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Technology Trends Outlook 2025

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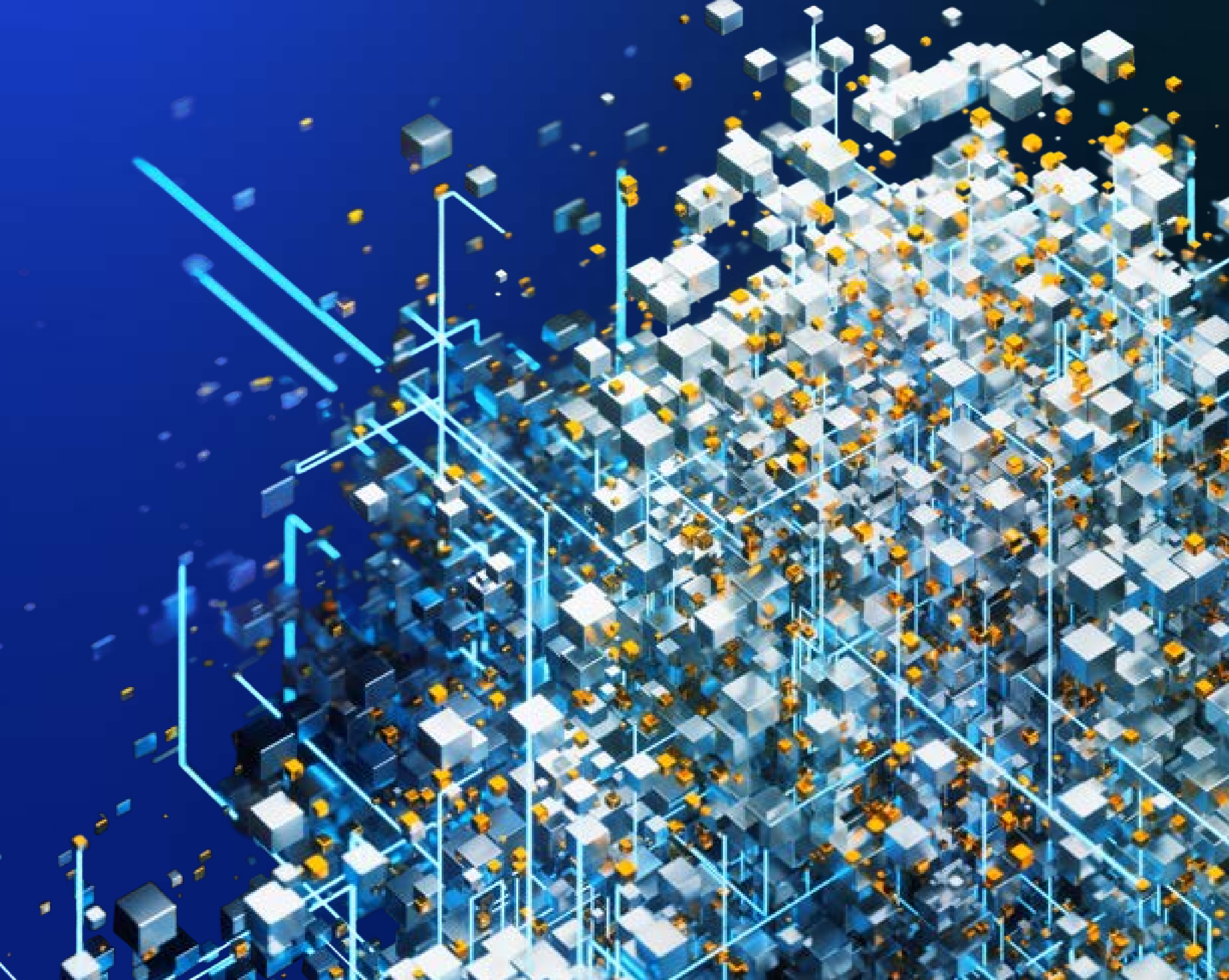

Which frontier technologies matter most for companies in 2025? Our annual tech trends report highlights the latest technology breakthroughs, talent trends, use cases, and their potential impact on companies across sectors.

by Lareina Yee, Michael Chui, Roger Roberts, and Sven Smit

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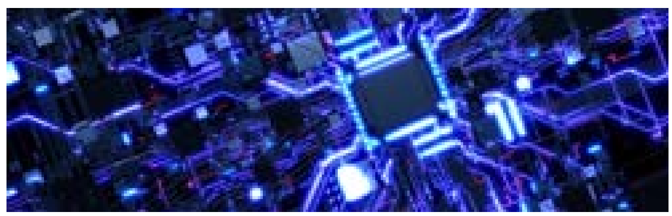

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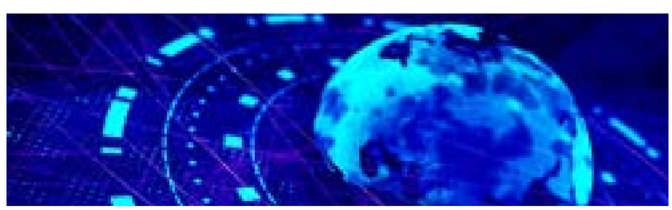

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Introduction

The global technology landscape is undergoing significant shifts, propelled by fast-moving innovations in technologies. These are exponentially increasing demand for computing power, capturing the attention of management teams and the public, and accelerating experimentation. These developments are occurring against a backdrop of rising global competition as countries and corporations race to secure leadership in producing and applying these strategic technologies.

This year's McKinsey Technology Trends Outlook provides in-depth perspectives on 13—a "baker's dozen"—frontier technology trends with the potential to transform global business. Executives today face a mandate to navigate rising complexity, scale emerging solutions, and build trust in a world where the lines between digital and physical and centralized and decentralized continue to blur. The insights in this report can help business leaders decide which of these frontier technologies are most relevant to their companies by demonstrating how others are starting to apply them today. These findings emerge from our analysis of quantitative measures of interest, innovation, equity investment, and talent that underpin each of the 13 trends and explore the underlying technologies, uncertainties, and questions around them. (For more about our research, please see the sidebar, "Research methodology.")

This outlook highlights transformative trends that are driving innovation and addressing critical challenges across sectors. Artificial intelligence stands out not only as a powerful technology wave on its own but also as a foundational amplifier of the other trends. Its impact increasingly occurs via a combination with other trends, as AI both accelerates progress within individual domains and unlocks new possibilities at the intersections—accelerating the training of robots, advancing scientific discoveries in bioengineering, optimizing energy systems, and much more. The evolution of AI solutions in the marketplace increasingly combines

About the McKinsey Global Institute

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This annual report is developed by the McKinsey Global Institute (MGI) to further our understanding of how science and technology can advance economic productivity and innovation. We work together with McKinsey's Technology, Media & Telecommunications Practice; QuantumBlack, AI by McKinsey; and McKinsey Technology to provide insight on how companies are applying these new technologies to transform their businesses.

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aspects of trends we previously analyzed separately as applied AI and generative AI, so this year, they are examined together.

Even as excitement about AI applications and their use cases builds, realizing AI's full potential across sectors will require continued innovations to manage computing intensity, reduce deployment costs, and drive infrastructure investment. This will also demand thoughtful approaches to safety, governance, and workforce adaptation, creating a wide range of opportunities for industry leaders, policymakers, and entrepreneurs alike.

New and notable

In addition to the growing reach of AI, another new trend we have chosen to highlight in this year's report is agentic AI, which has rapidly emerged as a major focus of interest and experimentation in enterprise and consumer technology. Agentic AI combines the flexibility and generality of AI foundation models with the ability to act in the world by creating "virtual coworkers" that can autonomously plan and execute multistep workflows. Although quantitative measures of interest and equity investment levels are as yet relatively low compared with more established trends, agentic AI is among the fastest growing of this year's trends, signaling its potentially revolutionary possibilities.

AI is also the primary catalyst for another trend we highlight this year: application-specific semiconductors. While Moore's Law and the semiconductor layer of the technology stack have long been key enablers of other tech trends, innovations in semiconductors have spiked as reflected in quantitative metrics such as number of patents. These innovations have come in response to exponentially higher demands for computing capacity, memory, and networking for AI training and inference, as well as a need to manage cost, heat, and electric power consumption. This has given rise to a slew of new products, new competitors, and new ecosystems.

Technology trends also have a variety of profiles along the dimensions we analyzed. AI is a widely applicable, general-purpose technology with use cases in every industry and business function—and thus lots of innovation and interest—and it is scaling rapidly across the business landscape. Quantum technologies have a different profile. Quantum computing has the potential for transformative impact in certain critical domains, such as cryptography and material science, and the basic technology continues to be developed. Recent announcements, particularly by technology giants, have sparked increased interest, but real-world business impact will require even more technology advancements to make quantum computing practical. Other trends and subtrends vary across the multiple dimensions we analyzed, offering different approaches—from watchful waiting to aggressive deployment—to business leaders depending on their industries and competitive positions.

From the rise of robotics and autonomous systems to the imperative for responsible AI innovations, this year's technology developments underscore a future where technology is more adaptive, collaborative, and integral to solving global problems. This is illuminated by themes that cut across trends this year:

— *The rise of autonomous systems.* Autonomous systems, including physical robots and digital agents, are moving from pilot projects to practical applications. These systems aren't just executing tasks; they're starting to learn, adapt, and collaborate. Autonomy is moving toward broad deployment, whether through coordinating last-mile logistics, navigating dynamic environments, or acting as virtual coworkers, among other skills.

$1.1
billion
equity investment in agentic AI, 2024

+985%
difference in postings for jobs in agentic AI, 2023–24

- *New human–machine collaboration models.* Human–machine interaction is entering a new phase defined by more natural interfaces, multimodal inputs, and adaptive intelligence. From immersive training environments and haptic robotics to voice-driven copilots and sensor-enabled wearables, technology is becoming more responsive to human intent and behavior. This evolution is shifting the narrative from human replacement to augmentation—enabling more natural, productive collaboration between people and intelligent systems. As machines get better at interpreting context, the boundary between operator and cocreator continues to dissolve.

- *Scaling challenges.* The surging demand for compute-intensive workloads, especially from gen AI, robotics, and immersive environments, is creating new demands on global infrastructure. Data center power constraints, physical network vulnerabilities, and rising compute demands have exposed cracks in global infrastructure. But the challenge isn't just technical: Supply chain delays, labor shortages, and regulatory friction around grid access and permitting are slowing deployments. As a result, scaling now means solving not only for technical architecture and efficient design but also for the messy, real-world challenges in talent, policy, and execution.

- *Regional and national competition.* Global competition over critical technologies has intensified. Countries and corporations have doubled down on sovereign infrastructure, localized chip fabrication, and funding technology initiatives such as quantum labs. This push for self-sufficiency isn't just about security; it's about reducing exposure to geopolitical risk and owning the next wave of value creation. The result is a new era of tech-driven competition where nations have a stake in critical industries.

- *Scale and specialization are growing simultaneously.* Growth on these vectors is enabled by innovation in cloud services and advanced connectivity. On one hand, we see rapid growth in general-purpose model training infrastructure in vast, power-hungry data centers, while on the other, we observe accelerating innovation "at the edge," with lower-power technology embedded in phones, cars, home controls, and industrial devices. This is creating ecosystems that deliver massive large language models with staggering parameter counts, as well as a growing range of domain-specific AI tools that can run almost anywhere. Leaders will balance centralized scale with localized control: Think modular microgrids for clean energy or bespoke robotics for niche manufacturing.

- *Responsible innovation imperatives.* As technologies become more powerful and more personal, trust is increasingly the gatekeeper to adoption. Companies face growing pressure to demonstrate transparency, fairness, and accountability, whether in AI models, gene editing pipelines, or immersive platforms. Ethics are no longer just the right thing to do but rather strategic levers in deployment that can accelerate—or stall—scaling, investment, and long-term impact.

The following illustrations show how different frontier technologies can work together to provide innovative solutions in the future:

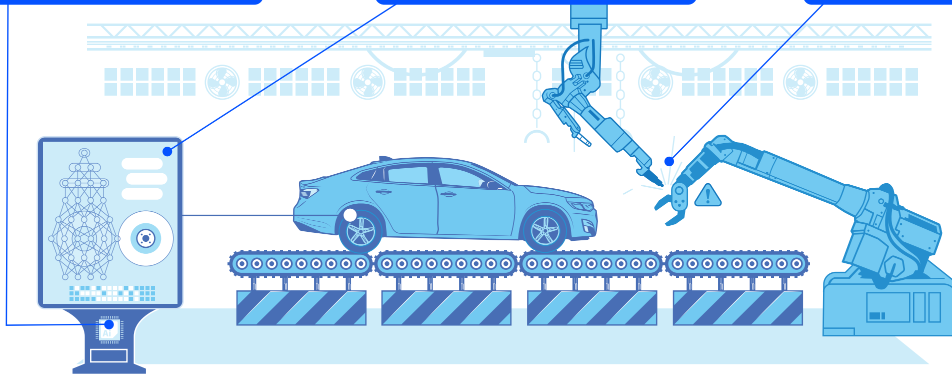
Three examples illustrate the combinatorial power of technology trends.

Factory machine repair

Artificial intelligence
AI model utilizes advanced pattern recognition to diagnose issues

Agentic AI
AI agents autonomously create repair plans, oversee quality checks, and order parts for repairs

Robotics
Robotic arms autonomously perform mechanical repairs

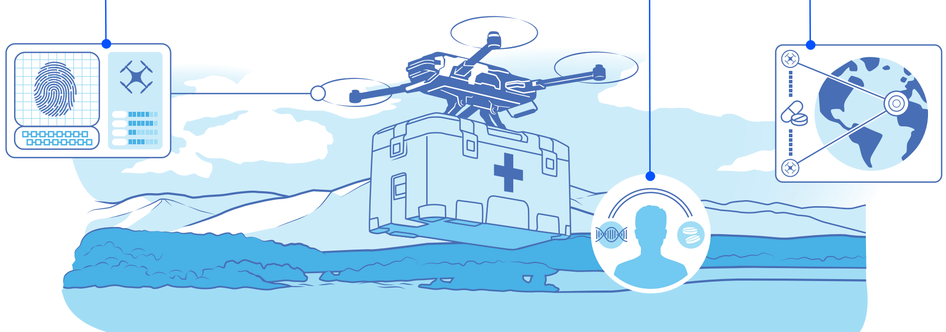


Personalized medicine delivery

Digital trust
Biometric blockchain technology establishes an immutable chain of custody for each required medication

Bioengineering
Doctors create personalized treatments (eg, turning a tumor biopsy into targeted antibodies that directly attack and eliminate cancer cells)

Future of mobility
Autonomous drones deliver critical medications to the most remote or underserved areas

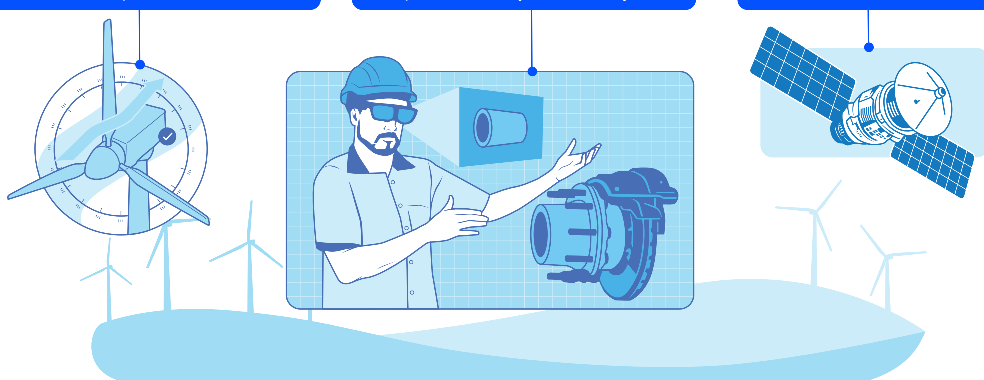


Wind farm maintenance crew

Energy and sustainability
Wind farms need to maintain peak efficiency year-round, maximizing clean-energy output while minimizing downtime and operational costs

Immersive reality
Technicians use augmented reality goggles that provide visual guidance to help them maintain and repair complex turbine systems safely

Advanced connectivity
Low-Earth-orbit satellites provide technicians with access to real-time data and cloud-based diagnostic tools from remote locations



