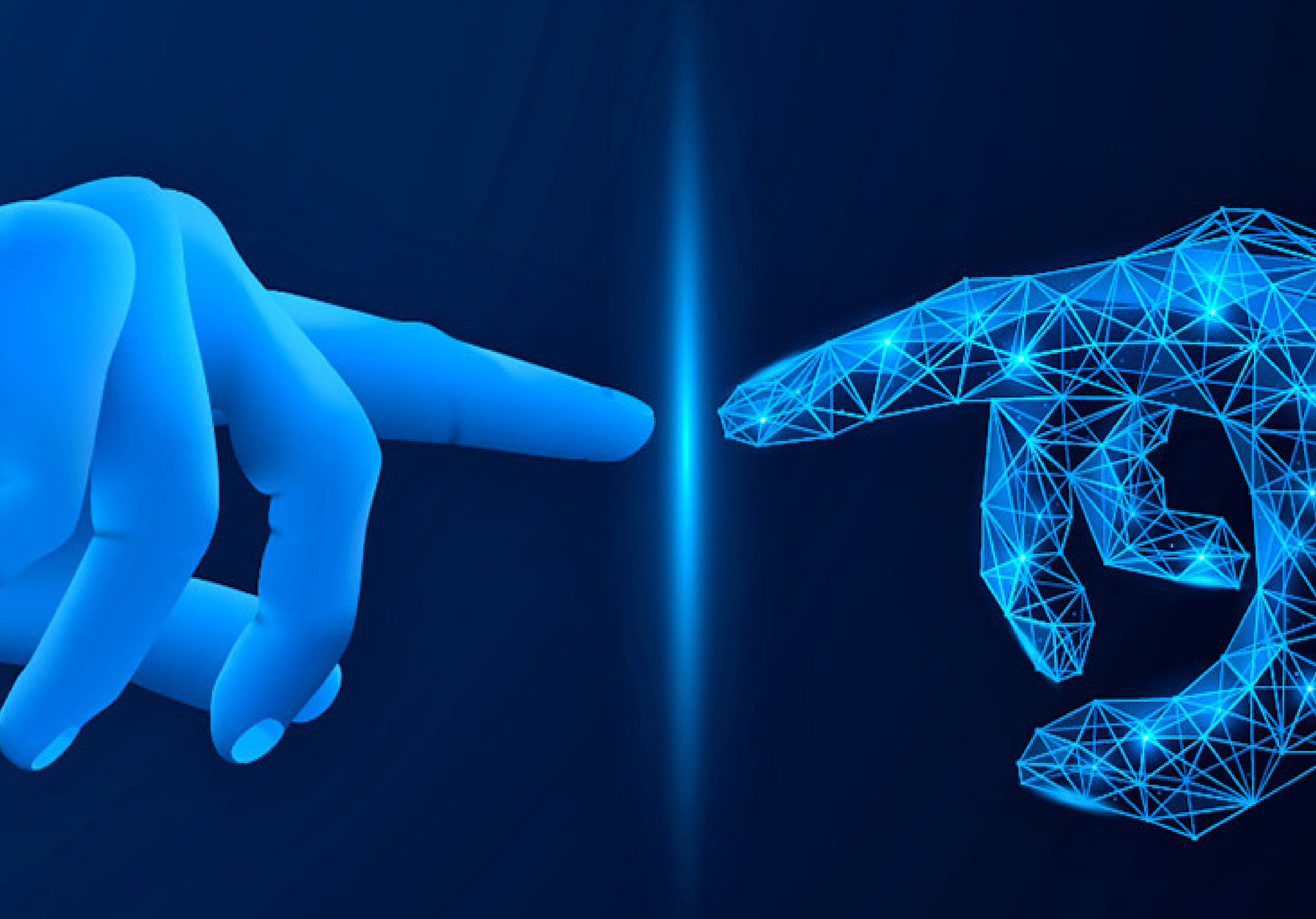
— *Trends added since last year's study:* industrializing machine learning, Web3, immersive-reality technologies, future of mobility, and future of space technologies

— *Trends not carried over from last year's study:* next-level process automation and virtualization (now considered an implication of several trends) and next-generation materials (partially represented by other trends)

— *Trends with adjusted definitions:* next-generation software development (partly covered under future of programming in 2021), trust architectures and digital identity (partly covered by trust architecture in 2021), future of sustainable consumption (disaggregated from future of clean technologies), and future of clean energy (disaggregated from future of clean technologies)

— *Trends with minor changes to definition:* applied AI, advanced connectivity (previously called future of connectivity), cloud and edge computing (previously called distributed infrastructure), quantum technologies (previously called next-generation computing), and future of bioengineering (previously called Bio Revolution)

Trend summaries: Silicon Age



Advanced connectivity

The trend—and why it matters

The latest connectivity protocols and technologies power networks with more data throughput, higher spectrum efficiency, wider geographic coverage, less latency, and lower power demands. These improvements will enhance user experiences and increase productivity in industries such as mobility, healthcare, and manufacturing. Companies have been quick to adopt advanced connectivity technologies that build on existing standards, but newer technologies such as low-Earth-orbit (LEO) connectivity and private 5G networks have seen less uptake to date.

Industry relevance

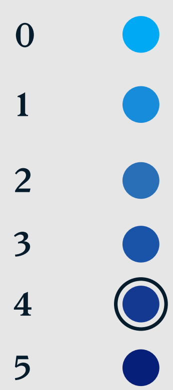
Advanced connectivity is becoming a critical technology for all industries. The value at stake is greatest, we believe, in the following sectors:

— *Telecommunications.* Telecommunications companies are using advanced connectivity to introduce new B2C and B2B service offerings, such as improved cellular services for retail customers and private 5G solutions for enterprise customers.

— *Aerospace and defense.* Self-driving, connected vehicles are packed with features that depend on high-quality network access.

Scoring the trend

Interest in advanced connectivity—especially 5G/6G, Wi-Fi 6, and LEO satellites—has risen significantly. Innovation has been incremental. Investment by private-equity and venture capital firms is recovering after a pandemic drop.



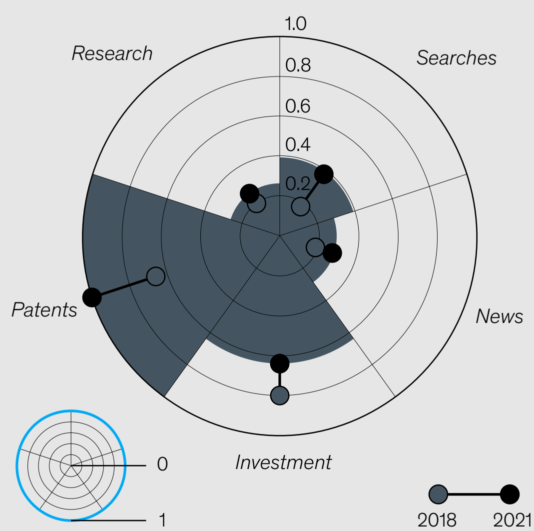
Adoption rate score, 2021

(0 = none; 5 = mainstream)

$166 billion

investment, 2021

Score by vector (0= lower; 1 = higher)



Searches
Search engine queries for terms related to trend

News
Press reports featuring trend-related phrases

Investment
Private- and public-market capital raises for relevant technologies

Patents
Patent filings for technologies related to trend

Research
Scientific publications on topics associated with trend

— *Aviation, travel, and logistics.* Low-power, wide-area (LPWA) wireless technology lets logistics providers track and trace products and provides data to help customers optimize supply chains.

— *Healthcare systems and services.* Connectivity will be a boon for the treatment of chronic diseases as AI-powered diagnostics can be conducted using data from patients while they are monitored at home through connected medical devices.

— *Aerospace and defense.* From critical communications through nonterrestrial networks (NTN) to connected field assets, connectivity expansions such as 5G networks can vastly boost capabilities and performance for aerospace and defense users.

— *Information technology and electronics.* Demand for smart sensors and Internet of Things (IoT)-enabled devices will grow as connectivity improves and cost drops.

— *Construction and building materials.* Faster, more effective onsite connectivity can allow for swift and secure construction; Building Information Modeling (BIM), onsite 3-D printing, and augmented-reality applications will all require high-speed, low-latency, expansive connectivity networks.

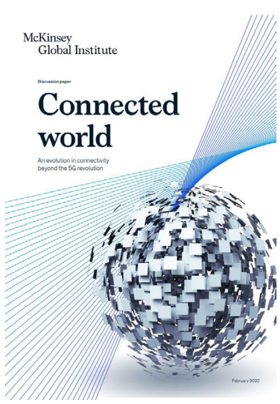
— *Metals and mining.* Across the value chain from prospecting to reclamation, the mining industry can leverage expanded coverage to enable "smart mining" and digitization or automation practices that will enhance the sector's productivity and safety.

— *Media and entertainment.* The ability to cater to increased data creation and the growth in the number of connected devices for consumers allow for better entertainment experiences as new devices (for example, AR and VR devices) enter the market.

— *Electric power, natural gas, and utilities.* Implementing a smart utility grid with smart meters, sensors, and other cloud devices will require advanced connectivity that expands coverage and maximizes digitization.

— *Oil and gas.* Players can leverage advanced connectivity technologies to permit and optimize real-time monitoring of drilling and production activities, as well as to deploy digital tools and analytics to offshore operators.

— *Retail.* Advanced connectivity enables the development of better digital and cross-channel experiences, resulting in increasingly personalized and targeted shopping experiences for consumers.



"The use cases we identified in … four commercial domains alone could boost global GDP by $1.2 trillion to $2 trillion by 2030."

—*Connected world: An evolution in connectivity beyond the 5G revolution,* McKinsey Global Institute, February 20, 2020

Key uncertainties and big questions

Ongoing adoption of advanced connectivity will depend in part on the scale of capital investments in networks supporting some technologies, such as high-band 5G and LEO satellites, and on the development of business ecosystems capable of providing services and solutions. Operators also need to find viable business models for some connectivity technologies. As technologies advance, competition between incumbent and new technologies will increase. The contests between terrestrial connectivity and space-to-Earth connectivity; between 4G LTE, 5G, and high-band 5G; and between 5G and LPWA for IoT applications are likely to be pivotal.

Underlying technologies

Advanced-connectivity technologies provide meaningful performance improvements over current standards. These technologies include the following:

— *Optical fiber.* Physical cables provide the most reliable form of high-throughput, low-latency connectivity.

— *Low-power, wide-area (LPWA) networks.* These wireless networks support large numbers of connected devices.