Illustrations: T.M. Detwiler

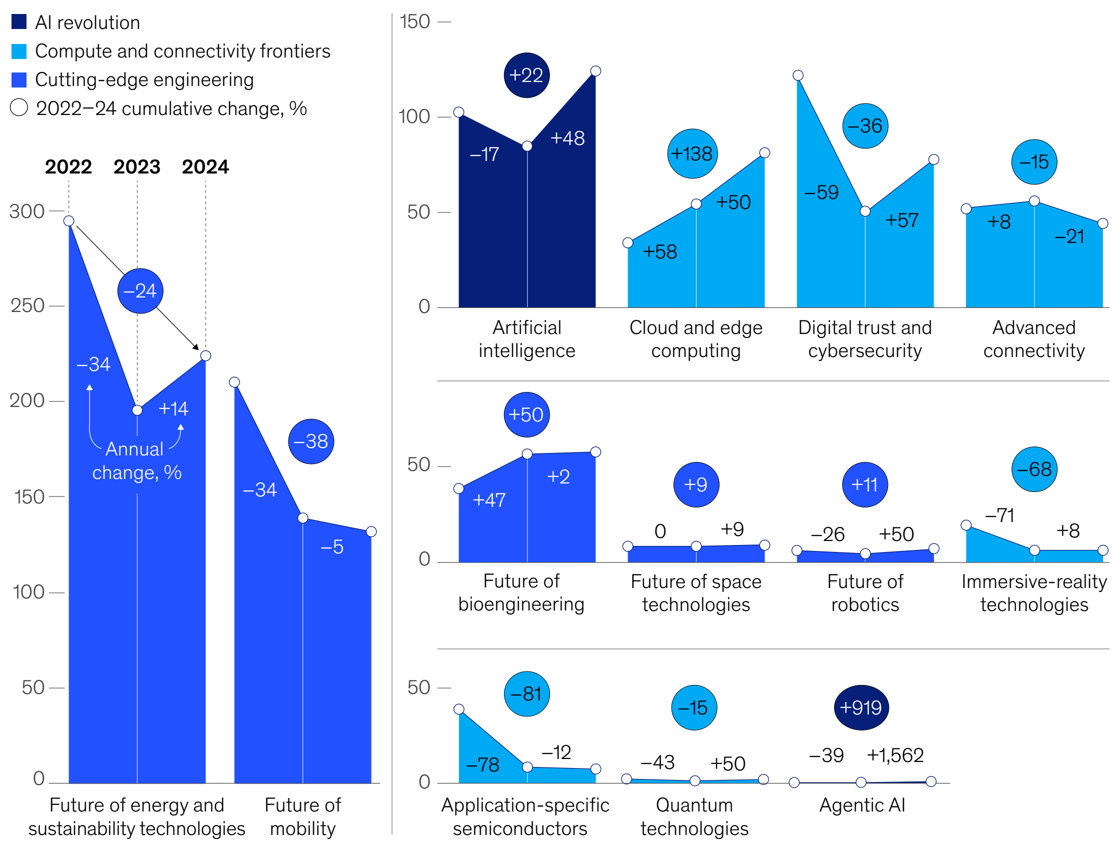
After a year in which the macroeconomic environment and broader market weakness provoked significant declines in equity financing for technology across several of our trends, the investment climate for frontier technologies stabilized and, in many cases, rebounded in 2024. Levels of equity investment in trends such as cloud and edge computing, bioengineering, and space technologies increased despite the broader market dip in 2023, while investments in other trends, such as AI and robotics, dipped only to recover to higher levels in 2024 than they achieved two years prior. The two trends with the highest levels of equity investment, the future of energy and sustainability technologies and the future of mobility, declined overall in 2023, but the former bounced back in 2024 (Exhibit 1).

Our baker's dozen of technology trends shaping 2025 underscores the vast potential of emerging technologies and the need for strategic alignment in an AI-powered future.

Exhibit 1

Equity investments increased in ten of 13 technology trends in 2024.

Trend investments, 2022–24, $ billion



Note: Data includes private-market and public-market capital raises across venture capital and corporate and strategic M&A (including joint ventures), private equity investments (including buyouts and private investment in public equity), and public investments (including IPOs). Excludes corporate capital and operational expenditures.
Source: PitchBook; McKinsey analysis

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For executives, success will hinge on identifying high-impact domains in which they can apply these trends, investing in the necessary talent and infrastructure, and addressing external factors like regulatory shifts and ecosystem readiness. By fostering collaboration, bridging ecosystem gaps, and maintaining a long-term vision, leaders can accelerate adoption and position their organizations to drive the next wave of technological transformation. Those who act with focus and agility will not only unlock new value but also shape the future of their industries and the future of today's emerging frontier technologies.

The 13 tech trends

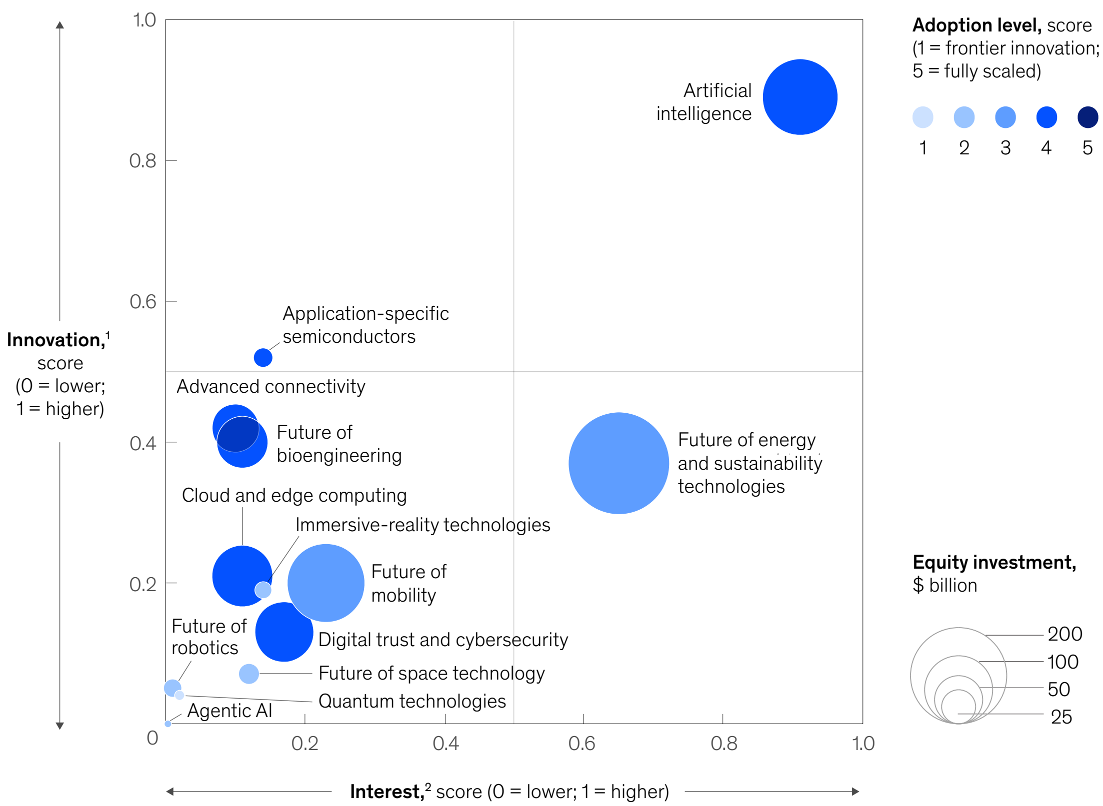
This report lays out considerations for all 13 technology trends. For easier consideration of related trends, we grouped them into three broader categories: the AI revolution, compute and connectivity frontiers, and cutting-edge engineering. Of course, there's significant power and potential in looking across these groupings when considering trend combinations.

To describe the state of each trend, we developed scores for innovation (based on patents and research publications) and interest (based on news and web searches). We also estimated the level of equity investments in relevant technologies and rated their level of adoption by organizations (Exhibit 2).

Exhibit 2

Each trend is scored based on its level of innovation, interest, equity investment, and adoption.

Innovation, interest, investment, and adoption, by technology trend, 2024



Note: Innovation and interest scores for the 13 trends are relative to one another. All 13 trends exhibit high levels of innovation and interest compared with other topics and are also attracting significant investment.
[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.

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Research methodology

To assess the development of each of the 13 technology trends highlighted in this report, we collected data on six tangible measures of activity: search engine queries, news articles, patents, research publications, equity investment, and talent demand. For each measure or vector, we used a defined set of data sources to find occurrences of keywords associated with each of the trends, screened those occurrences for valid mentions of activity, and indexed the resulting numbers of mentions on a 0–1 scoring scale 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
to companies linked with the trend. Data sources for the scores include the following:

— *Patents.* Data on patent filings are sourced from Google Patents, which highlights data on the number of patents granted.

— *Research.* Data on research publications are sourced from The Lens.

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

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

— *Equity investment.* Data on private-market and public-market capital raises across venture capital and corporate and strategic M&A, including joint ventures; private equity investments, including buyouts and private investment in public equity; and public investments, including IPOs, are sourced from PitchBook. Investment data excludes corporate capital and operational expenditures.

— *Talent demand.* The number of job postings is sourced from McKinsey's proprietary Organizational Data Platform, which stores licensed, de-identified data on publicly available professional profiles and job postings. Data are drawn primarily from English-speaking countries.

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

— An overarching artificial intelligence category replaces these four trends: applied AI, generative AI, industrializing machine learning, and next-generation software development.

— The agentic AI and application-specific semiconductors trends have been added since last year's publication.

— Two separate trends from last year, electrification and renewables and climate technologies beyond electrification, have been combined into a single trend: future of energy and sustainability technologies.

The data sources and keywords have been updated. For equity investment insights into the future of space technologies and quantum technologies, we built on research from McKinsey's Aerospace & Defense Practice and the Quantum Technology Monitor.

Insights gathered from McKinsey expert interviews were utilized to assign enterprise-wide adoption scores (on a 1–5 scale) for each trend, defined as follows:

— *1—Frontier innovation.* This technology is still nascent, and few organizations are investing in or applying it. It is largely unproven in a business context.

— *2—Experimentation.* Organizations are testing the functionality and viability of the technology with small-scale prototypes, typically without a focus on a near-term ROI. Few companies are scaling or have fully scaled the technology.

— *3—Piloting.* Organizations are deploying the technology in the first few business use cases, via pilot projects or limited implementation, to test its feasibility and effectiveness.

— *4—Scaling in progress.* Organizations are scaling the deployment and adoption of the technology across the enterprise.

— *5—Fully scaled.* Organizations have fully deployed and integrated the technology across the enterprise. It has become the standard and is being used at a large scale as companies have recognized the value and benefits of the technology.

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AI revolution

01

Agentic AI

Agentic AI is an artificial intelligence system capable of independently planning and executing complex, multistep tasks. Built on foundation models, these agents can autonomously perform actions, communicate with one another, and adapt to new information. Significant advancements have emerged, from general agent platforms to specialized agents designed for deep research.

The trend—and why it matters

Agentic AI has quickly gone from a fringe concept to one of the most talked-about shifts in enterprise technology. It is gaining traction as organizations explore new ways to automate workflows and delegate tasks to "virtual coworkers," rather than just converse with chatbots. What sets agentic AI apart is its ability to act in the world, often using digital tools, instead of simply providing outputs. These systems are built on top of AI foundation models and can autonomously plan and execute multistep tasks.

Imagine a customer service AI agent that can answer questions about products, process orders, and manage returns by connecting to a company's logistics systems. Several companies have released deep-research agents that design their own workflows to research topics on the web and produce reports. More and more companies are using software programming agents, applying their multistep reasoning to write, deploy, and test code, given a description written in English or another natural language.

The benefits that AI agents deliver over other previous systems include the following capabilities:

— *Serving a long tail of unpredictable tasks.* To create software that could act autonomously, developers previously had to painstakingly program step-by-step, rule-based systems. Many such applications had a long tail of exceptions to their rules, which a human had to address. By contrast, large language models (LLMs) are good at responding correctly to inputs they have never before encountered, enabling an LLM-based agent to handle a long tail of tasks not easily codified into preset rules.

— *Using digital tools designed for a person.* Previously, sending or receiving data required custom code that would connect each new digital system. However, AI agents can use the same tools that a person would, such as a web browser, to "read" websites using their LLMs and fill out forms.

— *Receiving instructions in natural language.* Because LLMs can process natural language, AI agents can be managed like virtual coworkers, including giving them instructions and coaching them on how to do their jobs better, using the same kind of language you would use to interact with a human coworker.

— *Generating work plans that can be understood and modified.* AI agents based on LLMs generate work plans and, depending on their design, can communicate among themselves. Because these agents use language that humans can read, they can describe what they're doing and be guided via feedback on their work plan.

The potential of agentic AI has persuaded many industries to explore enlisting agentic virtual coworkers for a variety of functions and roles.

THE AI REVOLUTION

Agentic AI

Scoring the trend

Although interest in agentic AI (as measured by news and searches) was relatively low in 2024, it is growing faster than in any other tech trend. Agentic AI patents are also increasing quickly off a small base, reflecting rapid development and increasing investment in this emerging field.

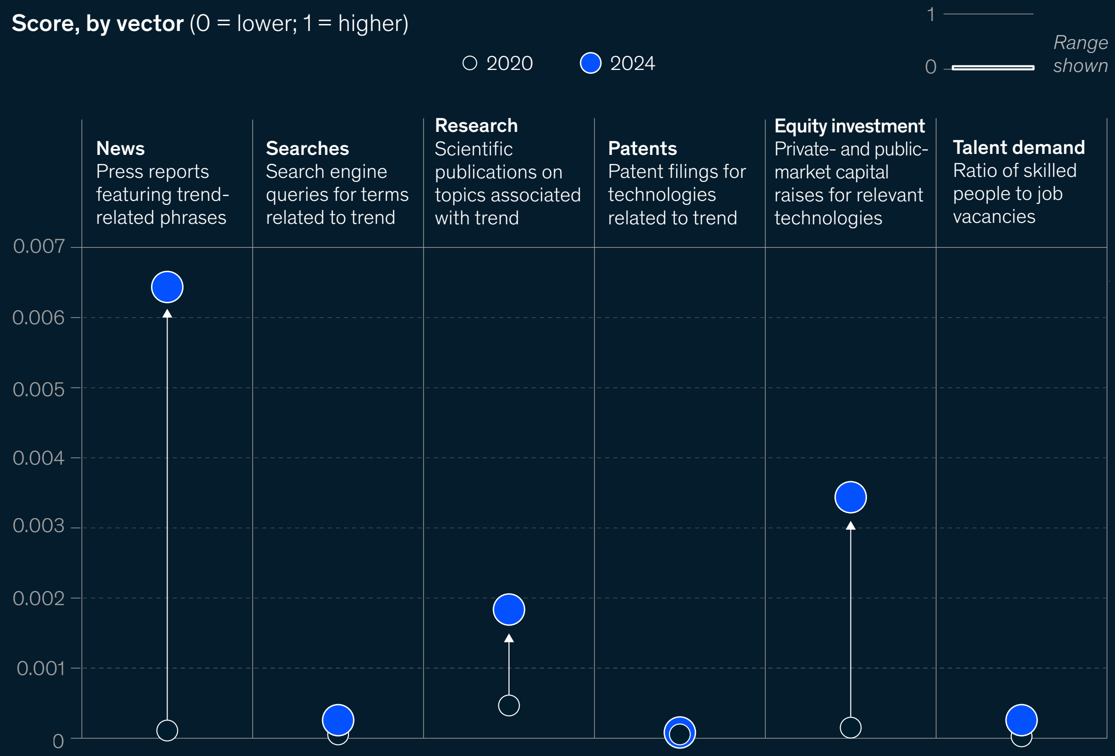
Equity investment, 2024

$1.1 billion

Job postings, 2023–24, % difference

+985%

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



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

The development of AI agents capable of autonomous decision-making and interagent communication presents exciting possibilities. However, the rapid progress of agentic AI underscores a critical need for robust governance frameworks to address trust, liability, and ethical concerns. The latest developments in agentic AI include the following:

— *Developers are building AI-powered, general-purpose agent platforms.* Some companies are adding agentic capabilities to their existing AI offerings, while others are building on these capabilities to create targeted, task-specific applications.[1] These additional capabilities enable the development of agents that can interact with users through natural language and perform many different tasks. Progress is most rapid in fields that have more robust data sets for training and evaluation, such as software coding and mathematics.

— *Increasingly long chains of effective multistep reasoning reflect meaningful progress in agentic AI.* Over the past year, new techniques

[1] *Google Blog*, “Gemini 2.0 is now available to everyone,” blog entry by Koray Kavukcuoglu, February 5, 2025; “Introducing Operator,” OpenAI, January 23, 2025; “Introducing computer use, a new Claude 3.5 Sonnet, and Claude 3.5 Haiku,” Anthropic, October 22, 2024.

have improved AI's ability to tackle complex, novel tasks by breaking them into smaller steps. Rather than relying solely on scaling foundation models, developers are now deploying multiagent workflows in which a "manager" agent builds a work plan and delegates tasks to specialized subagents. While there is more to do to assure trust and security, this shift allows for more accurate, context-aware outputs, a major step forward in how AI systems reason and operate.[2]

— *There is a new focus on agentic AI for specific business solutions.* AI agents are increasingly being developed to address specific, high-value business problems. More specialized and tuned to their specific tasks, these agents reduce the need for users to craft complex prompts. Early attention has focused on the use of agentic AI for software development, where capabilities have been advancing rapidly. In addition, there is significant interest in AI applications that can deliver measurable improvements in core business metrics, particularly sales optimization and customer support automation. As this trend evolves, enterprises will need to balance the use of specialized agents in workflows with the potential for more general agents to execute a variety of tasks.

— *Momentum behind deep-research knowledge agents is growing.* Multiple providers are advancing tools that can autonomously conduct multistep explorations for relevant content, execute searches, evaluate hundreds of sources, and synthesize information into comprehensive reports. These agents reflect a broader shift toward using AI not just for retrieval but also for reasoning enabled by faster knowledge generation that can be scaled.[3]

— *AI agents can "talk" to one another.* Recent advances in AI include models that can communicate with one another and create their own languages.[4] Neural networks can now learn tasks and describe them to other AI systems. Processing this AI-to-AI communication costs less than processing AI-to-human interaction. These developments in AI-to-AI communication have implications for robotics, complex problem-solving, and other fields, though they also raise concerns about transparency and control.[5]

— *Rising concerns about trust, governance, and liability are influencing the development and deployment of agentic AI.* As AI agents take on more autonomous roles that include executing financial transactions and interacting across digital platforms, businesses are increasingly grappling with accountability and legal frameworks. Recent high-profile pilot deployments have brought these risks into sharper focus, especially as AI systems act independently across jurisdictions. Designing robust guardrails and providing the right operational context for agents will be essential to ensure reliability and accountability.

'AI agents wont just automate tasks, they will reshape how work gets done. Organizations that learn to build teams that bring people and agent coworkers together will unlock new levels of speed, scale, and innovation.'

— Lareina Yee, senior partner and McKinsey Global Institute director, Bay Area

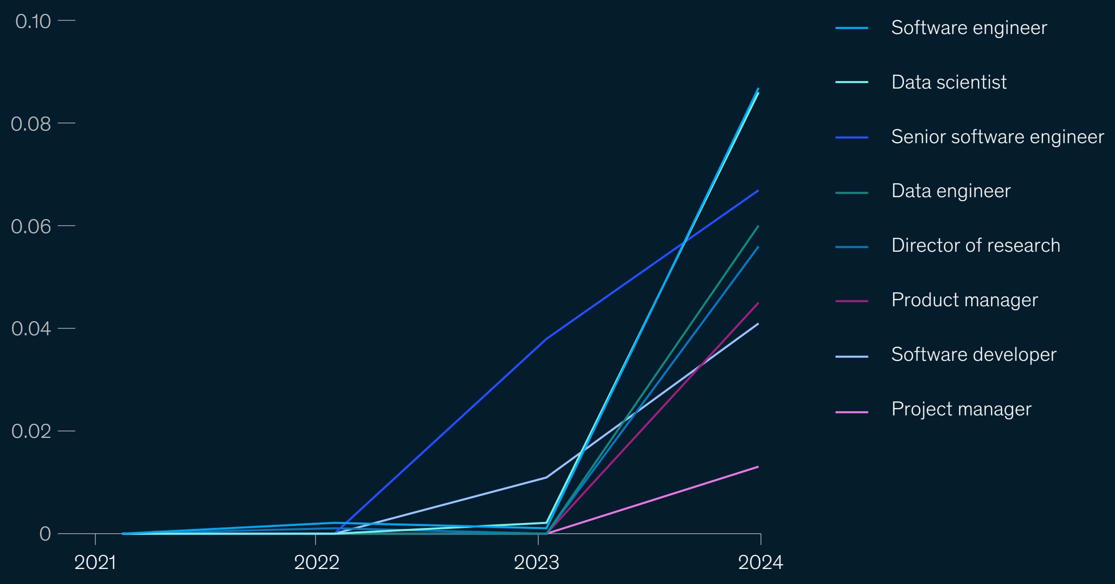
[2] "Why agents are the next frontier of generative AI," McKinsey, July 24, 2024.
[3] *Google Blog*, "Try Deep Research and our new experimental model in Gemini, your AI assistant," blog entry by Dave Citron, December 11, 2024; "Introducing Perplexity Deep Research," Perplexity, February 14, 2025; "Introducing deep research," OpenAI, February 2, 2025.
[4] Two artificial intelligences talk to each other," ScienceDaily, March 18, 2024.
[5] "AI models work faster together when they speak their own language," *New Scientist*, November 15, 2024.

Agentic AI

Demand

The volume of job postings related to agentic AI remains small, yet it has grown significantly since 2021, particularly for roles such as software engineers, data scientists, and data engineers. This growth suggests an increasing interest and investment in developing AI systems capable of autonomous decision-making and action.

Job postings, by title, 2021–24, thousands

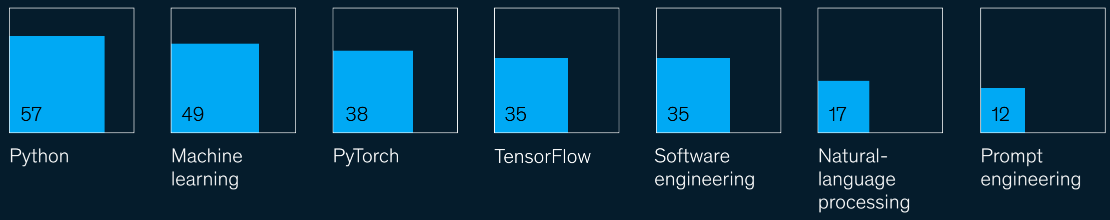


Skills availability

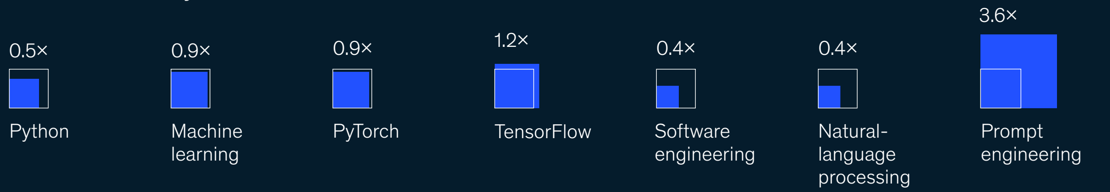
Agentic AI development relies on a blend of technical skills, such as Python programming, machine learning, and software engineering, as well as emerging areas like prompt engineering and natural-language processing. While demand for talent is high, the picture is mixed. Some skills, such as using TensorFlow, are more readily available, relative to demand, while others, such as expertise in Python, are in shorter supply versus demand.

Beyond availability alone, agentic AI is reshaping the nature of work itself, shifting responsibilities from deterministic coding tasks to higher-order activities like task planning, tool orchestration, and contextual decision-making. This evolution is changing how roles are defined, what skills are valued, and how organizations structure technical teams.

Talent required, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Adoption score: 2—Experimentation.
Organizations are testing the functionality and viability of agentic AI with small-scale prototypes, typically without a focus on a near-term ROI. Few companies are scaling or have fully scaled the technology.

Despite significant interest and investment in agentic AI, the technology remains largely untested in real-world business contexts. Many companies are actively testing the functionalities of AI agents through small-scale prototypes, but full-scale adoption remains limited. Given rapid advances in the technology, agentic AI is worth watching closely, as deployment and impact could accelerate quickly.

In real life

Leading AI companies are developing advances that facilitate the implementation of agentic AI in real-world scenarios.

Real-world examples involving AI-powered, general-purpose agent platforms include the following:

— *OpenAI Operator, launched in January 2025, is an AI agent that can autonomously perform various web-based tasks, such as booking flights, making reservations, and ordering groceries.* Operator can navigate websites, fill out forms, and handle complex interactions.[6]

— *Manus AI, launched in March 2025, is a general-purpose agent platform.* It autonomously handles tasks like research, writing, and task management, acting as a flexible digital teammate.[7]

— *On June 17, 2025, Google released Gemini 2.5 Flash for the Gemini API in both Google AI Studio and Vertex AI.* Gemini 2.5 Flash enables developers to build production applications with browser automation features (for example, handling visiting websites, clicking buttons, typing queries, and extracting data based on a natural-language prompt), supporting emerging use cases in agentic workflows.[8]

The following is a real-world example involving multistep reasoning:

— *McKinsey's QuantumBlack Labs implemented agentic workflows to automate credit memo drafting for a bank. Initial results showed that the productivity of credit analysts increased by as much as 60 percent.* An LLM that acted as a manager of multiagent systems created work plans and assigned tasks to specialized subagents for data analysis, verification, and output creation.[9]

Real-world examples of agentic AI built for specific business solutions include the following:

— *Darktrace uses autonomous AI agents to detect and respond to complex cyberthreats in real time.* Darktrace's AI agents continuously monitor enterprise network traffic, identify anomalies, and decide the best course of action to mitigate potential damage.[10] This approach is modeled on the human immune system, enabling immediate responses to previously unseen cyberattacks without human intervention. By automating routine surveillance and threat detection tasks, these agentic AI systems allow human security teams to focus on strategic challenges and critical interventions.

— *Salesforce's Agentforce platform enables organizations to deploy autonomous AI agents across various business functions, enhancing efficiency and scalability.* These agents can autonomously handle tasks such as resolving support tickets, scheduling meetings, sending follow-up emails, and qualifying leads.[11]

— *Cursor, developed by Anysphere, is one of the tools revolutionizing the software development industry by automating coding tasks through natural-language processing.* The platform allows developers to generate code by simply describing the desired functionality in plain language, significantly accelerating the software development process.[12]

6 "Introducing Operator," OpenAI, January 23, 2025.
7 Sajid Khan, "Introducing Manus: The general AI agent that's redefining intelligence," Medium, March 11, 2025.
8 *Google Blog*, "We're expanding our Gemini 2.5 family of models," blog entry by Tulsee Doshi, June 17, 2025.
9 "Delivering tangible business impact from generative AI," Medium, February 27, 2025.
10 Sophie Rice, "Darktrace's AI transforms global cybersecurity landscape," *Cyber Magazine*, April 22, 2025.
11 "Salesforce launches Agentforce 2dx with new capabilities to embed proactive agentic AI into any workflow, create multimodal experiences, and extend digital labor throughout the enterprise," Salesforce press release, March 5, 2025.
12 Anna Tong and Krystal Hu, "AI startups revolutionize coding industry, leading to sky-high valuations," Reuters, June 3, 2025.

‘Agentic AI moves AI from a passive tool to an active collaborator with enterprise workflows. As these systems gain autonomy and decision-making capabilities, it is also critical to invest more in figuring out how to work with AI when it’s seen as a colleague versus a tool. At the same time, we will need strong governance, transparency, and ethical guardrails to ensure that these agents operate with accountability and build lasting trust.’

— Delphine Nain Zurkiya, senior partner, Boston

Real-world examples involving agent-to-agent communications include the following:

— *Anthropic introduced the Model Context Protocol (MCP) as an open-standard, open-source framework to standardize the way AI models such as LLMs integrate and share data with external tools, systems, and data sources.* Google, Microsoft, Open AI, and many others, have announced they would adopt MCP.

— *Google introduced the Agent2Agent (A2A) protocol, an open standard to facilitate secure collaboration between AI agents across vendors.* Supported by more than 50 partners, A2A enables use cases such as candidate sourcing and supply chain coordination, complementing efforts like MCP to unlock scalable, multiagent ecosystems.[13]

Underlying technologies

The technologies that power agentic AI include the following:

— *Machine learning (ML).* These models make predictions after being trained with data rather than following programmed rules.

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

— *Application layer.* Typically, this is the interface that the end user interacts with—for example, chat.

— *Integration/tooling layer.* Sitting between an application layer and a foundation model, this layer integrates with other systems to retrieve information, filter responses, save inputs and outputs, distribute work, and enable new features. Examples include

[13] *Google Blog*, “Announcing the Agent2Agent Protocol (A2A),” blog entry by Rao Surapaneni et al., April 9, 2025.

the large-language programming framework LangChain and vector databases such as Pinecone and Weaviate.

- *Foundation models.* These are deep learning models trained on vast quantities of unstructured, unlabeled data that can be used for a wide range of tasks out of the box or adapted to specific tasks through fine-tuning.
- *Reasoning models.* These are foundation models that have been trained specifically to execute multistep reasoning tasks, such as solving problems involving logic and making inferences beyond pattern recognition.
- *Observability tools.* These are tools (for example, LangSmith) that enable observability (to gain insights into the behavior, performance, and decision-making processes). They monitor and analyze AI models throughout their life cycle to ensure reliability, transparency, and accountability.
- *Programming frameworks.* Such frameworks are comprehensive software tool kits designed to facilitate the development and implementation of AI applications such as Autogen and CrewAI.

Key uncertainties

The major uncertainties affecting agentic AI include the following:

- Agentic AI failure modes, such as making erroneous decisions or taking unintended actions, can raise operational risks. Additional risks are associated with the quality of data used to train these agents, drift in decision-making models, adversarial attacks, and the ongoing need for human oversight to manage increasingly autonomous systems.
- The degree to which agents will be able to reach autonomy remains uncertain and is a subject of ongoing research and debate in the AI field.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with agentic AI:

- What are the workforce implications of agentic AI at scale—which will include a combination of human and digital labor?
- What trust and safety tooling and techniques will be needed to mitigate risks as companies adopt agentic AI?
- Is agentic AI more likely to elevate expert talent by automating routine tasks or to displace large segments of the workforce whose roles are built on structure and repetition?
- To what extent should agentic AI be allowed to operate independently? How do we strike a good balance between AI autonomy and human oversight?
- How can companies get ahead of their competitors and capture the value at scale, either in revenues or cost benefits, associated with agentic AI?

02

Artificial intelligence

Artificial intelligence refers to computer systems designed to perform tasks that typically require human intelligence. These systems leverage algorithms, data, and computational power to recognize patterns, make decisions, and learn from experiences.

The trend—and why it matters

Artificial intelligence is no longer just a technological curiosity. Today, it drives tangible change across industries and daily life. From powering natural conversations and automating complex analyses to controlling physical systems such as robots and drones, AI's influence is broad and deep. The most effective solutions often blend multiple forms of AI: generative models for language, analytical engines for data-driven insights, and increasingly, systems capable of autonomous decision-making and taking action that are called agentic AI (covered in the previous section of the report). This convergence is quietly reshaping how businesses operate and individuals interact with technology.

Seventy-eight percent of organizations surveyed in McKinsey's *The state of AI* report are using AI in at least one business function, and 92 percent of executives are planning to invest more over the next three years, as highlighted in our *Superagency in the workplace* report on AI.[1] That said, it's still an early trend, as only 1 percent of leaders say their companies are fully mature in their AI deployments.[2] Rapid advances in AI's underlying capabilities over the past year have made the long-term potential of AI even more promising for businesses. The cost of deploying powerful models is dropping sharply, and a new generation of smaller, domain-specific models is giving more organizations and a wider range of devices access to AI than ever before.

Multimodal AI, which can process and generate text, images, video, and audio, has opened new creative and scientific frontiers, enhancing the quality and versatility of AI-powered outputs. As a result, enterprises and consumers now find it easier to integrate AI into workflows and daily routines. The impact on workflows is especially visible in software development. The rise of natural-language-based tools has democratized programming so that both professionals and amateurs can build and prototype software faster than ever. Yet this acceleration also brings new challenges, such as managing technical debt and ensuring code quality as the pace of development quickens.

Generative AI usage, which became commercially available widely less than three years ago, has grown extremely quickly: Most of the companies that report using AI also state that they are regularly using gen AI. However, as mentioned above, organizations have a long way to go to achieve the full potential of gen AI. The big gap between potential and progress can be explained by the time required for organizations to adapt, develop complementary innovations, and reskill their workforces. Therefore, the true economic benefits of gen AI may become visible only after substantial organizational and structural changes have taken place.

As we look to the year ahead, several pivotal questions emerge: Will lower model inference costs and the explosion of small, specialized models continue to reshape access to and benefits from AI? Which enterprise strategies will unlock the most value as organizations race to move from experimentation to full-scale adoption? And, as innovation accelerates, how can leaders ensure that responsible practices—around ethics, transparency, and governance—keep pace with AI's rapid integration into business and society?

1 "The state of AI: How organizations are rewiring to capture value," McKinsey, March 12, 2025; "Superagency in the workplace: Empowering people to unlock AI's full potential," McKinsey, January 28, 2025.
2 "Superagency in the workplace: Empowering people to unlock AI's full potential," McKinsey, January 28, 2025.