— *Wi-Fi 6.* Next-generation Wi-Fi (also called industrial Wi-Fi) offers higher throughput, more controllable quality of service, and security similar to that of cellular networks.

— *5G/6G.* These next-generation cellular protocols and technologies boast higher spectrum efficiency, enabling high-bandwidth, low-latency services.

— *Low-Earth-orbit (LEO) satellite constellations.* Composed of large numbers of much lower-cost satellites, these systems deliver wide coverage with significantly reduced latency, compared with existing satellite offerings that operate in geostationary orbits.

Applied AI

The trend—and why it matters

With AI capabilities, such as machine learning (ML), computer vision, and natural-language processing, companies in all industries can use data and derive insights to automate activities, add or augment capabilities, and make better decisions. In a 2021 McKinsey Global Survey on the state of AI, 56 percent of respondents said their organizations had adopted AI, up from 50 percent in the 2020 survey. The 2021 survey also indicated that adopting AI can have financial benefits: 27 percent of respondents attributed 5 percent or more of their companies' EBIT to AI. Companies are developing and adopting more applications for AI, but organizational, technical, ethical, and regulatory issues must be resolved before businesses can realize the technology's full potential.

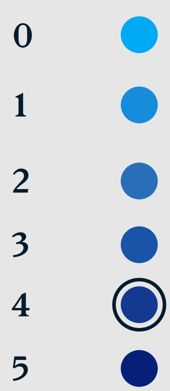
Industry relevance

AI applications continue to emerge across industries and business functions. The technology industry leads in AI adoption. Among business functions, product development and service operations have generally seen the most benefits from applied AI. Industries might use AI in the following ways:

— *Information technology and electronics.* AI applications will likely become pervasive in the technology industry and constituent sectors, such as software, hardware, and electronic devices. Product developers, for example, might use generative AI models to create 3-D visuals for software simulations.

Scoring the trend

High innovation and investment scores for applied AI are commensurate with its large potential impact. Each year from 2018 to 2021, applied AI has had the highest innovation scores of all the trends we studied. Its investment score also ranks in the top five.



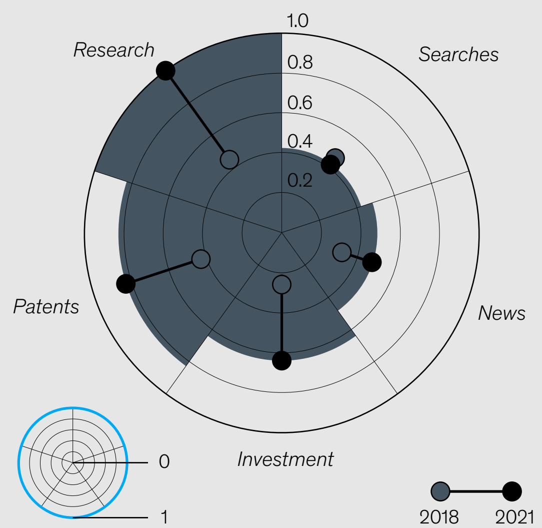
Adoption rate score, 2021

(0 = none; 5 = mainstream)

$165 billion

investment, 2021

Score by vector (0= lower; 1 = higher)



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Research
Scientific publications on topics associated with trend

- *Telecommunications.* A telecommunications service operations department, for example, can program AI models to identify recurring customer concerns and deliver solutions before complaints arise.

- *Pharmaceuticals and medical products.* Pharmaceutical companies can use AI algorithms to explore relationships across different medical treatments and their combined outcomes for the discovery of new drugs.

- *Aerospace and defense.* AI and ML can aid aerospace manufacturers in the design process (for example, through visual simulations of aircraft performance under different conditions) as well as in security and risk mitigation processes.

- *Healthcare systems and services.* AI-enabled functions like automated pathology recognition and diagnosis-decision support can enhance healthcare services.

- *Financial services.* AI can support risk management in financial services in many different ways. An example is detecting credit card fraud to reduce incidents of loss.

- *Retail; consumer packaged goods.* Retailers might boost sales by using ML to analyze huge sets of purchasing data, discern patterns, and give shoppers customized recommendations.

- *Education.* AI can improve personalized learning based on students' progress.

- *Aviation, travel, and logistics.* Multimodal fusion, enabled by AI, might combine inputs from various sensors to help operate autonomous vehicles.

- *Agriculture.* From productivity forecasting to driverless tractor applications, AI enables the optimization of operations. AI and ML also enable precision agriculture (that is, tailoring of interventions to the precise farm needs and conditions).

- *Automotive and assembly.* AI is central to the development of autonomous vehicles and also allows OEMs to automate quality testing and manufacturing and assembly processes.

- *Chemicals.* AI can optimize chemical development and production cycles by recognizing molecules, generating chemical compound formulas, and analyzing chemical mixtures. Automating these processes and optimizing forecasting techniques can help minimize chemical waste.

- *Construction and building materials.* AI applications include autonomous machinery and robots, computer-vision-enhanced safety procedures, and 3-D design optimization software.

- *Electric power, natural gas, and utilities.* AI can optimize energy production and scheduling, detect equipment defects early to minimize downtime, and analyze consumer energy use data to inform personalized recommendations.

- *Metals and mining.* AI and ML can improve worksite process optimizations to increase efficiencies and aid in the development of digital twins that can generate visualizations and models of remote sites.

- *Oil and gas.* Players in this industry can use computer vision in exploration to assess the value of holdings and use AI and ML to customize drilling plans for geologically complex areas and forecast demand.

- *Public and social sectors.* Organizations can leverage AI and ML to expedite delivery of key services (for example, the use of natural-language processing for tax FAQ handling). Additionally, AI and ML can be used as tools to help in audit mechanisms to ensure the proper use of resources (for example, predictive tools to help focus tax auditing).

- *Real estate.* Real estate players can leverage AI to provide personalized customer property recommendations, perform market analyses to help developers manage risk and price volatility, as well as optimize ROI.

“The biggest shift affecting AI’s broad adoption is tied to more mature tooling and the emergence of a canonical tech stack that is drastically simplifying how AI solutions are engineered and integrated with other digital applications. AI is quickly becoming more consumable, and solutions that use AI are accessible even to organizations with few to no AI engineers of their own.”

—Jacomo Corbo, partner, McKinsey

Key uncertainties and big questions

The development and use of new AI applications could be affected by the availability of resources, such as talent and funding, despite technical advances in solutions for industrializing ML and in IT infrastructure. Cybersecurity concerns, notably those related to data risks and vulnerabilities, could slow the uptake of AI—55 percent of respondents to the 2021 McKinsey Global Survey on the state of AI cite cybersecurity as a leading risk. Companies may also face questions from stakeholders about the responsible, trustworthy use of AI, touching on such issues as data governance, equity, fairness, and “explainability.” Those questions may prompt policy makers to establish regulations and compliance requirements that affect AI research and applications. For companies, addressing such issues could mean building more features into their AI applications and putting risk management mechanisms in place.

Underlying technologies

AI comprises several technologies that perform cognitive-like tasks. These include the following:

— *ML.* This term refers to models that make predictions after being trained with data rather than algorithms that follow programmed rules.

— *Computer vision.* This type of ML works with visual data, such as images, videos, and 3-D signals.

— *Deep reinforcement learning.* This type of ML uses artificial neural networks and training through trial and error to make predictions.

— *Natural-language processing.* This type of ML analyzes and generates language-based data, such as text and speech.

— *Knowledge graphs.* These databases are organized as networks that show complex relationships among data points.

Cloud and edge computing

The trend—and why it matters

Cloud platforms, built from "hyperscale" data centers that deliver and enable enormous computing and storage capabilities, and connected by fast, high-capacity networks, enable an array of services that grow ever broader and richer. Increasingly, these platforms also incorporate computational and data resources at network edge nodes located near end users or in their facilities. These edge resources fulfill needs for low latency (that is, minimal processing delays) in real-time systems such as warehouse automation. Edge resources are also being used more and more in mobile applications such as vehicles. Ongoing integration of cloud and edge resources will let users extend the cloud's speed and quality to edge and real-time systems, thereby accelerating innovation, lifting productivity, and creating business value.

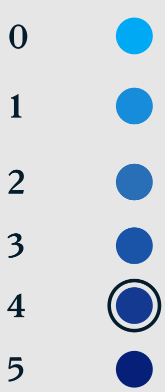
Industry relevance

Cloud computing can enable more than $1 trillion in EBITDA improvement across Fortune 500 companies alone, according to McKinsey estimates. That is achieved by benefits such as shorter time to value for innovative applications of AI, increased productivity and velocity in IT delivery, risk reduction, and hyperscalability of workloads in the face of uncertain demand. All industries will see these benefits. Examples include the following:

— *Telecommunications.* Cloud and edge computing allow for increased revenue streams from technologies such as multi-access edge computing (MEC), given telecommunication companies' roles as primary owners of the networking infrastructure required for distributed computing.

Scoring the trend

While relatively low levels of general interest reflect the increasing maturity of these platforms, cloud and edge computing have become core technologies for many digital solutions.



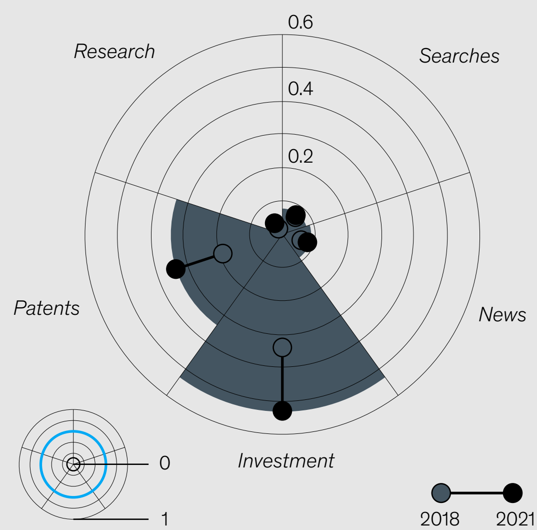
Adoption rate score, 2021

(0 = none; 5 = mainstream)

$136 billion

investment, 2021

Score by vector (0= lower; 1 = higher)



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- *Automotive and assembly.* Cloud and edge computing allows for efficient distribution of computing and storage across onboard and remote data-center-based resources to deliver new services to drivers and passengers and enable higher levels of autonomy.

- *Aviation, travel, and logistics.* Using cloud to combine information from multiple data streams enables more effective demand forecasting, schedule management, and route optimization. Well-orchestrated data decentralization can also provide resilience against data loss.