THE AI REVOLUTION

Artificial intelligence

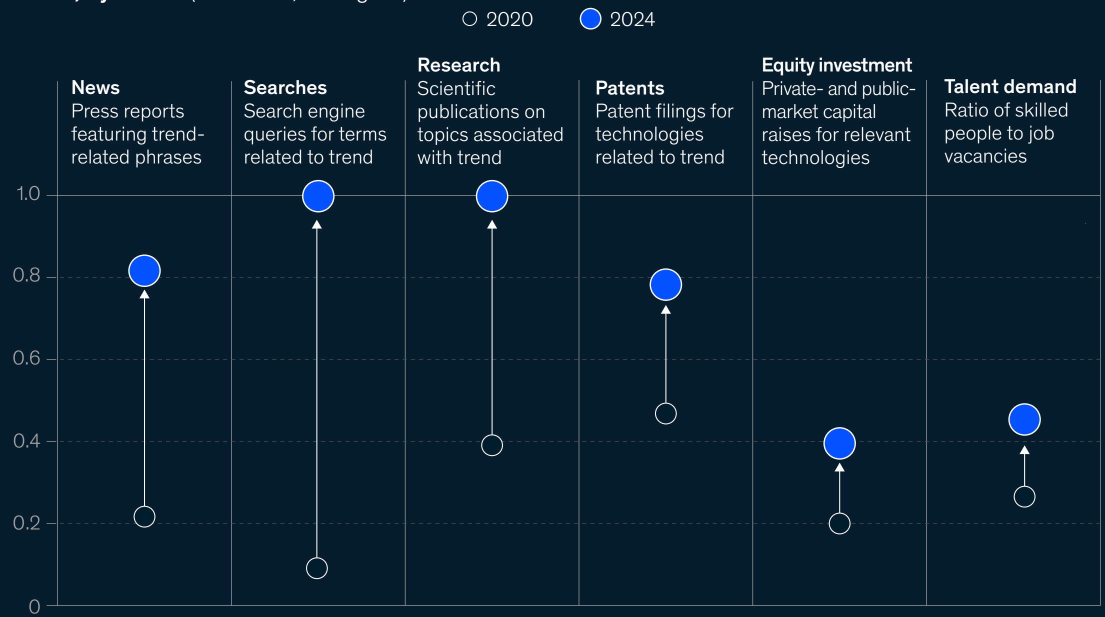
Scoring the trend

Artificial intelligence experienced a surge in innovation and interest from 2023 to 2024, as the rollout of gen AI fueled interest in all AI. AI led technology trends in patent activity, Google searches, and research publications, reflecting its rapid adoption across industries and disciplines. In the first quarter of 2025, AI companies raised $52 billion, including the SoftBank-led $40 billion investment in OpenAI, which marked the largest venture capital (VC) funding deal ever recorded.[1]

Equity investment, 2024
$124.3 billion

Job postings, 2023–24, % difference
+35%

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



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

[1]Swagath Bandhakavi, "AI companies secure at least $52bn in global funding during Q1 2025," *Tech Monitor*, April 17, 2025; "New funding to build towards AGI," OpenAI, March 31, 2025; Hayden Field and Kate Rooney, "OpenAI closes $40 billion funding round, largest private tech deal on record," CNBC, April 1, 2025.

Latest developments

AI innovation in 2025 is accelerating around enhancing model capabilities, efficiency, and real-world applications, driven by competition among tech giants and start-ups, while the field increasingly grapples with responsible deployment, regulation, and scaling commercialization.

Recent developments involving AI include increased competition and decreasing inference costs, small-model explosion, advancements in multimodal AI and multistep reasoning capabilities, accelerating software development, concerns around responsible AI, and growing global investment:

— *A proliferation of foundation models has increased competition and driven down costs.* Many competitors offered free access and reduced pricing for high-quality, text-based outputs, and the emergence of start-ups further fueled innovation. The number of high-quality open-source models has also increased.

— *The AI landscape witnessed a "small-model explosion," as distillation and quantization techniques enabled the creation of highly capable, domain-specific AI models derived from larger "parent" models.* These smaller models deliver high-quality outputs while requiring much less computing power, dramatically reducing costs and energy

‘The development of AI technology has continued to race ahead, and almost 80 percent of the companies in our global State of AI survey say that they are using AI. But capturing value at scale from AI is a journey. Only 1 percent of companies in a complementary survey reported that their use of AI is fully mature. There is still a lot of headroom for transforming companies and industries.’

— Michael Chui, senior fellow, Bay Area

consumption. Previously, enterprises often used larger models, many of which could handle more than a trillion parameters, but many now recognize that smaller models, handling ten billion and fewer parameters, are comparably effective. As a result, AI is now being integrated into a vast array of devices and applications, from smartphones and household appliances to trucks and industrial equipment.

— *Companies are redoubling their efforts to develop multimodal gen AI models to integrate and process multiple types of data input and generate outputs, such as text, images, video, and audio.* These multimodal models enhance natural-language interactions for more effective prompting and improved outputs. Multimodal outputs are also improving, encompassing video and higher-complexity scientific outputs, such as identifying subtle correlations between protein folding and drug efficacy. Gartner projects that by 2027, 40 percent of gen AI solutions will be multimodal, up from just 1 percent in 2023.[3]

— *AI is getting better at complex, multistep reasoning, a significant shift in its capabilities.* Recent advances enable foundation models to strategically plan, adapt to variability, and generalize knowledge across tasks, increasing its efficiency and reliability. Optimized training algorithms, deep-research tools, and other techniques demonstrate how AI can reason more quickly and apply insights to new challenges,[4] including software engineering.

— *The industry is moving from principles to action on responsible AI.* As gen AI adoption accelerates, concerns persist over plagiarism, accountability, data poisoning, bias, and fairness. The use of copyrighted material to train gen AI models has ignited debates on intellectual property rights and fair use. Concerns about a lack of transparency in how outputs—especially nonmathematical outputs—are determined have increased interest in “explainable AI,” which can articulate its reasoning. To address these challenges, organizations are implementing AI governance platforms and seeking third-party trust and risk evaluations.

— *Global investment is expanding, but its distribution varies across regions.* Sovereign AI, which has the potential to foster local innovation, economic growth, and national interests, has gained significant traction globally. France, Italy, Spain, and the United Kingdom are among the nations developing domestic AI infrastructure by fostering an ecosystem of technology firms and cloud and telecommunication providers.[5] In Vietnam, Nvidia is collaborating with the government on a new AI research center, while Japan, Singapore, and Thailand are

[3] “Gartner predicts 40% of generative AI solutions will be multimodal by 2027,” Gartner, September 9, 2024.
[4] Daya Guo et al., *DeepSeek-R1: Incentivizing reasoning capability in LLMs via reinforcement learning*, DeepSeek, January 22, 2025.
[5] “Europe builds AI infrastructure with Nvidia to fuel region’s next industrial transformation,” Nvidia press release, June 11, 2025.

encouraging the development of localized AI models tailored to national priorities, such as healthcare and natural disaster management.[6] In the Middle East, countries including the United Arab Emirates are rapidly positioning themselves through large-scale infrastructure projects and cross-border partnerships, such as Emirates NBD Bank's recent collaboration with BlackRock.[7] By contrast, regions such as Africa lag in adoption due to a lack of digitization, high costs, and other challenges.[8]

— *VC investment in AI has surged dramatically, driven largely by gen AI start-ups.* This influx of capital is spurring innovation across the entire AI stack, from hardware pioneers such as SambaNova Systems developing advanced chips to application-focused companies such as Writer creating tailored solutions for various industries. Corporate AI investment has reached an unprecedented scale, with tech giants and leading AI companies collectively directing hundreds of billions of dollars annually toward infrastructure, models, and deployments. Google parent Alphabet, Amazon, Meta, and Microsoft are each projected to spend $70 billion to more than $100 billion on AI-related capital expenditures in 2025, driven by data center expansions and custom silicon development.[9] This massive spend, far exceeding early cloud investments, underscores AI's strategic importance and fuels rapid innovation.

'The pace of AI innovation is accelerating, with breakthroughs in generative and autonomous systems rapidly expanding what's possible across industries. Today, the true differentiator is not just technical capability; it is the ability to rewire operating models, talent, and governance, embedding AI deeply into workflows to deliver measurable business impact. Organizations that move decisively from experimentation to scaled adoption, while building robust guardrails for trust and accountability, will be best positioned to capture AI's transformative potential.'

— Alex Singla, senior partner and coleader of QuantumBlack, AI by McKinsey, Chicago

6 *Nvidia Blog*, "Thailand and Vietnam embrace sovereign AI to drive economic growth," blog entry by Isha Salian, December 6, 2024; *Nvidia Blog*, "Nvidia to help elevate Japan's sovereign AI efforts through generative AI infrastructure build-out," blog entry by Masataka Osaki, May 14, 2024; *Macquarie Data Centres Blog*, "Sovereign AI," Macquarie Technology Group, September 16. 2024.
7 "AI spending in the Middle East, Türkiye, and Africa set to soar as region commits to an AI-fueled digital future," IDC, January 21, 2025; "Dubai's Emirates NBD partners with BlackRock to offer private markets access," Reuters, March 26, 2025.
8 Tuhu Nugraha, "Why is AI adoption slower in the Global South, and how can it leap forward?," *Modern Diplomacy*, March 4, 2025.
9 Samantha Subin, "Tech megacaps plan to spend more than $300 billion in 2025 as AI race intensifies," CNBC, February 8, 2025; Jaspreet Singh and Aditya Soni, "Meta's Zuckerberg pledges hundreds of billions for AI data centers in superintelligence push," Reuters, July 15, 2025.

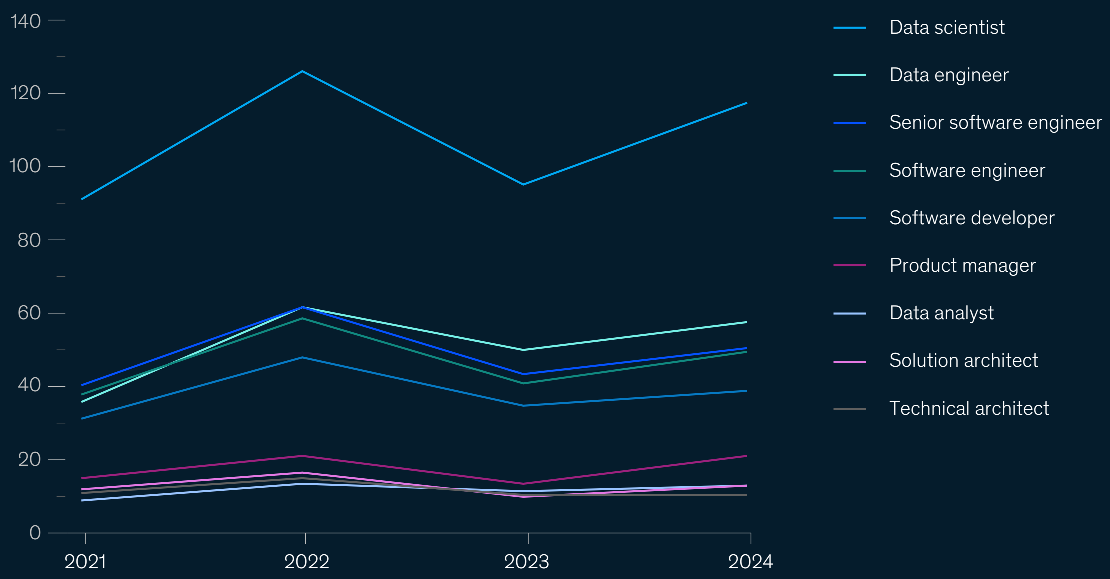
Artificial intelligence

Demand

AI talent demand continues to evolve as organizations transition from early experimentation to broader deployment. Although 2023 saw a sizable pullback, 2024 brought renewed hiring—particularly for data scientists and engineers—as companies seek to embed AI more deeply into core workflows. Demand for software roles has stabilized, while growth in product and solution-focused positions suggests an increasing emphasis on driving business integration and user impact.

While 46 percent of leaders cite skill gaps in their workforces as a major barrier to AI adoption, and more than 20 percent of employees surveyed report minimal training, addressing today's upskilling needs is only one part of the equation. As AI agents become more integrated into enterprise workflows, the talent landscape will continue to evolve, shifting toward capabilities that support human–AI collaboration. Over time, this symbiotic relationship between workers and AI will become less exceptional and more foundational, gradually reshaping how teams operate, how decisions are made, and how value is created within organizations.[1]

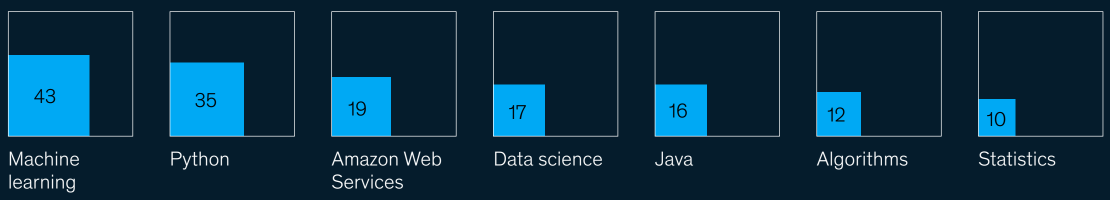
Job postings, by title, 2021–24, thousands



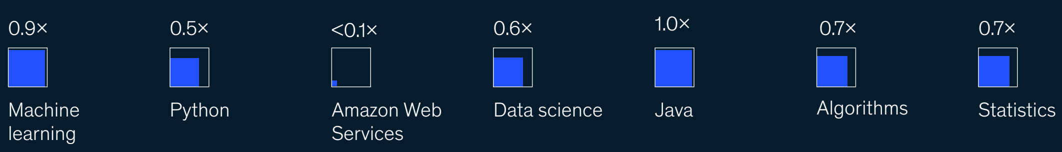
Skills availability

The AI talent pipeline is under pressure. Core skills such as machine learning, Python, and data science are in high demand, though supply still lags for the latter two. Cloud infrastructure expertise is especially scarce, particularly with platforms such as Amazon Web Services. Even as some programming and math-related capabilities are more readily available, gaps in foundational AI skills could slow momentum unless addressed through focused upskilling and development.

Talent required, % share of postings requiring skill



Talent availability, ratio of talent to demand



[1] "The state of AI: How organizations are rewiring to capture value," McKinsey, March 12, 2025; "Superagency in the workplace: Empowering people to unlock AI's full potential," McKinsey, January 28, 2025.

Adoption developments across the globe

Adoption score: 4—Scaling in progress. Organizations are scaling the deployment and adoption of AI across their enterprises.

The value proposition of AI solutions is now widely established, as evidenced by the many people who use gen AI in their day-to-day lives. As a result, the integration of gen AI capabilities is increasingly viewed as a requirement for enterprises to remain competitive. Deployment is hindered by ongoing challenges related to data privacy, output quality, and ethical considerations, prompting organizations to adopt AI governance platforms and seek third-party evaluations.

In real life

Increased competition among AI providers is driving down costs:

— *A wide range of industry players, such as Anthropic, Google, and OpenAI, and new entrants, such as DeepSeek, have significantly reduced prices for their gen AI services.* Across a set of benchmarks and performance thresholds, Epoch AI found inference costs are declining between nine times and 900 times a year, with a median of 50 times annually.[10] Lower prices from proprietary model providers, combined with ongoing innovation among open-source alternatives, increase availability for developers and businesses.[11]

Real-world examples of the rise of smaller and more efficient AI models include the following:

— *Inflection 3.0, a smaller large language model (LLM), reportedly achieved performance comparable to frontier models but using fewer computational resources, which could give businesses cost-efficient AI assistants.* Fine-tuned versions of this model can power customer service chatbots that handle specific inquiries with conversational and empathetic responses.[12] Anthropic, Google, and OpenAI also offer smaller models, labeled “haiku,” “flash,” and “mini,” respectively.

— *Meta’s Llama 3 8B quantized models enable real-time language conversion directly on users’ phones.* Meta says these smaller models, used in translation apps, have improved accuracy while operating offline, reducing cloud costs and latency.[13]

Real-world examples of companies redoubling efforts to develop multimodal gen AI models include the following:

— *OpenAI’s latest flagship model, GPT-4.1, released in April 2025, builds on GPT-4o’s strong multimodal foundation with improved handling of extended multimodal inputs.* Optimized for efficiency and high-volume front-end coding, this upgraded tool also reliably follows instructions and features solid image generation and real-time, natural voice interactions.

— *Claude 4, Anthropic’s latest AI model family, was released in May 2025.* With its advanced abilities to integrate text and data, this multimodal tool performs particularly well at coding and document analysis. Its multistep reasoning skills, deep contextual understanding, and hybrid thinking models (near instant responses versus extended thinking) make it ideal for complex problem-solving, including but not limited to high-level programming challenges.

— *Gemini 2.5, Google’s latest AI model, offers native multimodality with a one-million-token context window for enhanced reasoning and advanced coding tasks.* It uses various input sources, such as text, audio, images, video, and even code repositories.

— *Significant advances in Google DeepMind’s AlphaFold 3 can enable advances in pharmaceuticals, biotechnology, and even food.* This multimodal AI tool accelerates the process of identifying and optimizing drug candidates by accurately predicting protein structures and molecular interactions. The tool can be used to engineer proteins and enzymes.

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[10] Ben Cottier, Ben Snodin, David Owen, and Tom Adamszewski, “LLM inference prices have fallen rapidly but unequally across tasks,” Epoch AI, March 12, 2025.
[11] “Open source technology in the age of AI,” McKinsey, April 22, 2025.
[12] “Inflection AI unveils enterprise offering with new Inflection 3.0 models,” Maginative, October 7, 2024.
[13] “Introducing quantized Llama models with increased speed and a reduced memory footprint,” Meta, October 24, 2024; “Meta LLaMA 3: Use cases, benchmarks, and how to get started,” Acorn Labs, June 6, 2024.

Real-world examples of AI performing complex, multistep reasoning include the following:

— *MIT researchers have developed a more efficient algorithm, MBTL, that trains reinforcement learning models for variable and complex tasks.* MBTL selects a subset of tasks for training to maximize an algorithm's overall performance across a related collection of tasks. MBTL models how well an algorithm would perform independently on a task and how much its performance degrades when applied to other tasks (generalization performance). It does this by first choosing the task delivering the most improved performance, then selecting additional tasks for marginal improvements. MBTL is between five times and 50 times more efficient than standard approaches.[14]

— *Starting in late 2024, tech giants such as Anthropic, Google, OpenAI, and Perplexity began introducing advanced "deep research" AI tools.* These AI assistants can rapidly browse the web, analyze vast amounts of data, and produce comprehensive reports, significantly reducing research time. This potential to reshape cognitive work has implications for knowledge workers, increasing concerns about output verification and displacement.

— *The newest products from Anthropic (Claude Code), Google (Gemini Code), and OpenAI (Codex) demonstrate strong multistep reasoning skills beyond code comprehension and generation.* This allows them to handle difficult coding scenarios using logical deductions, breaking down tasks, and producing code that demonstrates a deeper understanding of a problem and the steps required to solve it. These agents can act semiautonomously, expanding their capabilities throughout a product development life cycle.

Real-world examples of the impetus for the industry to move from principles to action on responsible AI include the following:

— *Efforts are underway in the United States to enact legislation that would establish guardrails for AI, reflecting a movement within the tech industry known as "responsible AI."* For example, California's AI Transparency Act (Senate Bill 942), effective January 1, 2026, has set a precedent by requiring providers of widely adopted gen AI systems to offer free AI detection tools and include disclosures in AI-generated content.

— *On August 12, 2024, US District Judge William Orrick ruled that several AI companies were illegally storing visual artists' works in their image generation systems.* The ruling established a precedent in copyright law as it applies to AI-generated content that could influence future cases involving AI and intellectual property rights.

Real-world examples of innovations driven by VC and corporate investments in AI include the following:

— *GitLab, a comprehensive DevSecOps (development, security, and operations) AI platform, is advancing software development processes.* By integrating AI capabilities across the entire software life cycle, the platform enables developers to automate repetitive tasks and streamline workflows. For instance, when Ally Bank implemented GitLab, it increased its ability to update and deploy software applications by 55 percent and realized significant cost savings.[15]

— *Regrello, an AI-first enterprise resource planning (ERP) platform, generates complex workflow applications in minutes.* By streamlining workflows and collaboration, Regrello claims to reduce manual tasks by up to 45 percent.[16]

— *Bolt.new, developed by StackBlitz, helps users create and deploy web applications quickly using AI.* Integrated in StackBlitz's browser environment, it helps users easily install packages and configure backends, making it suitable for rapid prototyping.[17]

Underlying technologies

Multiple types of software and hardware power AI across the entire tech stack. These include the following:

— *Application layer.* Typically, this is an interface with which an end user interacts, such as chat.

[14] Adam Zewe, "MIT researchers develop an efficient way to train more reliable AI agents," *MIT News*, November 22, 2024.
[15] "Ally Financial cuts pipeline outages and eases security scanning with GitLab," GitLab, accessed March 19, 2025; *GitLab Blog*, "GitLab receives Ally Technology Partner Award for Operational Excellence," blog entry by Sandra Gittlen, June 17, 2024.
[16] "Regrello," Crunchbase, accessed March 19, 2025.
[17] "Bolt.new," Stackblitz, accessed June 4, 2025.

- *Integration or tooling layer.* Placed between an application layer and a foundation model, this layer retrieves information, filters responses, saves inputs and outputs, distributes work, and enables new features across a system.
- *Foundation models.* These deep-learning models, trained on vast quantities of unstructured, unlabeled data, can perform a wide range of tasks out of the box or can be adapted to specific tasks.
- *Physical infrastructure.* This encompasses hardware, such as data centers and AI accelerator chips, that enables computation, data storage, and networking.
- *Digital infrastructure.* This involves using the digital abstraction of physical infrastructure to support data storage, processing, and computation. Digital infrastructure includes databases (for example, SQL and NoSQL) and core tech services (for example, compute, storage, and networking).
- *Explainable AI.* This AI model increases the transparency and interpretability of the inputs, weightings, and reasoning underpinning the output of machine learning algorithms.
- *Machine learning (ML).* ML is the process of training models with data rather than following programming rules.
- *Computer vision.* This type of ML works with visual data, such as images, videos, and 3D signals.
- *Natural-language processing.* This is a type of ML that analyzes and generates text and speech.
- *Deep-reinforcement learning.* This type of ML is trained by artificial neural networks to use trial and error to make predictions.
- *Reasoning models.* These are foundation models trained specifically to execute multistep reasoning tasks, such as solving problems involving logic and making inferences beyond pattern recognition.

Key uncertainties

The most significant uncertainties affecting AI include the following:

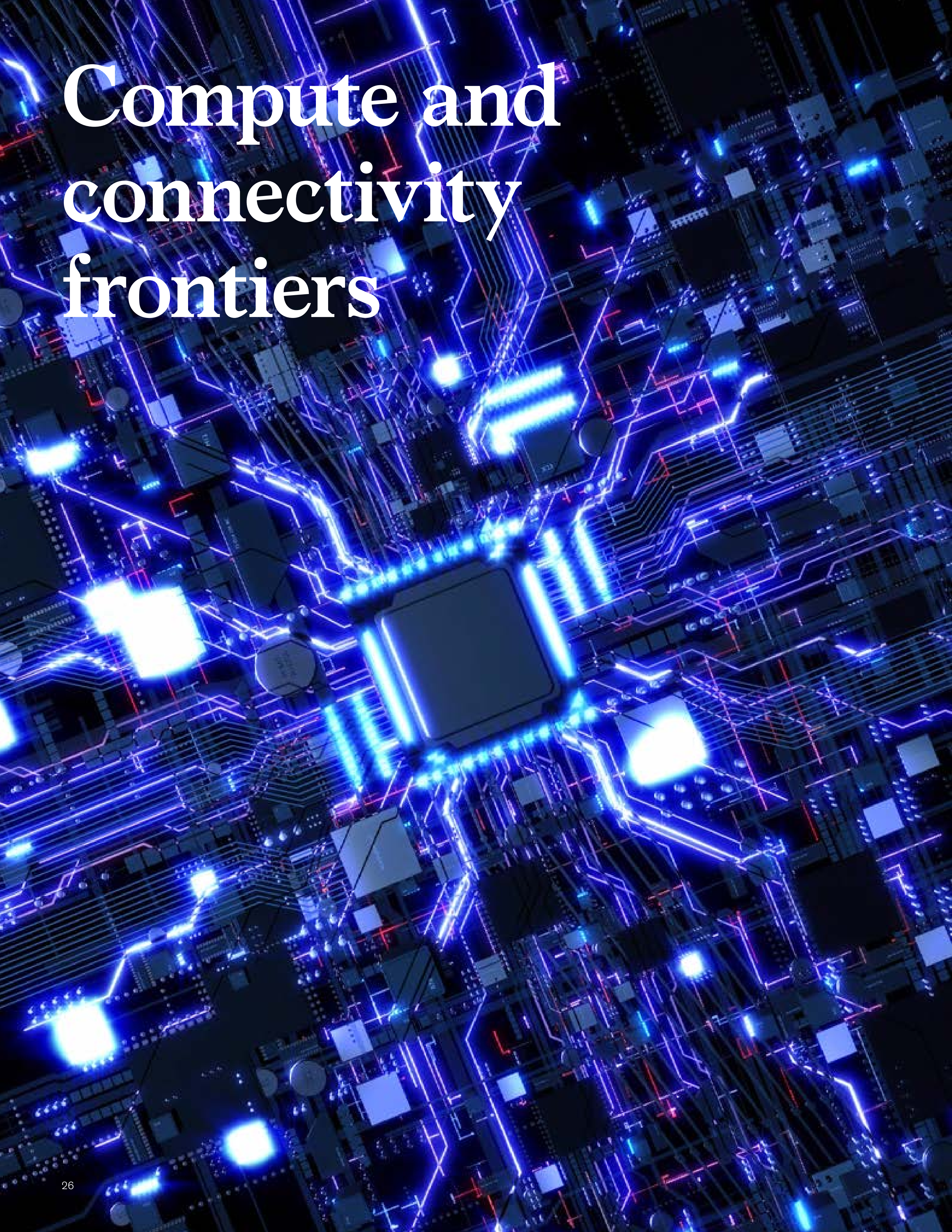
- The potential for data leakage and other vulnerabilities, including to customer and protected data, continues to raise cybersecurity and privacy concerns.
- AI continues to raise ethical concerns about data governance, justice and fairness, accountability, and explainability.
- A growing effort to devise regulations and compliance for AI could affect research on gen AI and its potential applications.
- Copyright ownership and content protection remain an open question for open-source models.
- As training models expand exponentially and require more computational resources, their environmental impact may also increase, raising sustainability issues that could also potentially hinder innovation.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with AI:

- As technological advances continue in AI models, accelerators, and throughput, what primary use cases should companies prioritize, and how should companies position themselves to drive innovation, adapt leading solutions, or build proprietary capabilities?
- How can organizations evolve their operating models, talent, and governance fast enough to scale adoption and capture the value of AI, rather than merely deploying the technology?
- How will the economics of smaller, specialized, and open-source AI models shift the balance of power away from monolithic frontier models in enterprise decision-making?
- What is the appropriate corporate response to risks posed by AI, including data privacy and security, equity, fairness, compliance, and intellectual property protections?
- How will supply bottlenecks, AI infrastructure energy needs, and diminishing high-quality training data constrain the development and deployment of AI systems?
- How can AI models and their decision-making processes become more transparent to users and regulators?

Compute and connectivity frontiers



03

Application-specific semiconductors

Application-specific semiconductors are purpose-built chips optimized to perform specialized tasks. Unlike general-purpose semiconductors, they are engineered to handle specific workloads (such as large-scale AI training and inference tasks) while optimizing performance characteristics, including offering superior speed, energy efficiency, and performance.

The trend—and why it matters

Few technologies are as critical to future business growth as semiconductors, which now shape innovation trajectories across sectors from computing to automotive. Application-specific semiconductors are chips optimized for performing specific tasks, such as graphics processing units (GPUs), application-specific integrated circuits (ASICs), and potentially, silicon-based photonics for compute and neuromorphic architectures. For their specialized workloads, these tailored semiconductors provide greater computing power and cost efficiency than general-purpose compute architectures, like CPUs, can deliver.

AI workloads have driven much of the recent innovation in application-specific semiconductors. These highly customized chips have provided the specialized processing required for AI training and inference at scale and for the immense computational demands of AI algorithms. With the corresponding exponential growth in energy demand from AI, power efficiency has also become a critical performance factor, as has thermal management. Going forward, application-specific semiconductors will likely be increasingly used across computing memory and networking. As AI continues to advance, the symbiotic relationship between AI and application-specific semiconductors will continue to drive innovations in chip design, with emerging technologies such as silicon photonics.

‘While the semiconductor industry has long relied on global interdependence, differing geopolitical priorities are accelerating a shift toward regionalization and supply chain diversification. But this will take time, given the capital-intensive nature of the sector and concentrated points of supply. Navigating the evolving landscape will be essential to maintaining resilience, continuity, and long-term innovation across the sector.’

— Bill Wiseman, senior partner, Seattle

CUTTING-EDGE ENGINEERING

Application-specific semiconductors

Scoring the trend

Innovation bloomed across all technology trends from 2023 to 2024, reflected in a broad increase in patent activity, and the semiconductor industry leads the way with the highest number filed overall. In fact, patenting in semiconductors is accelerating rapidly, setting the pace for technological progress across sectors. This reflects the growing importance of semiconductors in addressing specialized needs across industries, including automotive, AI, and telecommunications. The trend also saw strong growth from 2023 to 2024 across Google searches, with searches growing by more than 38 percent, while mentions of the technology in publications increased by 68 percent, and equity investments were up by 97 percent. The total value of equity investments that we estimated could be considered conservative. While we have observed some leading players expanding their ecosystems through M&A in other layers of the tech stack (such as software, server systems, and cloud services), we focused on investments in companies that design or build application-specific-semiconductor components.

Equity investment, 2024

$7.5 billion

Job postings, 2023–24, % difference

+22%

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

Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

With the accelerating demand for application-specific semiconductors tailored for artificial intelligence, the industry landscape is being reshaped by disruptive entrants, the rapid expansion of global data centers, and the complex geopolitical dynamics influencing supply chains and industry strategies.

Recent developments involving application-specific semiconductors include the following:

— *AI's rapid advance has spurred companies to develop chips explicitly optimized for training and inference.* Training chips, such as GPUs, are computational powerhouses designed to use parallel processing on vast data sets. ASIC-based AI accelerators, which are used for inference, efficiently deploy trained AI models, enhancing their operational efficiency and real-time execution. These semiconductors also aim to improve energy efficiency, increase scalability, and reduce costs.

— *New AI hardware vendors are challenging established leaders.* Seeking to reduce reliance on third-party suppliers like Nvidia, tech companies, including Amazon, Google, Meta, and Microsoft, have invested heavily in custom ASICs and other proprietary semiconductor technologies. This enables these companies to optimize performance for specific workloads

‘The rise of gen AI isn’t just a software revolution; it’s a tectonic shift in hardware demand. As models scale exponentially, breakthroughs in accelerated compute, custom silicon, high-bandwidth interconnects, and power-optimized system design aren’t optional. They are the new foundation of innovation.’

— Diana Tang, associate partner, Bay Area

(such as training and inference), lower operational costs, enhance energy efficiency, and maintain tighter integration with their proprietary software stacks. Simultaneously, we are seeing the emergence of start-ups that specialize in specific workload chip design, such as Cerebras, Groq, and SambaNova Systems. CPU vendors are also developing competing GPU offerings, although Nvidia remains the market leader.[1]

— *Demand for higher computing capacity is driving data center expansions and increased manufacturing supply.* The evolution of AI and exponentially growing demand for computing power have increased the need for more innovation across all areas of technology. McKinsey analysis suggests that, in a midrange scenario, demand for AI-ready data center capacity will rise at an average rate of 33 percent a year between 2023 and 2030.[2] This means that about 70 percent of total demand for data center capacity will be for data centers equipped to host workloads from AI systems by 2030. While data center capacity is increasing, it needs adequate semiconductor supplies to scale effectively. Manufacturing capacity expansion requires significant planning and investment, but technology changes quickly, raising concerns about how demand will be met in a couple of years and how sustainable that demand will be, given that keeping these data centers open and empty isn’t viable.