- *Retail.* Customer experiences are enhanced by frictionless checkout, real-time personalized promotions, and other use cases relying on low-latency edge computing and analytics applied to a range of in-store data streams from video feeds to diverse types of sensors.

- *Healthcare systems and services.* These technologies result in improvements in digital use cases, such as remote diagnostics, active drug monitoring, and wellness and fitness trackers.

- *Aerospace and defense.* Better networking and data latency make automated manufacturing technologies more effective, leading to higher overall productivity for aerospace players, while flowing data to cloud platforms for efficient analytics.

- *Media and entertainment.* Providers can maximize streaming performance and deliver large volumes of digital content with minimal delays and downtime, as well as enable flexible server capacity to meet unpredictable consumer demand while maintaining a high quality of service for users.

- *Information technology and electronics.* Technology companies can develop the products and tools that span cloud and edge environments and enable high-velocity innovation.

- *Pharmaceuticals and medical products.* Cloud technologies can accelerate drug discovery by enabling better use and storage of AI and ML models. Sensors and edge-computing capabilities allow for continuous monitoring of equipment that improves quality, safety, and yield of drugs and formulations.

- *Financial services.* Players can use cloud services to efficiently train, store, and deploy algorithms that model risk and improve fraud detection. Edge computing can optimize interactions by storing and using data closer to consumers or highly performance-sensitive users (for example, in quantitative finance applications).

"The growing need for near real-time insights, compliance with data residency and privacy regulations, uninterrupted and reliable operations, and security of centralized environments, combined with an appetite to move away from massive infrastructure investments, drives tremendous demand for edge to bring compute and storage much closer to where the action is."

—Bhargs Srivathsan, partner, McKinsey

Key uncertainties and big questions

The adoption of cloud and edge technologies will depend on how service providers and users respond to technical and practical issues that could arise as platforms and networks expand. Service providers would have to maintain networks that supply interoperability and next-generation access for an increasing number and variety of edge devices. Providers would have to meet growing demand for data movement and AI-enabled analytics, while assuring resilience against cyberthreats and catastrophic events and simultaneously meeting sustainability expectations. In addition, they would need to establish business models that remain cost-effective as technical complexity increases. As for users, they will need to decide whether to bear the expense of adding more edge nodes and devices (because edge computing doesn't benefit from the same economies of scale as cloud computing) or rely on better networks to enable cloud solutions in cases where low-latency or other requirements might seem to call for edge technologies.

Underlying technologies

Cloud and edge networks will consist of a few technology components:

— *Data centers.* These large groups of networked computer servers can function as public, private, or even hybrid cloud-computing infrastructure.

— *Edge devices.* Local servers or end-user devices and real-time systems enable low-latency computing for applications at the network edge.

— *Networking infrastructure.* 5G networks and other networking technologies are needed to enable edge computing.

— *The Internet of Things.* The proliferation of low-cost, real-time, sensor-driven systems, connected by internet-style standard interfaces, allows analytics and automation.

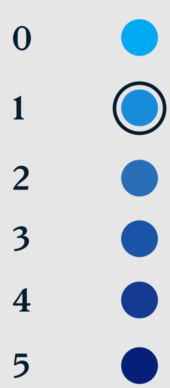
Immersive-reality technologies

The trend—and why it matters

Immersive-reality technologies use spatial computing to interpret physical space, simulate the addition of data, objects, and people to real-world settings, and enable interactions in virtual worlds, with various levels of immersion provided by augmented reality (AR), virtual reality (VR), and mixed reality (MR). Venture capital investors provided about $4 billion of funding to AR and VR start-ups in 2021, the second-largest amount in any year (behind 2018). This heralds the development of new applications for many industries, putting the global market on pace to grow by approximately 20 percent per year, forming the foundation for a trillion-dollar market over the next ten to 15 years. For now, though, adoption is constrained by a number of factors, including the need for technological advances, such as improvements in the feature sets, battery life, weight, and ergonomics of wearable immersive-reality devices, as well as the maturity of the development tool chain required to create great immersive experiences more efficiently.

Scoring the trend

While interest levels have held steady in the past several years, innovation has increased, and investments have rebounded.



Adoption rate score, 2021

(0 = none; 5 = mainstream)

$30 billion
investment, 2021

Score by vector (0= lower; 1 = higher)

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Scientific publications on topics associated with trend

Industry relevance

Although uptake of immersive reality has been limited, several industries have been pioneering new applications:

— *Information technology and electronics.* For the technology industry, the focus will be on clearing the path to wide adoption of immersive-reality technologies by improving them in multiple respects, from fundamentals like lower weight and sensory precision to larger challenges like user comfort (for example, mitigating nausea for VR) and integration into enterprise architectures to unlock business use cases.

— *Media and entertainment. VR has enabled lifelike participation in real-world events such as concerts, conferences, games, and fashion shows.*

— *Retail.* Some retailers are using immersive-reality technologies to offer shoppers a sense of how products look and feel—for example, by letting them "try on" apparel or visit virtual stores. A recent McKinsey survey found that about one-third of customers who are active in the metaverse have purchased real-world items there.

Looking ahead, industries that employ many "deskless" workers—who total some 2.7 billion people, or about 80 percent of the global workforce—show potential to use immersive reality for many applications. These sectors include the following:

— *Healthcare systems and services.* Immersive-reality technologies could help with surgical procedures, surgical training, telemedicine, imaging and pathology, and the treatment of mental-health issues.

— *Education.* Technologies could provide immersive learning experiences, as well as hands-on training in skills for procedures in unusual or dangerous scenarios.

— *Aviation, travel, and logistics.* Immersive technologies could help diagnose flow constraints in warehouses or manage vehicle fleets.

— *Construction and building materials.* Technologies could help model and test new buildings and infrastructure projects as virtual environments.

"The initial surge of use cases for immersive reality has concentrated on gaming and retail applications. But we will start to see more B2B use cases that transform how people conduct a wide range of tasks—how they perform surgery, design and build skyscrapers, and operate factories, among many other activities."

—Lareina Yee, senior partner, McKinsey; chair, McKinsey Technology Council

— *Electric power, natural gas, and utilities.* Immersive-reality tools could help companies visualize underground infrastructure to improve safety or analyze energy losses to reduce waste.

— *Aerospace and defense; automotive and assembly.* In manufacturing, immersive reality enables users to simulate product and factory designs, analyze quality and productivity issues, facilitate maintenance on plant floors, and guide repairs. These technologies also provide platforms for training, where people can build skills during simulations of dangerous situations while avoiding most of the real-world risk.

— *Real estate.* Immersive reality has many applications across the real-estate value chain, from design to user experience, including interior design, floor and furniture planning, and virtual tours or property showcases.

Key uncertainties and big questions

At present, the mainstreaming of immersive-reality technologies is constrained chiefly by the state of the available hardware. However, further improvements should give rise to a wider variety of end-user devices that are also smaller, lighter, more durable, and more precise than today's models (including headsets that generate less heat, run on batteries, and mitigate users' nausea). As devices get better, immersive-reality technologies could be applied to the needs of many more users, covering segments from niches to mass markets. Enthusiasm and uptake may be further influenced by users' perceptions of whether immersive-reality technologies provide adequate security and privacy and whether they contribute to (or counter) social ills.

Underlying technologies

Immersive-reality technologies include the following:

— *Spatial computing.* These technologies help create immersive reality by introducing virtual 3-D objects to physical spaces.

— *Augmented reality (AR).* These technologies enable partial immersion by adding information to real-world settings.

— *Virtual reality (VR).* These technologies immerse users in entirely virtual settings.

— *Mixed reality (MR).* These technologies enable a level of immersion between AR and VR, adding virtual elements to the real world so that users can interact with both.

— *On-body and off-body sensors.* Embedded in handheld or wearable devices or mounted around users, these instruments detect objects and bodies for representation in virtual settings.

— *Haptics.* These technologies are feedback devices that convey sensations to users, usually as vibrations.

— *Location services.* This class of technologies allows mobile devices to locate users more precisely in the physical world, so that AR and MR overlays can be shown in the right places.

Industrializing machine learning

The trend—and why it matters

Industrializing machine learning (ML) involves creating an interoperable stack of technical tools for automating ML and scaling up its use so that organizations can realize its full potential. ML tools can help companies transition from pilot projects to viable business products, resolve modeling failures during production, and overcome limits on teams' capacity and productivity. Experience suggests that organizations that industrialize ML successfully can shorten the production time frame for ML applications by 90 percent (from proof of concept to product) and reduce development resources by up to 40 percent. While a small number of leading companies have pioneered the industrialization of AI, we expect its adoption to spread as more companies seek to use AI for a growing number of applications.

Industry relevance

Industrializing ML supports the development and application of AI solutions by enabling rapid training and deployment of models. As such, the trend relates to the same industries as the "Applied AI" trend. The industrialization of ML is expected to create the most impact in industries where accelerating production of ML applications will yield a competitive advantage. These industries include the following:

— *Information technology and electronics.* AI and ML will become more important to the design of hardware and software as devices become more integrated and connected with the natural world (for example, AI models to interpret voice commands, sensors).

— *Telecommunications.* Companies will rely more extensively on AI and ML across multiple business functions from marketing and sales (for example, upselling or cross-selling engines) to customer service (for example, call center volume forecasting and predictions) and network optimization.

— *Pharmaceuticals and medical products.* AI and ML will increasingly support the development of new drugs (for example, through exploring relationships between molecules and chemical compounds) and enable support functions (for example, manufacturing, supply chain optimization) for various medical treatments.

— *Financial services.* AI and ML will continue to support key services in the financial sector, including risk management, and assist in many other processes—for example, by detecting credit card fraud.

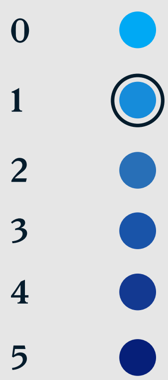
— *Aerospace and defense.* Players will increasingly augment their design and manufacturing processes through optimizations from AI and ML models (for example, AI models to aid in the 3-D simulations for aircraft design, supply chain optimization for manufacturing, security risk management).

— *Automotive and assembly.* OEMs will use AI and ML to enhance design and manufacturing processes such as predictive maintenance, automated quality testing, and demand forecasting and to provide customer services such as navigation.

— *Media and entertainment.* As consumers expect high levels of personalization in their media and entertainment experiences, AI and ML will become more important as models help provide tailored recommendations.

Scoring the trend

Scores for ML have approximately doubled across news, publications, patents, and investments. These increases suggest that the use of methods for industrializing ML could widen in the years ahead.