— *Geopolitical tensions affect global supply chains.* In 2024, the global semiconductor market hit an all-time high, as annual sales surpassed $600 billion for the first time, and that growth is expected to continue this year. These chips, which are crucial for computing advancements, are largely manufactured in Asia. Some leading technology companies import chips, while others, such as Intel, maintain in-house manufacturing. Supply chain disruptions due to trade restrictions, tariffs, and market fragmentation could impact global semiconductor supplies. This is especially true as regions like the United States and Europe increase their focus on technology sovereignty. AI development and large-scale computing operations rely on global semiconductor supply for raw materials and fabrication.[3]

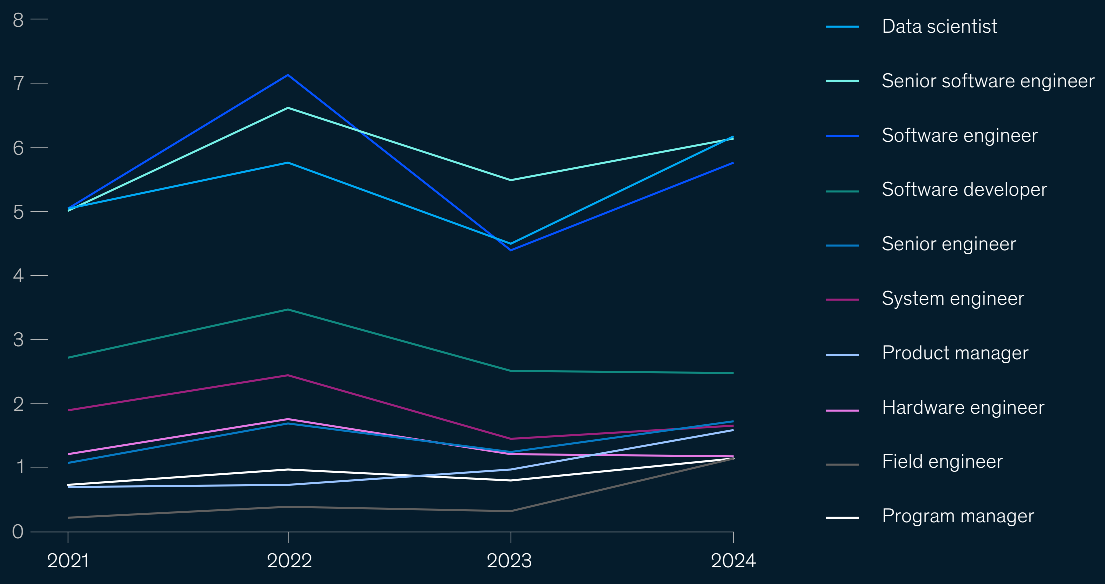
1 “NVIDIA’s meteoric rise: Can the AI chip giant sustain its dominance?,” EOS Intelligence, October 17, 2024.
2 “AI power: Expanding data center capacity to meet growing demand,” McKinsey, October 29, 2024.
3 “Global semiconductor sales increase 19.1% in 2024; double-digit growth projected in 2025,” Semiconductor Industry Association, March 3, 2025.

Application-specific semiconductors

Demand

Job postings for application-specific semiconductors saw substantial growth in 2024, particularly for roles like data scientists and software engineers. This surge highlights the increasing strategic importance of software in the semiconductor ecosystem for AI and other specialized applications, driving demand for professionals who can innovate in this rapidly evolving field.

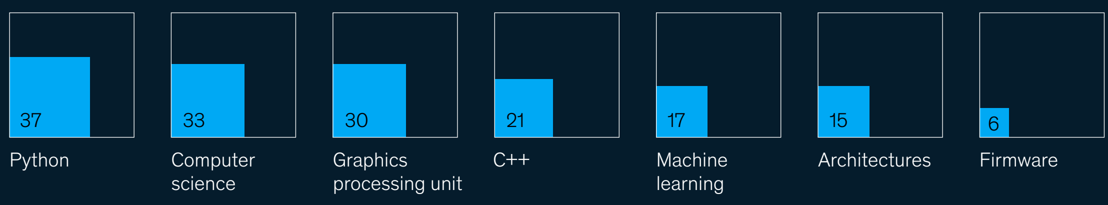
Job postings, by title, 2021–24, thousands



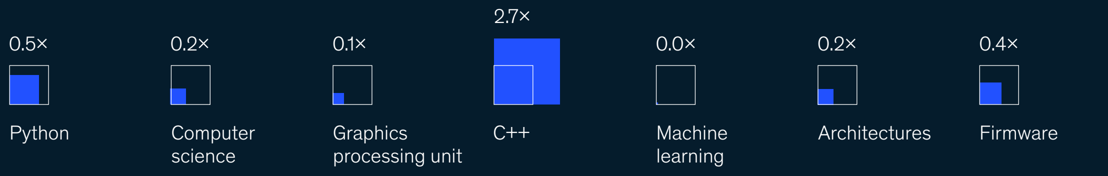
Skills availability

Application-specific semiconductors face a talent crunch, particularly for critical skills such as machine learning and GPU expertise. The talent availability for these skills is significantly lower than the demand, creating a competitive hiring environment where companies struggle to find professionals capable of developing these specialized semiconductor solutions.

Talent required, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Adoption score: 4—Scaling in progress. Organizations are scaling the deployment and adoption of the technology across the enterprise.

Adoption of application-specific semiconductors aligns closely with the scaled adoption of artificial intelligence, and these technologies rely heavily on the hardware of these semiconductors. Top players have been able to establish leading positions in the ecosystem, while other earlier-stage companies and start-ups are still experimenting and piloting, focusing on specific needs (for example, large-scale AI training and inference optimization).

In real life

Real-world examples involving the development of chips specifically optimized for AI training and inference include the following:

— *Nvidia is transitioning its complex chip-on-wafer-on-substrate (CoWoS) packaging technology (offered by Taiwan Semiconductor Manufacturing [TSMC]), moving from CoWoS-S (with Silicon Interposer) to CoWoS-L (with Local Interconnect) technology for new GPUs.* This shift to CoWoS-L enables the integration of multiple chips, including GPU cores and high-bandwidth memory (HBM), on a single substrate, resulting in better performance and efficiency.[4] It also enables the stacking of up to 12 HBM3 devices at a lower cost and uses local silicon interconnect bridges and an organic interposer that functions as a redistribution layer to increase interconnect densities, as well as provides a bandwidth of ten terabytes per second between compute chiplets. These features are particularly crucial for Nvidia's Blackwell architecture as the company increases the efficiency and power of its AI chip designs.[5]

— *Large cloud service providers are developing their own AI chips, competing with established players, like Nvidia, in the AI semiconductor market.* Trainium3 semiconductors from Amazon Web Services (AWS), which assist in AI training, have improved performance and energy efficiency, and in 2024, AWS improved the Inf2 chip used in AI model inference.[6] Google continued to develop new versions of tensor processing units (TPUs) optimized for machine learning tasks. Its seventh-generation TPU (Ironwood) offers five times more compute capacity and six times more HBM capacity compared with the previous generation (Trillium).[7] Microsoft rolled out Maia 100 as part of a strategy to optimize its AI infrastructure from silicon to software to systems, allowing for better integration and performance of its AI services.[8] This trend of in-house chip development among hyperscalers addresses their desires to reduce reliance on external suppliers, tailor performance for specific AI workloads, and lower costs. The move by these companies is reshaping the application-specific-semiconductor landscape by introducing more competition, diversifying supply chains, and driving innovation in AI hardware design and performance. The data center accelerator market, which includes these custom hyperscaler chips, could increase markedly in coming years.

Real-world examples reflecting the surge in demand for AI infrastructure and the expansion of data centers include the following:

— *In March 2024, Micron Technology sold out of its HBM for the rest of 2024 and had allocated most of its 2025 supply because of intense demand from AI companies.*[9] Such unprecedented demand increases the potential for bottlenecks in AI GPU production, for which HBM is a critical component.

4 Wen-Yee Lee, "Nvidia CEO says its advanced packaging technology needs are changing," Reuters, January 16, 2025.
5 Majeed Ahmad, "Nvidia, TSMC, and advanced packaging realignment in 2025," EDN, January 20, 2025.
6 AWS re:Invent 2024, Las Vegas, NV, December 2–6, 2024; Steven Dickens, "AWS launches Inf2 instances for high-performance generative AI," Futurum, April 14, 2023.
7 *Google Cloud Compute*, "Introducing Ironwood TPUs and new innovations in AI Hypercomputer," blog entry by Mark Lohmeyer and George Elissaios, April 9, 2025.
8 *Azure Infrastructure Blog*, "Inside Maia 100: Revolutionizing AI workloads with Microsoft's custom AI accelerator," blog entry by Sherry Xu and Chandru Ramakrishnan, Microsoft, August 27, 2024.
9 Satya Kumar, "Fiscal Q2 2024 earnings call prepared remarks," Micron Technology, March 20, 2024.

'We observe two main themes in the AI chip market currently: a rapid market growth and very fast-paced innovation. Both have been progressing faster than many projections have, and we expect players to push heavily on both fronts in the next years. This favors big incumbent players, and smaller players and new entrants must specialize to create value.'

— Klaus Pototzky, associate partner, Munich

— *Marvell, in a live demonstration, ran a 3D silicon photonics engine at 6.4 terabits per second and having 32 channels, each supporting 200 gigabits per second for electrical and optical interfaces.*[10] This engine integrates hundreds of components into its chips, including by putting transimpedance amplifiers and drivers on the same device. This first-of-its-kind engine is modular, enabling it to scale from 1.6 terabits to 6.4 terabits and beyond. Compared with discrete solutions, this integrated engine has a lower cost per bit and provides a more scalable option for meeting ever-increasing bandwidth demand.

The following is a real-world example of the impact of geopolitical shifts in the semiconductor supply chain:

— *TSMC is expanding manufacturing to the United States.* TSMC's total investment in the United States is anticipated to reach $165 billion, building on its current $65 billion commitment to advanced semiconductor-manufacturing operations in Phoenix.[11] The expansion includes plans for three new fabrication plants, two advanced packaging facilities, and a major R&D team center, establishing this project as the largest stand-alone foreign direct investment in US history.

Underlying technologies

The technologies related to application-specific semiconductors include the following:

— *GPUs.* These are optimized for parallel processing and image rendering.

— *Custom AI accelerators.* These are tailored for specific AI tasks like inference or training.

— *High-bandwidth memory (HBM).* HBM provides fast, high-capacity memory for data.

— *Advanced on-chip interconnects.* These wiring systems facilitate efficient data movement within the chip.

Key uncertainties

The major uncertainties affecting application-specific semiconductors include the following:

— *Geopolitical tensions.* Ongoing trade disputes and potential tariffs threaten global supply chains, leading to potential market fragmentation and nationalized tech ecosystems.

— *Labor shortages.* A global shortage of skilled semiconductor workers that could lead to a significant shortfall by 2030 is delaying production and threatening supply chain stability.

10 *Marvell Blogs*, "Silicon photonics comes of age," June 6, 2024.
11 "TSMC intends to expand its investment in the United States to US$165 billion to power the future of AI," Taiwan Semiconductor Manufacturing press release, March 4, 2025.

— *Rapid technological obsolescence.* The fast-paced demand for advanced AI chips accelerates chip obsolescence, complicating production cycles and long-term planning in the industry.

— *Supply versus demand.* Fabrication construction requires long lead times and significant capital, while long-term demand is uncertain. The industry has yet to realize sustainable end-market monetization and cost savings from gen AI.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with application-specific semiconductors:

— How may the increase in demand for AI-specific architectures reshape the semiconductor market?

— How can the semiconductor industry address AI's growing demand for HBM and high-performance computing applications amid supply chain challenges?

— What strategies will semiconductor companies employ to overcome the talent shortage and skill gap as technologies rapidly evolve?

— As energy demand in computing continues to rise, which innovations in semiconductor design and manufacturing will be most impactful in improving energy efficiency and supporting sustainability?

— How will shifting geopolitical alliances and national industrial policies reshape the global footprint for semiconductor design, manufacturing, and supply chain resilience?

04

Advanced connectivity

Advanced connectivity covers a suite of evolving technologies that enhance and expand digital communication networks. This includes wireless low-power networks, 5G and emerging 6G cellular systems, Wi-Fi 6 and 7 standards, and low-Earth-orbit (LEO) satellites.

The trend—and why it matters

Advanced-connectivity technologies continue to evolve consumer experiences. Innovation is enhancing existing technologies and turning technology concepts into reality, further enhancing the connectivity infrastructure, for example, by enabling integration with nonterrestrial networks.

As AI disrupts industries across the globe, connectivity is becoming even more important. Telecommunications companies, or telcos, have opportunities to develop new value streams, though whether they increasingly become value creators or remain value connectors remains to be seen.

COMPUTE AND CONNECTIVITY FRONTIERS

Advanced connectivity

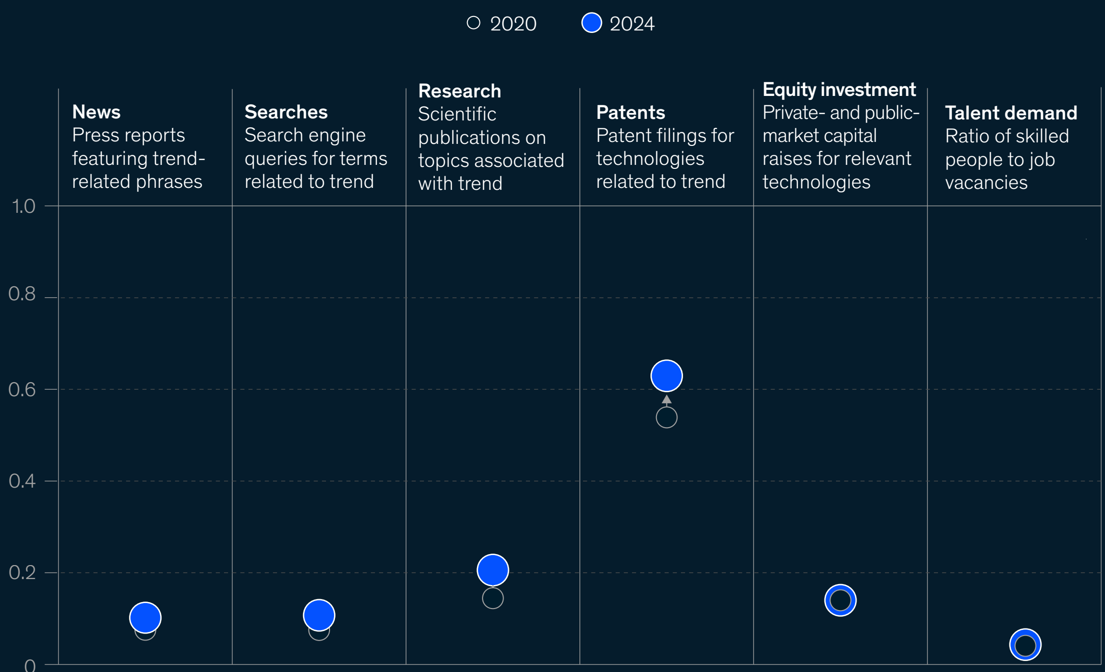
Scoring the trend

Advanced connectivity has continued to grow across interest and innovation metrics from 2023 to 2024 and is a leader among the trends for number of patents granted. Equity investments moderated in 2024 after large fiber infrastructure investments in 2022 and 2023.

Equity investment, 2024
$44.2 billion

Job postings, 2023–24, % difference
–14%

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



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

Recent developments in advanced connectivity include the following:

— *The 5G rollout has created a foundation for 6G.* In 2024, 5G-Advanced, or 5.5G, was commercialized.[1] Its integrated sensing and communications is designed to help lay the foundation for 6G networks to act as large-scale sensor systems.[2] Whereas 5G connects devices, focused on bandwidth, latency, and reliability, 6G aims to go one step further and enable sensing for data generation. Technical implementation hasn't begun, although standardization studies have sparked momentum.[3]

— *The network-slicing market is growing as 5G networks mature.* The global network-slicing market, which provides specific performance characteristics across each slice of a network, is projected to reach $1.69 billion in 2025, an increase of 49.6 percent compared with $1.13 billion in 2024.[4] Network slicing uses cutting-edge technologies, such as software-defined networking and network function virtualization, which enable more dynamic, flexible, and efficient network management. By tailoring each slice to specific requirements, network slicing can reduce waste and improve efficiency. Customers' demand for high-speed connectivity and better network solutions, which is spurring key players to collaborate and combine resources, skills, and technology, is helping to propel that growth.

— *Simultaneously, the private-wireless-network market is picking up steam.* Market size is projected to increase from $6.27 billion in 2024 to $32.86 billion by 2032, a CAGR of 23 percent.[5] Together with network slicing, private wireless delivers flexible, tailored connectivity solutions that can expand coverage beyond local facilities where private networks are deployed, tapping into public networks when needed. Key industries such as manufacturing, healthcare, transportation, and logistics are driving growth by seeking secure, reliable, and dedicated wireless communication services. However, high investment costs and deployment complexity challenge the rollout of private 5G.[6]

— *The explosion of AI data centers has increased demand for fiber.* From data centers to edge computing and smart applications, fiber optics enable AI with high-speed, reliable, and scalable infrastructure.