Adoption rate score, 2021

(0 = none; 5 = mainstream)

$5 billion

investment, 2021

Score by vector (0= lower; 1 = higher)

Searches
Search engine queries for terms related to trend

News
Press reports featuring trend-related phrases

Investment
Private- and public-market capital raises for relevant technologies

Patents
Patent filings for technologies related to trend

Research
Scientific publications on topics associated with trend

"One trend I'm spending real time on right now is MLOps, or machine learning operations. It's the set of practices and collaborations—the technology, the people, and the processes—that you need to make machine learning work at scale in your organization. Ultimately, it's the key to industrializing AI."

—Kate Smaje, senior partner, McKinsey; global leader, McKinsey Digital

Key uncertainties and big questions

As companies attempt to industrialize ML, they will likely have to manage changes in both internal and external conditions. Besides devoting funds and talent to building ML tools, many companies will also find it necessary to establish processes and governance structures for managing ML-related activities, meeting regulatory requirements, and upholding standards for responsible and trustworthy ML systems (for more, see the “Applied AI” trend). Businesses will also need to track the emergence of industrialized ML solutions and add (or replace) technologies to fulfill their goals.

Underlying technologies

Software solutions correspond to the stages of the ML workflow, which are as follows:

— *Data management.* Software helps improve data quality, availability, and control in feeding the ML system.

— *Model development.* Tooling is used to build ML models and standardize processes.

— *Model deployment.* Provision tooling brings ML models into production and standardizes processes.

— *Live-model operations.* Software helps maintain or improve the performance of models in production.

Hardware solutions include processing chips and mechanisms used in ML workflow operations:

— *Integrated hardware.* These solutions connect physical hardware chips to software frameworks. Two types include vertically and horizontally integrated hardware systems.

— *Heterogeneous computing.* This solution helps optimize computational workloads by allocating tasks to hardware chips such as graphical processing units (GPUs), tensor processing units (TPUs), and neuromorphic processing units (NPUs).

Next-generation software development

The trend—and why it matters

Next-generation technologies are transforming the capabilities of engineers at every stage of the software development life cycle (SDLC)—from planning and testing to deployment and maintenance—and enabling more and more nontechnical employees to create applications. These technologies, which include AI pair programmers, low-code and no-code platforms, and automated testing, can help simplify complicated tasks and reduce others to single commands. Adoption may be slow because of technical challenges, the need for large-scale retraining of developers and test engineers, and organizational hurdles. Nevertheless, the new technologies could enable both engineers and nonengineers to build applications quickly—thus accelerating digital transformation, delivering productivity gains, and lessening the need to recruit from a scarce, competitive pool of engineering talent.

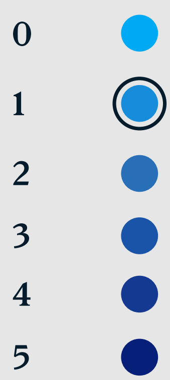
Industry relevance

Next-generation software development stands to benefit nearly every industry. The sectors that are adopting these technologies share similar qualities: process-heavy operations, significant needs for custom software solutions, and rapid innovation cycles (which applies especially to customer-facing companies). Examples of the primary industries affected at present include the following:

— *Financial services.* Evolving rules for processes such as onboarding, know-your-customer, and customer due diligence call for businesses to use software to streamline these processes.

Scoring the trend

Interest, investment, and innovation scores have all risen slightly over the past four years.



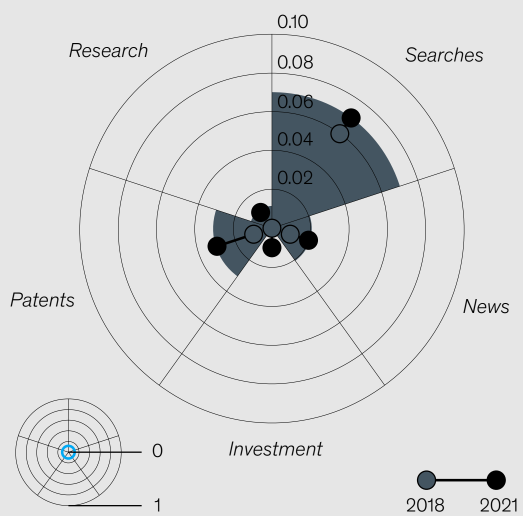
Adoption rate score, 2021

(0 = none; 5 = mainstream)

$2 billion

investment, 2021

Score by vector (0= lower; 1 = higher)



Searches
Search engine queries for terms related to trend

News
Press reports featuring trend-related phrases

Investment
Private- and public-market capital raises for relevant technologies

Patents
Patent filings for technologies related to trend

Research
Scientific publications on topics associated with trend

— *Information technology and electronics.* Companies in this sector produce the tools and solutions that enable next-generation software development; these include AI pair programmers, low-code and no-code platforms, and automated testing applications, among other products.

Key uncertainties and big questions

The next generation of software development tools and techniques is still young. How quickly it reaches maturity and mainstream adoption will depend on various factors. The cost–benefit balance of low-code and no-code development platforms is not yet apparent, and it may not favor all types of software applications. It is also likely to change over time, as these platforms alter the need for traditional developers while making it necessary for nonengineers to learn development skills. Developing software with next-generation tools could create complications: applications based on auto-generated code could be less secure, defects and inefficiencies might escape automated code reviews, and there could be intellectual-property issues regarding AI-written code. There might be practical concerns as well, such as how to monitor the quality of applications written by nonengineers and how to hold business units accountable for them.

Underlying technologies

The technologies that power next-generation software development include the following:

— *Low-code and no-code platforms.* Software development systems with graphical user interfaces make it easier for nonengineers to create applications by letting them assemble prewritten blocks of code instead of needing to write code from scratch.

— *Infrastructure as code.* Configuration templates help users create the IT infrastructure needed by applications.

— *Microservices.* These tools are small, self-contained, single-function components of software applications that can be combined to perform more complex functions.

— *AI pair programmer.* This AI-powered application makes code recommendations to human programmers based on context from input code or natural language.

— *AI-based testing.* Next-generation software can use AI to test units and performance to help reduce the time that developers spend on testing.

— *Automated code review.* These applications use predefined rules or AI to perform quality or security checks on source code and improve coverage.


McKinsey & Company

Technology, Media & Telecommunications

Developer Velocity at work: Key lessons from industry digital leaders

The experiences of several high-performing software development organizations in banking and retail offer a road map to excellence.

by Chandra Gnanasambandam, Neha Jindal, Shivam Srivastava, and Dilip Wagle

February 2021

“We created the Developer Velocity Index, a holistic measure of a company’s software development capabilities. . . . Companies in the top quartile of Developer Velocity Index scores outperformed bottom-quartile peers by up to five times on their 2014–18 revenue growth.”

—“Developer Velocity at work: Key lessons from industry digital leaders,” McKinsey, February 22, 2021

Quantum technologies

The trend—and why it matters

Quantum technologies promise to take advantage of the unique properties of quantum mechanics to perform specific types of complex calculations much faster than classical computers, transform networks by making them more secure, and enable significant improvements in the sensitivity of sensors. In principle, quantum technologies could generate simulations and solve problems that would lead to major advances in industries such as aerospace and defense, chemicals, information technology, and pharmaceuticals. However, prospective users of quantum technologies should prepare for an uncertain adoption road map because certain technological challenges must be overcome before fully error-corrected computers and scalable networks can be created.

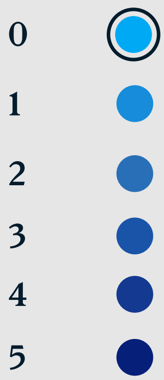
Industry relevance

Quantum technologies, which are in the very early stages of scientific development, have yet to make a major difference in any industry. Nevertheless, companies have started experimenting with current products to gain familiarity with them and explore uses for more mature products. The most promising applications can be found in information technology. Several other industries are grappling with problems that quantum technologies could help solve:

— *Information technology and electronics.* Companies are improving network security with quantum-key-distribution technology, which is relatively mature. Devices that transmit information with quantum particles are being prototyped. Cloud providers are developing capabilities or forming partnerships to offer quantum-computing services.

Scoring the trend

Despite research advances made in the past few years, quantum technologies remain nascent and have garnered less attention than more mature technologies.



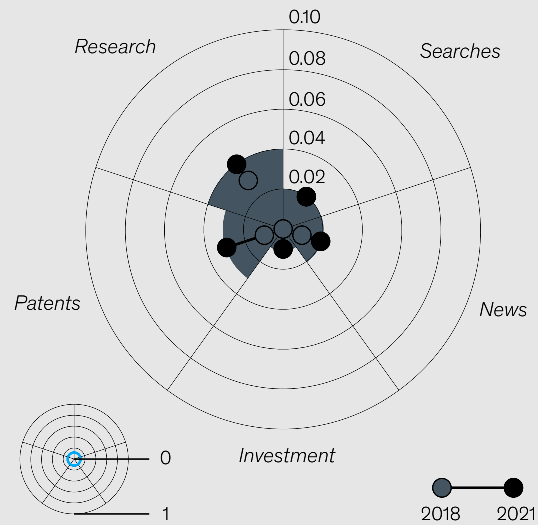
Adoption rate score, 2021

(0 = none; 5 = mainstream)

$3 billion

investment, 2021

Score by vector (0= lower; 1 = higher)



Searches
Search engine queries for terms related to trend

News
Press reports featuring trend-related phrases

Investment
Private- and public-market capital raises for relevant technologies

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Research
Scientific publications on topics associated with trend

"Quantum computing doesn't make sense for every company, but the range of potential applications we've seen is broad, from biopharma to automotive, and, of course, telecom and financial services."

—Rodney Zemmel, senior partner, McKinsey; global leader, McKinsey Digital, in *What technology trends will—and should—lead business agendas in 2022?*

- *Metals and mining; oil and gas.* Quantum-sensing technology can increase the efficiency of companies' exploration and extraction activities.

- *Aerospace and defense.* Organizations can use quantum technologies to enable tamper-proof communication systems and develop augmented navigation systems.

- *Chemicals; pharmaceuticals and medical products.* Quantum computers could help with the molecular simulations involved in creating new materials and identifying potential drugs.