— *Direct-to-satellite networks and nonterrestrial networks (NTNs) have become a reality.* NTNs are wireless communication systems that operate above Earth's surface via platforms such as satellites in low-Earth orbit (LEO), medium-Earth orbit, and geostationary orbit, as well as high-altitude platforms (HAPs) and drones. NTNs enhance global communication coverage and extend coverage to remote areas, though they aren't expected to replace mobile connectivity due to the substantial up-front investment required.

— *Digital twins are being used by carriers to enable dynamic, intelligent solutions for monitoring, optimization, sustainability, and innovation.* These virtual replicas of physical assets and systems enable real-time monitoring and simulation of complex systems such as fiber networks and private-wireless setups. Integrated with AI and the Internet of Things (IoT), they can facilitate the navigation of complex modern systems and connectivity.

— *AI-RAN (artificial intelligence–radio access network) is an innovative approach to mobile network infrastructure that replaces traditional CPUs, application-specific integrated circuits, and field-programmable gate arrays with graphics processing units (GPUs).* This transformation enables a multipurpose infrastructure capable of supporting both RAN and AI workloads, creating opportunities for telcos to monetize AI workloads while optimizing network efficiency and performance. While AI-RAN requires network virtualization and fiberization, the implementation is not cost-prohibitive, especially in urban areas.

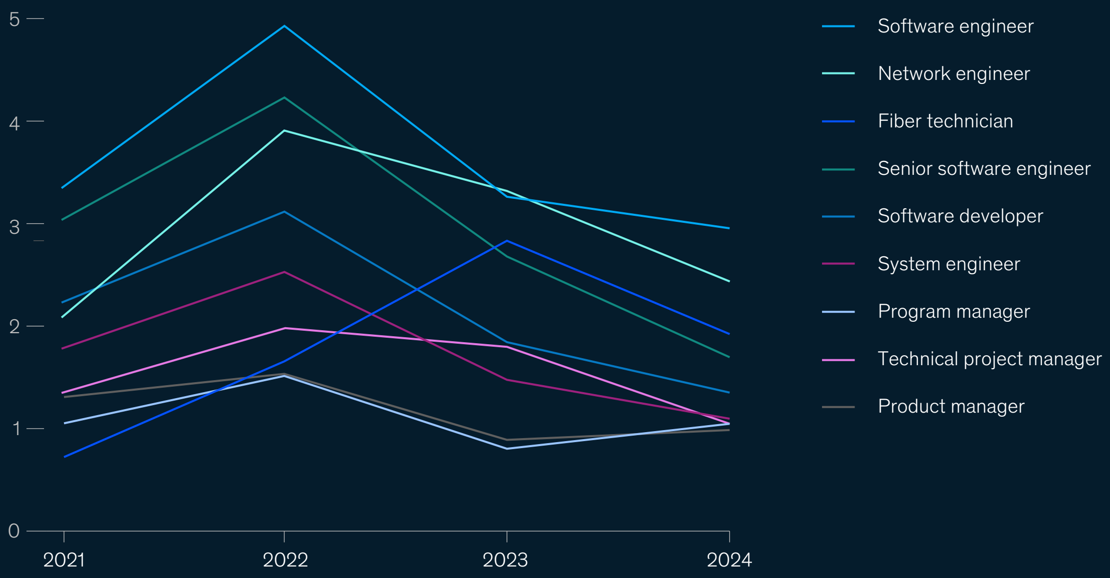
1 "5G-Advanced poised for take-off in 2024," Mobile World Live, April 9, 2024.
2 Sarah LaSelva, "6G standards to get boost from 5G Advanced in 2024," RCR Wireless News, January 12, 2024.
3 Zina Cole, Tomás Lajous, Fabian Queder, and Martin Wrulich, "Shaping the future of 6G," McKinsey, February 28, 2024.
4 "Network slicing market size, share and forecast to 2033," Straits Research, accessed May 14, 2025.
5 *Global Private Wireless Market: Industry analysis and forecast (2025-2032) trends, statistics, dynamics, segmentation by type, application*, Maximize Market Research, March 2025.
6 James Blackman, "Private 5G will not reach potential – even as spending jumps 800% to $9bn by 2028," RCR Wireless News, January, 23, 2024.

Advanced connectivity

Demand

The advanced-connectivity talent market has shifted from rapid expansion to consolidation. After a spike in 2022, job postings across engineering and project roles have declined steadily, reflecting a broader industry pivot from rollout to refinement. The initial push to scale 5G and fiber networks drove demand for network engineers and field technicians, but by 2023–24, hiring slowed as infrastructure matured.
Meanwhile, software and systems roles saw sharper contractions over the past couple of years, suggesting a reduced appetite for new platform development. The sector's focus appears to be on optimizing existing assets, improving network efficiency, and building leaner, more resilient teams to support the next wave of connectivity innovation.

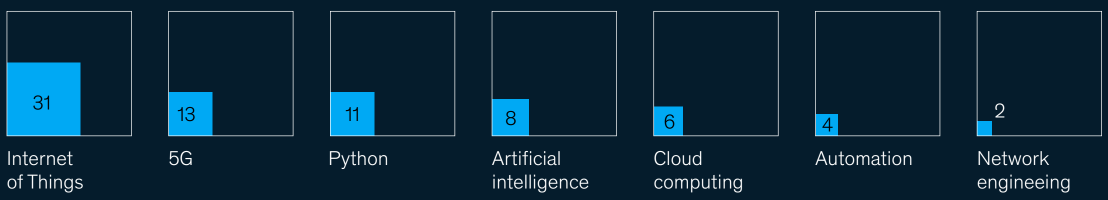
Job postings, by title, 2021–24, thousands



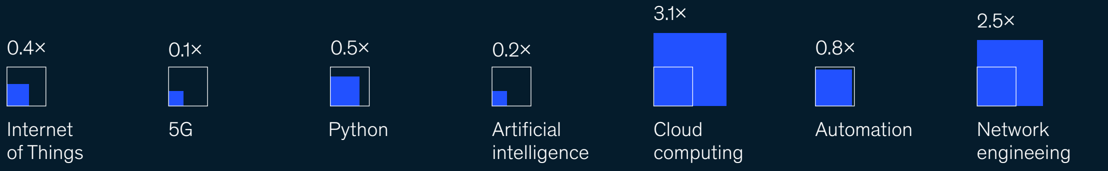
Skills availability

As advanced connectivity scales, companies are facing talent shortages in critical areas such as IoT, 5G, and AI. While roles in cloud computing and network engineering are somewhat easier to fill, gaps remain in automation and other emerging capabilities. Closing these gaps will be key to realizing the full potential of next-generation networks.

Talent required, % share of postings requiring skill



Talent availability, ratio of talent to demand



‘6G is coming from a standardization point of view and will introduce new capabilities like sensing. This will offer telcos a new monetization possibility, instead of just transporting data. With sensing, they can become data producers.’

— Martin Wrulich, senior partner, Vienna

Adoption developments across the globe

Adoption score: 4—Scaling in progress. Organizations are scaling the deployment and adoption of the technology across the enterprise.

Advanced-connectivity adoption is rapidly accelerating across the globe, with 5G technology leading the charge. As of 2025, there are 2.25 billion 5G connections globally, growing four times faster than 4G adoption at a comparable stage.[7] North America is at the forefront, with 77 percent population coverage and an expected 89 percent adoption rate by 2030, closely followed by Greater China at 88 percent.[8] More efficient and faster connectivity will be important for enhanced communication and supporting continuing innovation in emerging technologies such as autonomous vehicles, smart cities, and AI computing. Newer technologies such as AI-RAN and 6G remain in the “frontier innovation” stage of early adoption and are experimental for now.

In real life

Real-world examples of the 5G rollout, which has laid the foundation for 6G, include the following:

— *China continues to lead 5G stand-alone deployment, having achieved extensive multioperator rollouts that extended reach by 77 percent in 2024.*[9] Ten new 5G networks were launched last year in seven markets in sub-Saharan Africa, the leading region for new deployments that year.[10] Brazil expanded its 5G network to all state capitals by the end of 2024, and Telcel and AT&T Mexico deployed 5G services in major Mexican cities.[11]

— *The 3rd Generation Partnership Project (3GPP) has made strides in 6G development, establishing a timeline for 6G standardization aligned with the International Telecommunication Union (ITU) goal to launch commercial systems by 2030.*[12] 3GPP plans for its Release 21, the first to include normative work for 6G, to be finalized by June 2026.[13]

— *South Korea is rapidly moving along its 6G deployment timeline.* Its K-Network 2030 strategy aims to commercialize 6G services by 2028, two years ahead of the global timeline set by the ITU. The South Korean government is investing 625.3 billion South Korean won ($481.7 million) in research and development of core technologies such as LEO satellite communications and quantum cryptography.[14] Public–private partnerships are central building blocks to this strategy, intended to foster innovation in software-based networks and

7 “Global 5G adoption skyrockets to 2.25 billion, four times faster than 4G,” Business Wire, March 27, 2025.
8 “5G share of total mobile connections from 2023 to 2030, by region,” Statista, August 2023.
9 Luke Kehoe, “Illustrating the global state of 5G SA,” OOKLA, February 24, 2025.
10 Stephen Burton, “Operators in emerging regions continued to deploy 5G NSA in 2024, while 5G SA launches slowed worldwide,” Analysys Mason, February 25, 2025.
11 Maciej Biegajewski, “The state of 5G deployment around the world (2024),” RFBenchmark, September 19, 2024.
12 *Ericsson mobility report*, Ericsson, November 2024.
13 “3GPP’s 6G timeline officially launched,” Concept, April 25, 2024.
14 Ricky Tu, “South K-Network 2030 strategy pushes to upgrade backbone network for enhanced infrastructure, says DIGITIMES Research,” *DIGITIMES Asia*, August 25, 2023.

strengthen the supply chain needed to build high-capacity networks.[15]

Recent examples of network slicing include the following:

— *Cisco demonstrated the first-ever verification of its Cisco Network Controller transport slicing service across multivendor nodes.* This milestone simplifies deployment of network slicing by enabling interoperability and streamlining network slicing across diverse vendor platforms.[16]

— *With its stand-alone 5G network, T-Mobile has increased its reach into enterprise via network-slicing services.* T-Priority, a network slice dedicated to public safety, is built exclusively for first responders and is touted as more consistently delivering lower latency and faster 5G speeds than other providers. First responders have priority for voice and data services on T-Mobile's 5G network, receiving up to five times more bandwidth and capacity than a typical user.[17]

— *Nokia has been collaborating with UAE-based e& (etisalat and) and du, Dubai's mobile and payments business, on a trial of the world's first fixed end-to-end network-slicing solution for gaming.[18]* With du, Nokia completed the United Arab Emirates' first live transport network-slicing deployment, enabling dynamic resource allocation based on demand and traffic patterns.[19]

Recent examples of private wireless networks include the following:

— *Airbus and Ericsson expanded the aerospace manufacturer's private 5G networks across its European locations.* For example, Airbus's network covered a 3.6-square-kilometer campus in Hamburg, Germany, using 63 antennas, significantly fewer than required by traditional Wi-Fi.[20]

— *Ericsson's and Nokia's sales of private 5G networks set a record in 2024, supporting their overall enterprise sales performance.* Nokia now has 850 private-network customers globally. Revenues from Ericsson's enterprise wireless solutions unit increased 17 percent from 2023 to 2024.[21]

— *The Port of Barcelona and MasOrange deployed a private 5G network to improve port operations.* They connected over 400 CCTV cameras to enhance security and operational awareness.[22]

Additional real-life examples of advancements in advanced connectivity include the following:

— *Apple released C1, a chip that communicates directly with a device's processor to enhance network performance and prioritize data during periods of congestion.* C1 reduced Apple's reliance on external suppliers of 5G modems. Additionally, C1 is Apple's most power-efficient modem, enabling longer battery life in devices such as the iPhone 16e. The tight integration enables a modem to inform a processor about network conditions, leading to more intelligent network-switching decisions. However, its use is limited to sub-6-gigahertz 5G networks, as it prioritizes power efficiency over millimeter wave (mmWave) compatibility.[23]

— *Nvidia introduced Spectrum-X photonics switches that enable connections between millions of GPUs across sites.* Designed for AI factories, the silicon photonics in these switches deliver 3.5 times more power

[15] Juan Pedro Tomás, "Korea unveils new initiative to advance 6G cooperation," RCR Wireless News, July 22, 2024.
[16] "Multi-vendor MPLS SDN interoperability test 2024," EANTC, accessed April 1, 2025.
[17] "T-Mobile formally launches T-Priority for first responders, powered by 5G network-slicing technology," Urgent Communications, February 25, 2025.
[18] "Nokia and e& UAE showcase world's first fixed end-to-end network slicing solution for gaming applications," Nokia press release, December 19, 2024.
[19] "Nokia and du conclude successful transport network slicing trial in UAE," Nokia press release, November 26, 2024.
[20] Satyajit Sinha, "State of private 5G in 2024: Key growth trends, use cases, and forecast," IoT Analytics, September 17, 2024.
[21] James Blackman, "'Record quarter' and 'strong growth' – Nokia, Ericsson hail private 5G sales," RCR Wireless News, January 30, 2025.
[22] Juan Pedro Tomás, "MasOrange says 5G SA network at Port of Barcelona is operational," RCR Wireless News, July 10, 2024.
[23] "Apple's C1 modem is a quiet game-changer that's mostly flying under the radar," AppleInsider, March 13, 2025.

efficiency and 63 times better signal integrity than traditional methods, which is ideal for hyperscale AI infrastructure.[24]

— *SpaceX's Starlink initiated its direct-to-cell service, enabling smartphones to connect directly to satellites without the need for specialized hardware.* This service allows users to send messages and make emergency calls in remote areas lacking traditional cellular coverage.[25]

Underlying technologies

The technologies that power advanced connectivity include the following:

— *Optical fiber.* These are physical strands of glass that provide the most reliable high-throughput, low-latency connectivity.

— *Low-power wide-area networks.* These wireless networks, such as narrowband IoT, LoRa (long range), and Sigfox, are focused on providing connectivity for IoT. They cover large areas more efficiently, using less energy at the end points.

— *Wi-Fi 6 and 7.* Next-generation Wi-Fi confers higher throughput, more control over quality of service, and a cellular level of security by tapping into less-congested frequency bands.

— *5G and 6G cellular.* These next-generation cellular technologies provide high-bandwidth, low-latency connectivity services with access to higher-spectrum frequency bands capable of handling a large amount of connected end points, as well as delivering low-power connectivity suitable for IoT.

— *6G sensing.* Using high-frequency signals such as sub-terahertz and mmWave, massive antenna arrays, and AI, 6G networks can bounce signals off objects to determine their location, movement, composition, and even physiological states.

— *High-altitude platform systems.* These aerial radio stations are located at a fixed point 20 to 50 kilometers above Earth and can be deployed on lightweight aircraft to provide flexible capacity and access in remote locations.

— *Direct-to-handset satellite connectivity.* Telecom company partnerships with satellite players allow direct access from phone to satellite, expanding network coverage beyond the reach of traditional cellular towers.

— *Internet of Things.* This collective network of connected physical devices has sensors and processing capabilities to digitally monitor or control physical objects.

— *LEO satellites.* A constellation of satellites orbiting at relatively low altitudes above Earth's surface can connect remote or inaccessible locations with high-speed internet and have other use cases like satellite imaging.

Key uncertainties

The major uncertainties regarding advanced-connectivity technologies include the following:

— Reaching consensus during the 6G standardization process presents significant challenges, as differing regional priorities and technological agendas may lead some countries or regions to pursue early deployment

[24] "Nvidia announces Spectrum-X Photonics, co-packaged optics networking switches to scale AI factories to millions of GPUs," Nvidia press release, March 18, 2025.
[25] *Next Big Future*, "FCC allows SpaceX Starlink direct to cellphone power for 4G/5G speeds," blog entry by Brian Wang, March 10, 2025.

‘One of the most pronounced connectivity trends during the last year was a significant growth in data center connectivity demand driven by AI. We see hyperscalers looking to build or buy significantly more fiber than before, quite interesting mergers and acquisitions, and new entrants deploying fiber appearing in the market. Private capital interest is also rising.’

— Zina Cole, partner, New York

strategies rather than waiting for a unified global standard.[26]

— As networks expand to support AI-driven applications and massive IoT, which refers to the explosion of new connected devices like wearables and smart homes, ensuring energy efficiency is becoming a critical challenge. Developing sustainable network designs and power management techniques is essential to growth in this area, but prospects remain uncertain.[27]

Big questions about the future

Businesses and leaders should consider a few questions when proceeding with advanced-connectivity technologies:

— What opportunities does advanced connectivity, combined with other trends, offer to improve telecom industry growth and profitability?

— What needs to happen technologically and financially for network equipment players, telecom companies, enterprises, and chip manufacturers to invest in and commercialize 6G?