Key uncertainties and big questions

The major uncertainty facing quantum technologies is the time frame in which error-corrected quantum computers will be developed. One challenge that must be solved to make the technology practical is developing the ability to manage a sufficient quantity and quality of quantum bits (qubits) over enough time to derive meaningful computational results. Looking beyond that achievement, prospective users may need to wait for quantum computers to become cost-effective (traditional supercomputers can execute algorithms that solve many problems), for quantum-computing ecosystems to take shape as the talent pool deepens and as more commercial-hardware platforms emerge, and for new computing algorithms to be written that can enable more use cases. It also remains to be seen which use cases will be most compelling—and whether quantum computers can defeat current standards for data encryption.

Another major uncertainty is determining how much better than traditional computing approaches can quantum computing perform when solving optimization problems. Currently, the best quantum approaches yield only a quadratic speedup, which is not clearly superior to traditional computing when the additional overhead associated with quantum computing (such as error correction) is accounted for. However, better approaches to quantum optimization could arise in the future.

Underlying technologies

Quantum-mechanics principles can be applied to several different classes of technologies, which include the following:

- *Quantum computing.* This technology uses quantum properties of subatomic particles to examine a huge number of paths to possible computational results, thereby solving certain problems much faster than classical computers.

- *Quantum communications.* This is the secure, tamper-proof transfer of encoded quantum information between distant locations via optical fibers or satellites.

- *Quantum sensing.* Some instruments are capable of measuring some physical quantities at a sensitivity that is orders of magnitude higher than classical sensors.

Trust architectures and digital identity

The trend—and why it matters

Digital-trust technologies enable organizations to manage technology and data risks, accelerate innovation, and protect assets. What's more, building trust into data and technology governance can enhance organizational performance and improve customer relationships. The underlying technologies include zero-trust architectures (ZTAs), digital-identity systems, and privacy engineering. Other technologies help build trust by ensuring that AI models are secure, free from bias, and explainable. However, the adoption of digital-trust technologies has been hindered by a range of factors, including integration challenges, organizational silos, and a lack of talent. Building a comprehensive trust-first risk mindset and capabilities requires top-down leadership and deliberate changes to multiple spheres of activity, from strategy and technology to user adoption.

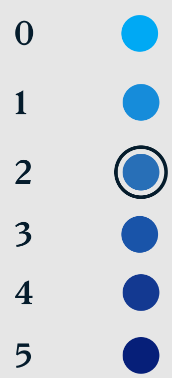
Industry relevance

Digital-trust technologies are becoming more important as businesses in every industry amass, manage, and analyze more data. Many industries in which businesses commonly manage highly sensitive data are at the forefront of adopting these solutions. These industries include the following:

— *Information technology and electronics.* ZTAs can mitigate risk from decentralized data. Digital-identity technologies reduce friction in customer journeys. Privacy engineering uses embedded protocols and controls to preserve the performance of models and solutions.

Scoring the trend

Investments in ventures working on trust architectures and digital identity doubled from 2018 to 2021, and patent filings increased by about 50 percent. While digital-trust technologies have received limited general attention, topics associated with digital trust generate significant coverage (for example, privacy breaches and AI biases).



Adoption rate score, 2021

(0 = none; 5 = mainstream)

$34 billion

investment, 2021

Score by vector (0= lower; 1 = higher)

Searches
Search engine queries for terms related to trend

News
Press reports featuring trend-related phrases

Investment
Private- and public-market capital raises for relevant technologies

Patents
Patent filings for technologies related to trend

Research
Scientific publications on topics associated with trend

- *Financial services.* ZTAs enhance security controls and remediation capabilities. Digital identity helps enable decentralized finance (DeFi) applications (see the “Web3” trend for more). Privacy engineering helps ensure regulatory compliance and simplify reporting.

- *Healthcare systems and services; pharmaceuticals and medical products.* ZTAs protect access to sensitive data (for example, medical records, patient data) and intellectual property. Digital identity enables the creation of a “single source of truth” for medical records and more effective coordination of care across providers. Privacy engineering helps balance value creation and data governance for drug design, diagnostics, and treatment.

- *Consumer packaged goods; retail.* With the large and growing amounts of consumer data, these sectors may be the next frontier for the comprehensive application of digital-trust technologies and privacy engineering.

- *Aerospace and defense.* Cyberattacks and data breaches in this sector threaten national security and classified information, so the industry will want to adopt ZTAs as one of many strategies to mitigate cyberthreats.

- *Education.* As education becomes more digitized and personalized, institutions can turn to trust architectures that protect students’ digital identities and data while ensuring access to educational resources.

- *Media and entertainment.* To protect intellectual property and media content, players are exploring ZTAs to limit vulnerabilities across a fragmented industry value chain dependent on flows of consumer data and intellectual property.

- *Public and social sectors.* The public sector will offer more services digitally in the coming years, so secure and verifiable individual identities in combination with cybersecurity measures like privacy engineering will be needed to protect citizen data.

- *Telecommunications.* Players can build digital-identity services on next-generation networks to expand their offerings, enable enhanced customer experiences, and extend that to third-party partners on their networks, while also applying ZTAs and privacy engineering to internal systems and processes.

- *Across all industries, explainable AI (XAI) tools identify and measure bias in data sets and models and help interpret model predictions, raising confidence and trust in model outputs.*

Key uncertainties and big questions

As organizations pursue efforts to implement digital-trust technologies, they may encounter challenging complications, which range from scarce resources (including talent), lack of standardized protocols and methods, and incompatible systems. They will need to implement new practices and manage new risks. Amid these changes, organizations will also seek to account for the changing expectations of customers, employees, and other stakeholders with respect to issues such as privacy (a priority that calls for not collecting demographic data) and fairness (a priority that is often met by collecting and using some demographic data to test for and correct biases). Regulations, too, could evolve as authorities attempt to reconcile past standards for data privacy, data permanency, and other issues with the capabilities and requirements of new trust technologies.

Underlying technologies

Digital-trust technologies include the following:

— *Zero-trust architecture (ZTA).* Zero-trust architecture is a type of IT system design which assumes that all entities, both within and outside of an organization, cannot be trusted and therefore applies cybersecurity controls to every interaction with each entity.

— *Digital identity.* An identity consists of all the digital information that characterizes and distinguishes an individual or an entity. With self-sovereign identity (SSI), users control which identifying information to share and with whom. Passwordless identity allows users to verify and authenticate themselves not with traditional alphanumeric passwords but with alternatives such as biometrics, devices and applications, and documents.

— *Privacy engineering.* This practice governs implementation, operations, and maintenance of privacy by design. It's focused on strategic reduction of privacy risks and enablement of purposeful decision making about resource allocation and effective implementation of privacy controls in information systems.

— *Explainable AI (XAI).* XAI helps enhance trust and confidence in models by making it easier to understand why they provide the outputs that they do.

Additional trust-building frameworks, such as the tool stack for industrializing machine learning (ML), will contribute to trust by design and trust in use at scale.

"Many organizations are cautious about adopting AI and ML until they can build out a solid basis for trust, both externally (by reassuring customers) and internally (by reassuring employees). Building trust-based architectures will significantly expand the scope of industries and use cases where AI and ML can be applied. Trust fuels innovation."

—Liz Grennan, associate partner, McKinsey

Web3

The trend—and why it matters

Web3 refers to a future model for the internet that decentralizes authority and redistributes it to users, giving them increased control over how their personal data are monetized and stronger ownership of digital assets. In addition, it provides a range of commercial opportunities: new business models governed by decentralized autonomous organizations (DAOs) and enabled by eliminating intermediaries through secure (smart contract) automation, and new services involving digital programmable assets. Although Web3 has drawn significant general interest, it has gained only limited traction with incumbent companies due to a variety of factors. Accordingly, Web3 has attracted large pools of capital and engineering talent, but viable business models are still being tested and scaled. Early adopters face several challenges, including unclear and evolving regulation and immature and emerging technology platforms, often with a poorer user experience than existing Web2 utilities.

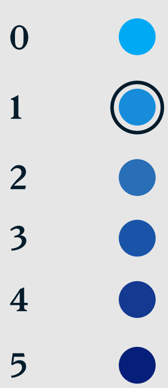
Industry relevance

Web3's potential applications span many industries. So far, the following industries have been the first to apply Web3 technologies:

— *Financial services.* Decentralized finance (DeFi) is an ecosystem of applications that could autonomously perform similar services to traditional financial institutions, albeit with very different levels of protection, and where the traditional revenues are handed back to users or liquidity providers of these applications. Many are governed through token-based distributed governance systems. Other areas of financial

Scoring the trend

Web3 has seen increases in all scores, with interest and investment scores that rank in the top five of all trends we studied.



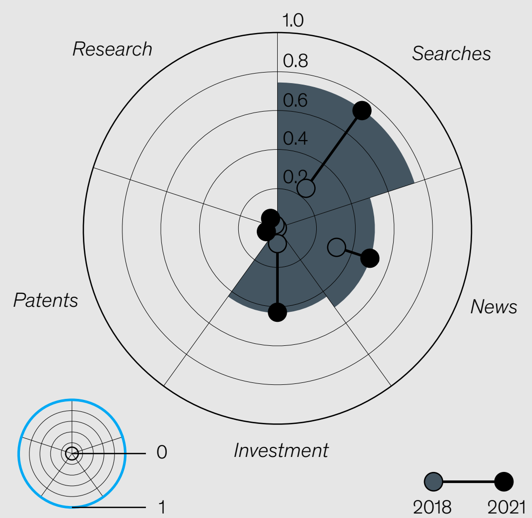
Adoption rate score, 2021

(0 = none; 5 = mainstream)

$110 billion

investment, 2021

Score by vector (0= lower; 1 = higher)



Searches
Search engine queries for terms related to trend

News
Press reports featuring trend-related phrases

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Private- and public-market capital raises for relevant technologies

Patents
Patent filings for technologies related to trend

Research
Scientific publications on topics associated with trend

services exploring Web3 applications include payments, asset management, and some areas of capital markets.

— *Media and entertainment: Gaming.* Web3 enables interoperable games and tokenized digital assets facilitating new gaming experiences and play-and-earn business models in which in-game rewards (for example, nonfungible tokens [NFTs], governance tokens) are distributed with different utilities.

— *Media and entertainment: Digital art and media.* Creation and ownership of digital media (for example, artworks, video content)—sold as NFTs—allow new business models and creative possibilities while providing artists with more control and, in some cases, ongoing perpetual royalties.

— *Retail.* Retailers are using Web3 technologies to create new offerings, devise new modes of customer engagement (for example, ecosystem loyalty programs, access to unique experiences), assure the authenticity of goods, tap into new royalty-based revenue streams, accept novel payment methods (such as "stablecoins"), and track and orchestrate logistics across loosely coupled global supply chains.

— *Information technology and electronics.* Innovators will use Web3 to create decentralized, peer-to-peer networks, enable social media users to create and sell their content, enable stronger user control of digital identity, and lay the groundwork for the adoption of metaverse platforms.

Key uncertainties and big questions

Before Web3 technologies can realize the potential that some envision, they will have to satisfy certain basic requirements. These include resilience against service failures and cyberattacks, interoperability with enterprise architectures and hyperscale Web2 platforms, and better user experience. More broadly, new business models and value chains must show they can produce more value for users than existing systems; achieve uptake beyond an enthusiastic cohort of early adopters; satisfy evolving regulations for consumer and investor protection, asset classification (for example, security versus commodity), and know-your-customer standards. These considerations apply equally to the new applications and environments, such as the metaverse, that may materialize as the Web3 trend blends and crosses over with other trends, such as immersive reality and advanced connectivity, to enable innovative user experiences.

Underlying technologies

The technologies comprising the Web3 stack include the following:

— *Blockchain.* This is a digitally distributed, decentralized ledger that exists across a network of computers which work together to facilitate the recording and confirmation of transactions.

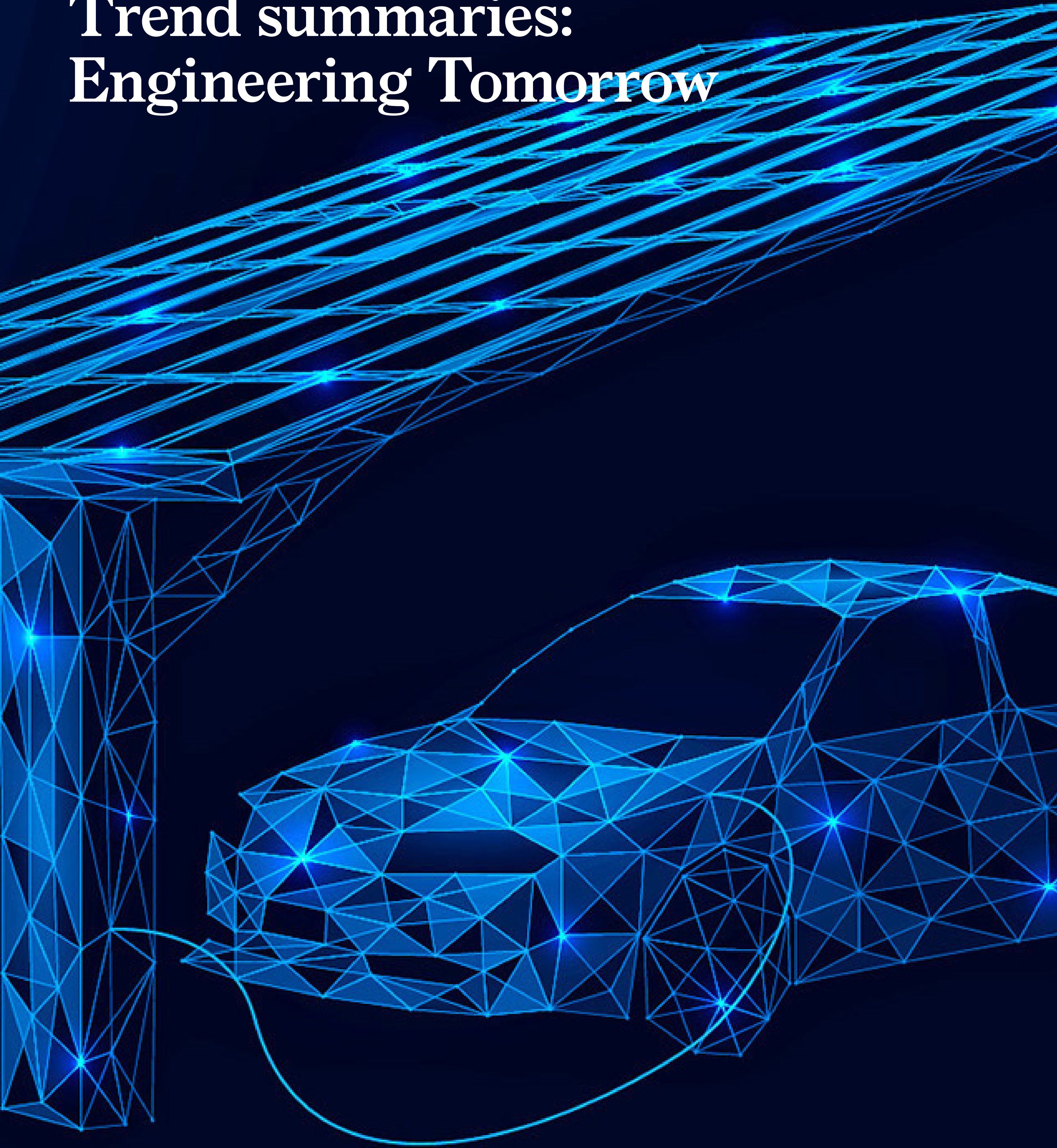
— *Smart contracts.* These are software programs established in immutable code and data on a blockchain, which are automatically executed when specified conditions (such as terms agreed on by a buyer and seller) are met.

— *Digital assets.* Examples of these digitally native intangible items include native cryptocurrencies, governance tokens, stablecoins, NFTs, and tokenized assets.

"Web3 fundamentally represents a disruption in business model and value capture, particularly for network-based businesses. While nascent in its implementation, companies could do well to understand the underlying mechanics and place their bets accordingly—the risk of not acting is too high, and the technology is not going away."

— Ian De Bode, partner, McKinsey; coleader, Web3 and Digital Assets

Trend summaries: Engineering Tomorrow



Future of bioengineering

The trend—and why it matters

Breakthroughs in biology, combined with innovations in digital technology, could help organizations respond to demands in areas as diverse as healthcare, food and agriculture, consumer products, sustainability, and energy and materials production by creating new products and services. McKinsey research suggests that some 400 use cases for bioengineering, almost all of which are scientifically feasible, could have an economic impact of $2 trillion to $4 trillion per year from 2030 to 2040. While certain gene therapies and bioproducts have gained acceptance, ethical, regulatory, and public-perception issues will need to be settled for bioengineering to realize its full economic potential.

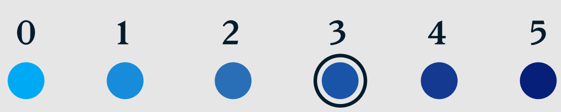
Industry relevance

While the bioengineering trend could affect all industries, healthcare and pharmaceuticals lead others in adoption and potential impact. The consumer goods, agriculture and food, and chemicals sectors follow closely. Potential applications for each sector include the following:

— *Healthcare systems and services; pharmaceuticals and medical products.* Novel therapies and solutions can help treat previously uncurable monogenic and polygenic diseases (diseases caused by variations in one gene and multiple genes, respectively).

Scoring the trend

Bioengineering ranked among the top five trends for interest in 2021. Measures of investment and news coverage have also doubled since 2018, signaling excitement about future technologies.

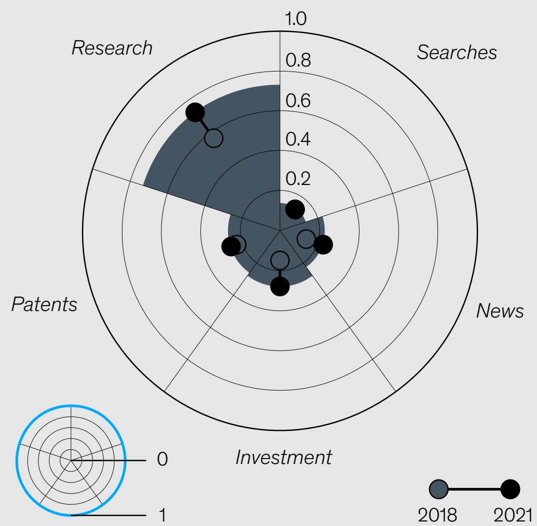


Adoption rate score, 2021
(0 = none; 5 = mainstream)

$72 billion

investment, 2021

Score by vector (0= lower; 1 = higher)



Searches
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Scientific publications on topics associated with trend

— *Consumer packaged goods.* Bioengineering can support the development and manufacturing of more sustainable, cost-effective products.

— *Agriculture.* Bioengineered products, such as cultivated meat, can offer sustainable, cruelty-free alternatives to conventional proteins.

— *Chemicals.* Advances in bioengineering could lead to sustainable, cost-effective, and higher-quality biochemicals and production processes.

Key uncertainties and big questions

Public opinion, policy choices, and ethical debates may prove to be powerful factors influencing the development and uptake of bioengineering technology. The public's willingness to accept the safety, cost, and quality of bioengineered products, for example, may determine how quickly markets develop. Regulation of bioengineering technology and products will also govern the pace of advancement to some extent. Additionally, society will consider people's values and principles in deciding which uses of bioengineering are ethical. All these considerations may only become more complicated as cross-disciplinary innovations make new bioengineering applications possible.

Underlying technologies

The future of bioengineering, we believe, will be defined by advancements in omics, tissue engineering, and biomaterials:

— *Omics.* This term encompasses biological sciences ending in the suffix "-omics," such as genomics and proteomics, which focus on different biological molecules. Omics are central to the development of bioengineering applications such as viral-vector gene therapy (which uses modified viruses to permanently replace poorly functioning genes that cause genetic diseases) and mRNA therapy (which temporarily uses synthetic mRNA to compensate for missing or mutated genes).

— *Tissue engineering.* Tissue-engineering technology enables the modification of cells, tissues, and organs. Cultivated meat is a product based on tissue-engineering methods; it's made by taking a sample of animal cells and growing them in a controlled environment to produce tissue similar to meat from whole animals.

— *Biomaterials.* Materials made using bioengineering technology fall into several different categories: bio-based drop-in chemicals (which can replace chemicals traditionally made from petrochemicals without changing surrounding operations), bioreplacements (new materials made from bio-based chemicals that provide similar quality and cost but better environmental performance than traditional chemicals), and biobetter materials (completely new materials produced via biochemical synthesis).

"This wave of innovation could be truly transformative, affecting what we eat and wear, the products we use, the diseases we could cure, and how we build our physical world. Some of these biological technologies are advancing faster than Moore's law—what used to take years and billions of dollars can now be done in an hour for $300."

—Michael Chui, partner, McKinsey and McKinsey Global Institute

Future of clean energy

The trend—and why it matters

Energy solutions that drive toward net-zero emissions span the entire value chain, from generation or production to storage and distribution. These increasingly important solutions include renewable sources such as solar power and wind power, sustainable fuels such as hydrogen, long-duration battery systems, and smart grids. McKinsey estimates that annual investments in energy supply and production could double by 2035, reaching approximately $1.5 trillion, and could be increasingly skewed toward nonfossil and decarbonization technologies. Overall, the shift to clean energy would trigger profound changes across both energy-producing and energy-intensive sectors. While capacity and reliability constraints could slow the uptake of clean energy, growing capital spending and more regulatory support could help accelerate adoption.

Industry relevance

The electric power, natural gas, and utilities sector will likely face direct consequences from the shift to clean-energy technologies:

— *Electric power, natural gas, and utilities.* Producers of electric power and sustainable fuels will be at the center of the clean-energy shift, using a combination of technologies to achieve net-zero emissions by 2050 (or sooner) and to meet growing global power demand.

Other industries are experiencing second-order consequences from the shift to clean-energy technology; these primarily entail changes in demand for resources and services and in value pools. Examples include the following:

— *Metals and mining.* Mining companies face growing demand for raw materials such as copper for electrification and lithium and cobalt for batteries.

— *Construction and building materials.* These companies are building additional transmission and distribution infrastructure to enable the delivery of electricity generated by renewable sources to where it is needed.

— *Oil and gas.* Amid declining fossil-fuel demand, producers can use various technologies to decarbonize upstream (production) operations while also exploring options to produce clean energy (such as green hydrogen).

— *Chemicals.* There is an increase in demand for chemicals needed for the production of renewables (for example, silicon for the development of photovoltaic cells).

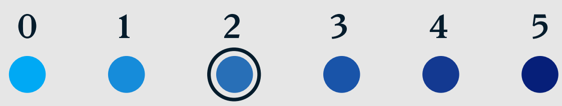
— *Public and social sectors.* Clean energy is a top priority for many governments. Public entities can provide greater regulatory clarity, decarbonization commitments, and investment incentives, among other actions.

All the industries described above are involved in the decommissioning of fossil-fuel assets and the environmental remediation of industrial sites and infrastructure.

For more industries affected by sustainable development, please see the “Future of sustainable consumption” trend.

Scoring the trend

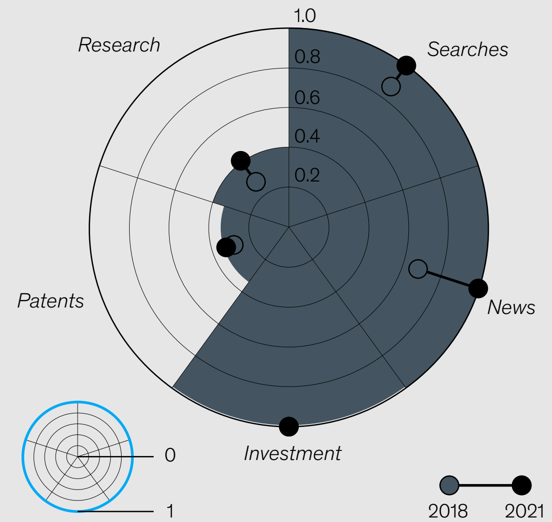
Investment and interest scores have consistently ranked the highest of the 14 trends we tracked during 2018 to 2021, and the innovation score rose by about one-third.



Adoption rate score, 2021
(0 = none; 5 = mainstream)

$257 billion
investment, 2021

Score by vector (0= lower; 1 = higher)



Searches
Search engine queries for terms related to trend

News
Press reports featuring trend-related phrases

Investment
Private- and public-market capital raises for relevant technologies

Patents
Patent filings for technologies related to trend

Research
Scientific publications on topics associated with trend

"In the context of COP26 [the 2021 UN Climate Change Conference], a large number of countries, as well as many of the world's largest corporations, have committed to achieving net-zero emissions within the next few decades. Although most of these pledges have yet to be translated into concrete policies and actions, the continued growth of low-carbon technologies shows that key enablers for the energy transition keep momentum."

—*Global Energy Perspective 2022,*
McKinsey, April 26, 2022

Key uncertainties and big questions

The transition to clean energy involves significant technological change not only to the energy value chain but also within the world's most energy- and emissions-intensive sectors. There will need to be cost-effective production and installation of reliable equipment for power generation, hydrogen and biofuel synthesis, electrification, energy storage, and smart grids. Infrastructure build-outs and upgrades, too, will have to be managed well. These activities, in turn, will depend on stable supply chains and the availability of critical resources. And their pace could be affected by changes in the regulation of energy and energy-intensive sectors, against a backdrop of government decarbonization commitments. All these factors will help decide how widely clean energy is adopted and which technologies and businesses deliver value.

Underlying technologies

Clean-energy technologies come in many forms for use across the value chain. Noteworthy examples include the following:

— *Solar photovoltaics.* These panels with semiconductors convert sunlight into electricity.

— *Low-wind-speed onshore and offshore generation.* These turbines are designed with larger rotors, longer blades, and greater height to tap slower, higher wind.

— *Hydrogen.* Hydrogen is a versatile energy carrier that can be produced with minimal or zero-carbon emissions.

— *Electrolyzers.* Electrochemical energy-conversion technologies are used to convert water into "green" hydrogen with oxygen as the only byproduct (thus achieving zero carbon emissions).

— *Long-duration energy storage (LDES).* LDES systems can store energy for more than eight hours, or for weeks or months, to meet peak demand or cope with temporary production shortfalls.

— *Smart grid.* Advanced, intelligent electric-grid systems have the ability to provide real-time insights and power-distribution control.

— *Electric-vehicle (EV) charging infrastructure.* These charging stations and distribution systems are used to power up EVs.

Future of mobility

The trend—and why it matters

More than a century after mass production of automobiles began, mobility has arrived at a second great inflection point: a shift toward autonomous, connected, electric, and smart (ACES) technologies. This shift promises to disrupt markets while improving efficiency and sustainability of land and air transportation of people and goods. ACES technologies for road mobility saw significant adoption during the past decade, and the pace could accelerate because of sustainability pressures. Advanced air-mobility technologies, on the other hand, are either in pilot phase (for example, airborne-drone delivery) or remain in the early stages of development (for example, air taxis) and face some concerns about safety and other issues.

Industry relevance

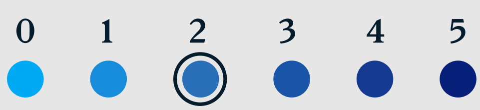
The automotive and assembly industry and the aviation, travel, and logistics industry are among those most affected by developments in ACES technologies. They will face changes in demand and in value pools, which could be met with new business models and value chains:

— *Automotive and assembly.* Automakers and suppliers are adapting to the wholesale shift to electric vehicles (EVs). The rise of shared mobility will require new operating models and partnerships.

— *Aviation, travel, and logistics.* New modes of aerial transportation, as well as novel propulsion, will expand aviation use cases and

Scoring the trend

Investment, interest, and innovation measures for ACES technologies have approximately doubled over the last few years, pointing toward advances in new solutions and wider applications of existing ones.

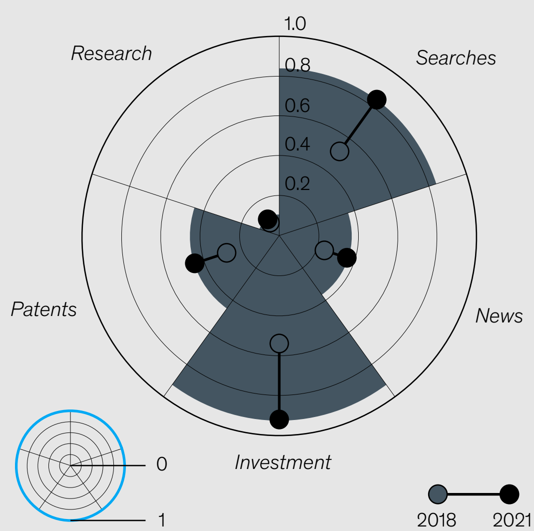


Adoption rate score, 2021
(0 = none; 5 = mainstream)

$236 billion

investment, 2021

Score by vector (0= lower; 1 = higher)



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drastically change unit economics. In addition, logistics players will need to alter their business models as large modal shifts (for example, rail to road) play out and integrated logistics marketplaces emerge.

More broadly, companies in the following sectors should anticipate secondary effects on their business models and markets:

— *Electric power, natural gas, and utilities.* Companies will need more generation capacity, as well as reinforcement of transmission and distribution networks, to meet increased demand for electricity from EVs.

— *Public and social sectors.* The future of mobility could increase tax revenue for the public sector, affect land-use planning (for example, autonomous vehicles and shared mobility, reducing the need for parking lots), and alter the ways in which the public and social sectors deliver services.

— *Financial services.* This sector can expect changes in insurance claims portfolios and personalized insurance rates.

— *Oil and gas.* Reduced demand for gasoline and diesel fuel as EVs reach scale will impact the oil and gas sector

— *Retail.* Companies could use airborne drones to make deliveries.

Key uncertainties and big questions

Wider adoption of ACES technologies will require advances that improve batteries (to electrify more forms of transportation, such as air mobility) and lower the costs of equipment and infrastructure. Companies will also need to address concerns about safety and accountability for uncrewed and autonomous mobility, about the noise and visual impact of advanced mobility, and about the privacy and security of algorithms and workflows. Some of these issues might be addressed through regulation, which is also likely to be needed to create certification frameworks. And advanced mobility could change the way that cities are planned and built.

Underlying technologies

A future of efficient, sustainable mobility, we believe, will be defined by ACES and adjacent technologies, such as the following:

— *Autonomous.* Automated systems with sensors and AI can make independent decisions based on data they collect.

— *Connected-vehicle technologies.* Equipment, applications, and systems use vehicle-to-everything communications to improve safety and efficiency.

— *Electrification technologies.* These solutions replace vehicle components that operate on a conventional energy source with those that operate on electricity.

— *Smart-mobility solutions.* Hardware and advanced digital solutions enable the use of alternative forms of transportation in addition to (or instead of) privately owned vehicles.

— *Lightweight technologies.* The use of new materials (such as carbon fiber) and processes (such as engine downsizing) can improve sustainability.

— *Value-chain decarbonization.* Technical levers (such as green primary materials) can abate emissions from materials' production and can increase the use of recycled materials.

"Sustainable mobility looks completely different depending on where you are. In urban areas, we will see a significant share of private cars replaced by mostly pooled shared mobility (some autonomous), public transport, and micromobility (some shared). In rural areas, private EVs, including some autonomous vehicles, will dominate the landscape."

—Kersten Heineke, partner, McKinsey; coleader, McKinsey Center for Future Mobility

Future of space technologies

The trend—and why it matters

The most significant development in space technologies over the past five to ten years has been decreasing costs, which are making new capabilities and applications more accessible. Decreasing component costs have been driven strongly by reductions in the size, weight, power, and cost (SWaP-C) of satellites and launch vehicles. These reductions have also led to shifts in system architectures, such as the shift from individual, large geosynchronous-equatorial-orbit (GEO) satellites to smaller, distributed low-Earth-orbit (LEO) satellites. The use of space technologies and remote-sensing analytics is substantial today, and analysis suggests that the space market could exceed $1 trillion. The future space economy could encompass activities that aren't being pursued at scale in space today, such as in-orbit manufacturing, power generation, and space mining, as well as scalable human spaceflight. Many also envision the development of a cislunar economy with increased government and commercial lunar missions anticipated to occur in the coming years, which have also inspired technological innovations from industries outside the space sector.

Industry relevance

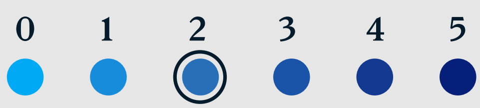
Applications for space technologies are being developed for many industries. For now, the following industries are the most relevant:

— *Telecommunications.* Satellites can provide broadband internet to planes and increase connectivity in remote areas.

— *Aerospace and defense.* Players can use enhanced satellite imagery for navigation and monitoring to achieve security and intelligence objectives.

Scoring the trend

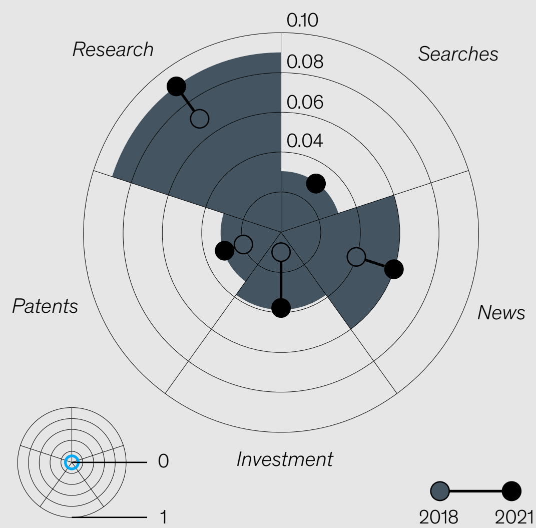
While interest and innovation in space technologies grew gradually over the past four years, investments nearly quadrupled $10 billion in 2021.



Adoption rate score, 2021
(0 = none; 5 = mainstream)

$12 billion
investment, 2021

Score by vector (0= lower; 1 = higher)



Searches
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News
Press reports featuring trend-related phrases

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Key uncertainties and big questions

As organizations consider undertaking more activities in space, they will probably confront questions about the cost-effectiveness and cybersecurity of these ventures. Space debris is building up, creating collision risks for satellites and spacecraft. More broadly, governance of many space activities is just beginning to develop. Therefore, new mechanisms will be needed to increase space-domain awareness to reach a common understanding about access rights and usage of properties and resources—especially as governments recognize space as a potential war-fighting domain—and to define limits on things like LEO satellite launches.

Underlying technologies

When establishing space capabilities in the near term, companies can rely on these technologies, which are more advanced:

— *Small satellites.* Modular small satellites can be custom built—by using "CubeSat" architectures and standard-sized building blocks—to perform a widening variety of missions.

— *Remote sensing.* Full-spectrum imaging and monitoring are used for observing Earth's features such as oceanography, weather, and geology.

— *SWaP-C advancements.* One of the drivers of cost-effectiveness has been a reduction in the size, weight, power, and cost of satellites and launch vehicles, resulting in less expensive and higher-resolution sensors, more-efficient power systems, and other improvements.

— *Launch-technology innovations.* Reuse of booster structures, engines, or otherwise, coupled with technology advancements (for example, material sciences, computer-aided design, 3-D printing) and increases in launch rate, are contributing to a reduction in operational costs and an increase in accessibility to space.

The space sector's transformation over the previous decade should also support the emergence of new technologies, including the following:

— *Laser communications.* Laser links would allow satellites to communicate using pulses of light for data transmission.

— *Nuclear propulsion.* Systems that use thermal or electric energy propel spacecraft faster and longer than traditional chemical or solar-electric propulsion, thus enabling deep-space navigation.

— *Refueling robots.* Automatons can refuel in-orbit satellites, thus extending mission lifetimes

— *Orbit repositioning.* These technologies can raise the orbit or change the inclination of a satellite.


McKinsey & Company

Aerospace & Defense Practice

The potential of microgravity: How companies across sectors can venture into space

Should you move your R&D and manufacturing into the ether? A new McKinsey analysis explores the opportunities.

by Carsten Hirschberg, Ireen Kulish, Ilan Rozenkopf, and Tobias Sodoge

June 2022

"The full impact of any commercial space opportunity is now difficult to estimate, but some exciting discoveries could benefit both businesses and society as a whole. If space-based R&D allows researchers to make breakthroughs in oncology compounds, for instance, the insights could save millions of lives."

—"The potential of microgravity: How companies across sectors can venture into space," McKinsey, June 13, 2022

Future of sustainable consumption

The trend—and why it matters

Sustainable consumption centers on the use of goods and services that are produced with minimal environmental impact by using low-carbon technologies and sustainable materials. At a macro level, sustainable consumption is critical to mitigating environmental risks, including climate change. For companies, the production of sustainable goods and services can support compliance with emerging regulations, create growth opportunities, and help attract talent. While many technologies that support sustainable consumption are technically viable, few have become cost-effective enough to achieve mass scale. The global push toward decarbonization could accelerate their adoption, as could the emergence of a generation of consumers willing to change their buying patterns.

Industry relevance

Many sectors are shifting to sustainable consumption. The following have made notable progress:

— *Automotive and assembly.* Electrification of the global fleet is rapidly expanding, with worldwide demand for electric vehicles growing sixfold from 2021 to 2030, according to projections by McKinsey.

— *Agriculture.* Companies along the value chain are using digital solutions and innovative practices to produce and distribute food in a more sustainable manner.

— *Construction and building materials.* New building techniques and sustainable materials are creating a greener construction industry.

— *Aviation, travel, and logistics.* Regulations are driving companies to modernize fleets, decarbonize fuels, and rethink routing and utilization.

— *Pharmaceuticals and medical products.* Companies can optimize their manufacturing processes to improve energy efficiency, reduce water consumption, and substitute plastic for more sustainable, recycled materials for packaging.

— *Public and social sectors.* Organizations can incentivize the market for sustainable goods and services and mandate shifts, boost innovation by securing funding, and deliver important initiatives to other parts of the economy.

Companies in the following sectors are also preparing for longer-term changes to their business models and markets:

— *Chemicals.* The markets for recycled plastics and specialty plastics created from captured CO_2 are growing.

— *Oil and gas.* The adoption of carbon sequestration to support enhanced oil recovery is increasing.

— *Metals and mining.* The mining industry is seeing decarbonization of operations (for example, hydrogen-fueled green steel production) and offset of production activity effects on natural capital, as well as increasing production of the minerals needed for clean energy and other sustainable technology.

— *Consumer packaged goods.* The demand for items and packaging with legitimate, verifiable sustainability attributes is rising.

— *Aerospace and defense.* Aerospace players are designing and manufacturing aircrafts that rely more on sustainable fuels and increase energy efficiency.

- *Retail.* Retailers can lessen the environmental impact of operations across the product life cycle, from green product sourcing, to in-house facility management (energy, water, packaging waste), to appropriately managing customer returns or disposal of products.

- *Information technology and electronics.* Technology players can consider optimizing electric-power consumption in data centers, powering data centers by renewable energy, and reducing waste across the consumer electronics value chain.

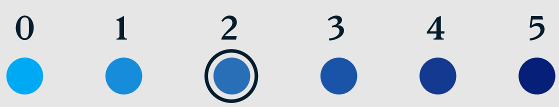
- *Electric power, natural gas, and utilities.* Demand for electric power will vary based on sustainable consumption trends such as electrification.

- *Real estate.* Real estate development will seek to optimize energy demand; markets will shift in response to changes in consumer preferences, urban planning, and infrastructure development, especially as other industries shift toward net-zero emissions.

- *Telecommunications.* As they serve an increasing volume of customers globally, telecommunications providers can optimize their energy consumption by upgrading to 5G and operating their networks with renewable energy.

Scoring the trend

Technologies enabling sustainable consumption have seen growth in all measures of activity other than patent filings.



Adoption rate score, 2021
(0 = none; 5 = mainstream)

$109 billion

investment, 2021

Score by vector (0= lower; 1 = higher)

Searches
Search engine queries for terms related to trend

News
Press reports featuring trend-related phrases

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Key uncertainties and big questions

The pace at which the world moves toward sustainable consumption is likely to depend on technological, financial, and social factors. The costs of the technologies used to produce sustainable goods and services must become competitive with the costs of conventional technologies. Critical inputs must be available and economical. To help meet these conditions, companies and governments can invest in building new, low-emission assets and value chains or decarbonizing existing ones, as well as make use of circular-economy practices and carbon removal technologies. Regulatory action and alignment of standards across borders and regions could catalyze further action. And consumers will need to favor sustainable goods and services over conventional ones.

Underlying technologies

The future of sustainable consumption will be defined in part by the following technologies:

— *Sustainable agriculture and alternative proteins.* These include innovative practices (such as microirrigation and vertical farming) and products (such as plant-based and cultured meats).

— *Natural capital.* This includes technology for the restoration of forests and natural ecosystems, coastal vegetation, biodiversity, and freshwater basins.

— *Circular technologies.* Design and production techniques can increase recycling and reuse and minimize waste.

— *Green construction.* This involves using sustainable practices (such as energy efficiency and waste reduction) and materials.

— *Carbon capture, use, and storage.* CO_2 can be captured directly from point sources, such as industrial facilities and power plants that use fossil fuels, as it is emitted.

— *Carbon removal.* After CO_2 has been emitted, it can be withdrawn from the atmosphere using methods that are either nature based (such as tree planting) or engineered (such as direct air capture).

"The net-zero transition is largely a technology transition: in Europe, up to 70 percent of decarbonization can be driven by 15 technologies. That is 15 massive markets that are being created or accelerated."

—Tomas Nauclér, senior partner, McKinsey; global coleader, McKinsey Sustainability

August 2022