— How will the rise of LEO constellations and direct-to-device satellite connectivity reshape global communications infrastructure and competitive dynamics across telecom and tech?

— How will the telecom industry develop advanced encryption methods and authentication protocols to safeguard critical infrastructure, healthcare, and financial applications in 6G networks?

— How should organizations navigate geopolitical concerns about undersea cables?

[26] Zina Cole, Tomás Lajous, Fabian Queder, and Martin Wrulich, “Shaping the future of 6G,” McKinsey, February 28, 2024.
[27] Imane Cheikh, Sébastien Roy, Essaid Sabir, and Rachid Aouami, *Energy, scalability, data and security in massive IoT: Current landscape and future directions*, arXiv, May 5, 2025.

05

Cloud and edge computing

Cloud and edge computing involve distributing workloads across locations, from hyperscale remote data centers to regional hubs and local nodes. This approach optimizes performance by addressing factors such as latency, data transfer costs, data sovereignty, and data security.

The trend—and why it matters

The rapid evolution of AI is reshaping the entire cloud infrastructure landscape, from semiconductors to data center design. As enterprises increasingly deploy AI-powered workloads, power constraints and shifting supply chains have become key challenges. Surging demand for AI computing has compelled deeper collaboration among chip developers, cloud providers, and infrastructure manufacturers. Additionally, hyperscale data center capacity is projected to triple by 2030, underscoring the need for scalable and efficient resource distribution.[1]

To address these computing constraints, organizations are expanding to areas with more robust energy infrastructure and working to develop more efficient computation. While massive, centralized clusters still dominate the landscape, businesses are training and deploying AI models across multiple locations, including edge environments, to optimize performance, reduce latency, and improve resource availability. This distributed approach not only alleviates computational bottlenecks but also enhances resilience by reducing reliance on concentrated infrastructure.

‘Of all the things I didn’t expect this year, the resurgence of the sovereign-cloud debate in Europe tops the list. Yet the current geopolitical uncertainty has reignited concerns over digital autonomy, slowing down cloud adoption—especially in regulated sectors where contingency planning now includes potential workload repatriation. What once seemed like a closed chapter is now being rewritten: European technology providers and investors are sensing a renewed, and perhaps brief, opportunity to reclaim ground many had already conceded.’

— Andrea Del Miglio, senior partner, Milan

1 “The cost of compute: A $7 trillion race to scale data centers,” *McKinsey Quarterly*, April 28, 2025.

COMPUTE AND CONNECTIVITY FRONTIERS

Cloud and edge computing

Scoring the trend

Cloud and edge computing grew steadily from 2023 to 2024, with patents increasing by 4 percent. Google searches for the term grew 17 percent, while mentions in news articles grew 18 percent.

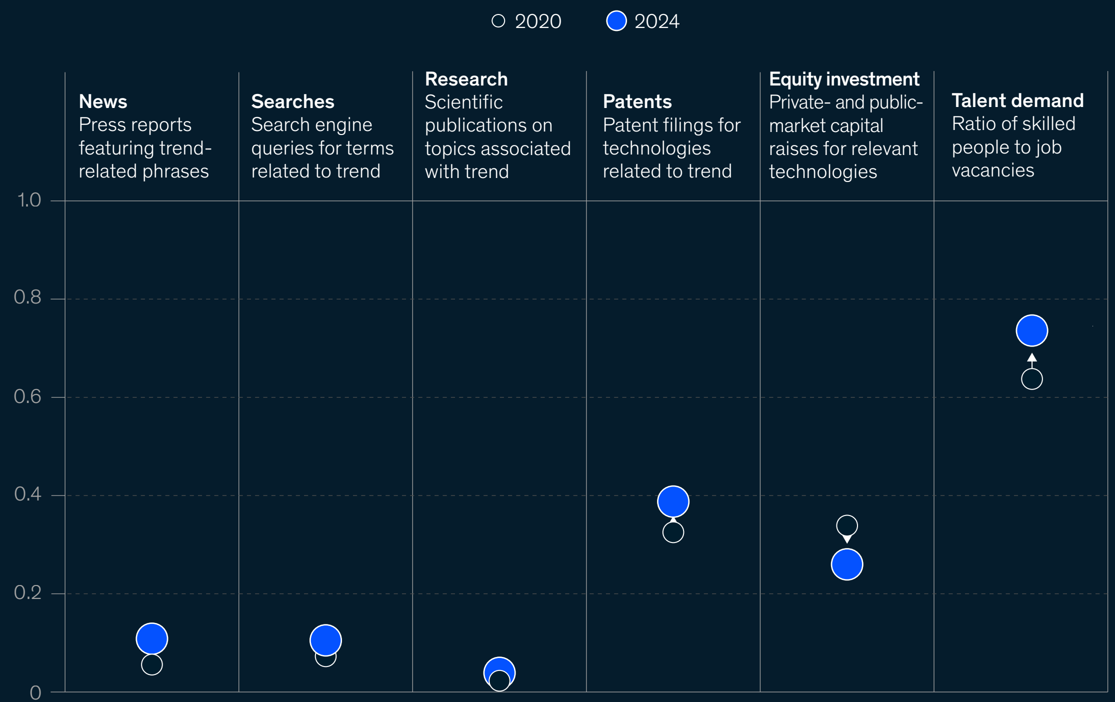
Equity investment, 2024

$80.8 billion

Job postings, 2023–24, % difference

+2%

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



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

Recent developments involving cloud and edge computing include the following:

— *The evolution of AI has disrupted all layers of the cloud stack, including semiconductors, servers, and data centers.* Across the value chain, power constraints have increased because demand for computing is so high. McKinsey analysis suggests that global demand for data center capacity could rise 19 to 22 percent annually from 2023 to 2030, more than tripling current demand and reaching 171 to 219 gigawatts a year.[2]

— *To overcome computing constraints, companies are moving to new locations, exploring creative power solutions, and distributing workloads.* As demand for AI grows exponentially, companies are relocating or expanding to areas with better infrastructure and power supply to support computing needs. Data centers are adopting sustainable power solutions; for instance, instead of relying primarily on uninterruptible-power-supply systems for backup power, data centers are utilizing batteries to shift energy consumption to off-peak hours. Companies are also optimizing cooling systems through innovations in liquid

2 "AI power: Expanding data center capacity to meet growing demand," McKinsey, October 29, 2024.

cooling and AI-enabled thermal management to enhance energy efficiency. At the same time, smaller AI models help reduce computational demands and can often run locally or on edge devices. Training and inference for larger and more complex models can also be distributed across multiple clusters to spread processing loads, reduce latency, and improve resilience by being closer to data sources or end users.

— *The cloud provider landscape continues to evolve.* Hyperscalers'[3] advances in hardware accessibility and investments from large organizations have enabled smaller players to enter the cloud market and grow rapidly. The availability of advanced computing chips, such as graphics processing units (GPUs) and specialized AI accelerators (discussed in the "Application-specific semiconductors" trend), has empowered these emerging providers to innovate and excel in niche areas. Using cutting-edge hardware, the new entrants can offer differentiated services such as AI-optimized cloud platforms or edge computing solutions that cater to specific customer needs. This shift is creating new market opportunities and fostering competition, driving further innovation across the cloud industry.[4] At the same time, some hyperscalers are planning to push the frontier of high-capacity data centers (two to five gigawatts).

— *Increasing concerns about data security, privacy, and geopolitical risks have increased demand for locally hosted data and compute.* Local infrastructure and sovereign clouds ensure that data storage and processing occur within specific national or regional boundaries, helping to safeguard regional interests. This simplifies compliance with local data protection laws and regulations, which are especially critical in the public sector and in industries such as healthcare and aerospace. Larger institutions, such as those in the financial sector, often manage a private cloud, but smaller organizations may need to continue to rely on large cloud services providers.[5]

'Previous investments in cloud are paving the way for AI. The learnings of deploying cloud at scale are lessons to be applied to AI. By having a framework that first supports the developer community, integrating security to ensure it is safe and easy to use, and extending it to users, we will see adoption take off.'

— Aamer Baig, senior partner, Chicago

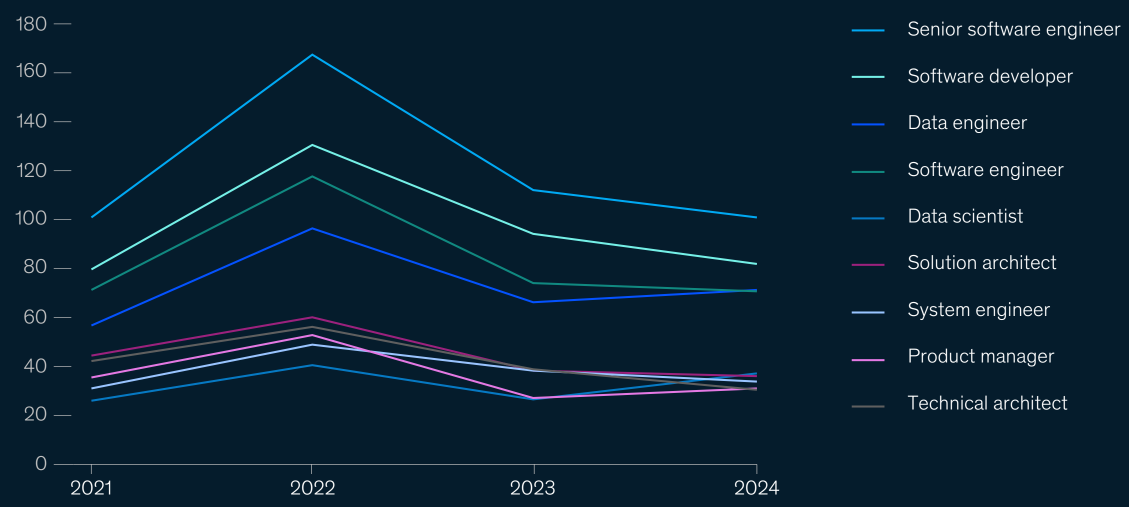
3 Examples of hyperscalers: Alibaba, Amazon Web Services (AWS), Baidu, Google, Huawei, Microsoft, and Tencent.
4 Elizabeth Wallace, "Meeting AI's compute demands with distributed training," RTInsights, November 8, 2024.
5 "Sovereign cloud market surges despite divided industry definitions, Broadcom research finds," Broadcom, February 17, 2025.

Cloud and edge computing

Demand

Job postings in cloud and edge computing have fluctuated since 2021, with roles such as senior software engineer, software developer, and technical architect peaking in 2022 before declining in 2024 to near 2021 levels. This pattern reflects the postpandemic push to accelerate cloud transformation. As those foundational builds matured, hiring shifted toward roles focused on optimization and data-driven value creation. Demand for product managers, data engineers, and data scientists has grown over the past year, after a period of macroeconomic tightening, reflecting the increasing importance of building and managing cloud-native data pipelines and AI and machine learning workloads.

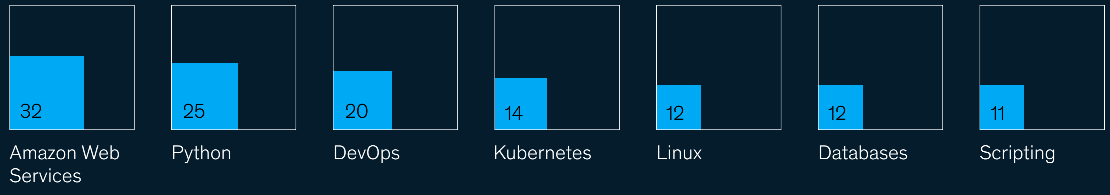
Job postings, by title, 2021–24, thousands



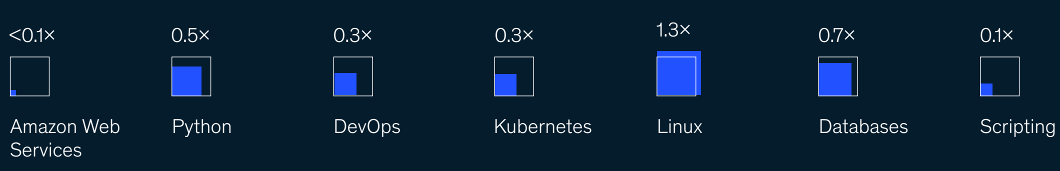
Skills availability

The demand for cloud and edge computing skills is high, but talent availability varies widely. Expertise in platforms such as Amazon Web Services (AWS) is especially scarce, with far fewer qualified professionals than job openings. Skills in DevOps (software development and IT operations), Kubernetes, and Python also face significant shortages, reflecting the growing need for automation and efficient cloud management. Meanwhile, skills in Linux and databases are more readily available, showing a better balance between supply and demand. Overall, this uneven talent landscape creates a competitive market as companies seek specialists to support expanding cloud infrastructure and emerging edge computing technologies.

Talent required, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Adoption score: 4—Scaling in progress. Organizations are scaling the deployment and adoption of the technology across the enterprise.

Many organizations across the globe have adopted cloud technologies, with the United States and Western Europe leading in adoption. However, as the demand for compute continues to grow, fully scaling the technology will be a challenge. Meanwhile, bottlenecks around power, hardware supply chain, and networks persist. Some areas of the globe where edge computing has not seen much traction, such as Africa, are lagging behind.

In real life

Evolutions in cloud and edge computing are enabling AI across the cloud stack, addressing compute and power constraints and giving rise to specialized cloud providers and sovereign cloud expansion.

Real-world examples involving AI disrupting the cloud stack include the following:

— *Meta has developed specialized data center networks that use GPU clusters to support distributed AI training at scale.* RDMA over Converged Ethernet version 2 (RoCEv2) was used as the internode communication transport for Meta's AI capacity. The company's network supports a wide range of reliable, real-world AI training tasks—such as ranking, content recommendation, and natural-language processing—running across its GPU clusters.[6]

— *The Stargate Project was announced in January 2025 with a $500 billion investment over the next four years to build new AI infrastructure for OpenAI.* Funders include MGX, OpenAI, Oracle, and SoftBank.[7]

Real-world examples of companies overcoming computing constraints include the following:

— *Hybrid cooling strategies are becoming increasingly essential as demand for computing power rises.* Data centers now combine air cooling for less intensive applications with liquid cooling for high-density racks. Microsoft has introduced a water-efficient, closed-loop chip-level cooling system that eliminates water evaporation and delivers precise temperature control.[8] Technologies such as HyperCool use waterless, two-phase, direct-to-chip cooling to handle AI GPUs up to 2,800 watts, using 10 to 20 percent less energy than traditional methods.[9]

— *As more data centers are built, the increasing power needed to operate them is becoming an issue in markets traditionally home to clusters of data centers, such as Northern Virginia and Santa Clara in the United States.* Many utility companies have been unable to build transmission infrastructure quickly enough and eventually may be unable to generate sufficient power.[10] Data centers devoted to AI models are being built in more remote locations in the United States where power is still abundant and grids are less strained, such as in Indiana and Iowa.[11] Similarly, Southeast Asian countries like Thailand and Indonesia, and Nordic countries such as Finland, which are abundant in renewable energy, are becoming key hubs for AI infrastructure.[12]

— *As AI models become more embedded in everyday applications, the industry is shifting focus from sheer scale to efficiency.* In this context, DeepSeek's R1 model stands out as a leading example. The R1 model uses techniques such as multihead latent attention (MLA) and FP8 precision quantization to dramatically reduce memory and compute requirements, enabling high-performance inference even on consumer-grade hardware. This approach reflects a broader trend in cloud and edge computing: optimizing AI workloads for

[6] Adi Gangidi and James Hongyi Zeng, "RoCE networks for distributed AI training at scale," Engineering at Meta, August 4, 2024.
[7] Sulbha Jain, "AI's biggest project: Stargate—what it may be?," Medium, March 8, 2025.
[8] Chris Paoli, "Microsoft rolls out water-saving datacenter design," Redmond, December 9, 2024.
[9] "At PTC 2025, ZutaCore highlights waterless direct-to-chip liquid cooling for AI factories and data centers," PR Newswire, January 20, 2025.
[10] "The power problem: Transmission issues slow data center growth," Data Center Frontier, May 30, 2023.
[11] Alissa Widman Neese and Arika Herron, "The Midwest's data center boom comes to Indiana," Axios, May 9, 2025.
[12] Anne Kauranen, "Nordics' efficient energy infrastructure ideal for Microsoft's data centre expansion," Reuters, March 7, 2025; David Chernicoff, "Thailand and Indonesia look to become data center hubs for APAC," Data Center Frontier, April 7, 2025.

responsiveness and resource efficiency to bring intelligence closer to where data is generated and decisions are made.[13]

— *Companies are distributing workloads across growing numbers of machines.* For example, AWS Trainium trained the Llama 2-7B model on 128 servers by splitting the model across chips, spreading tasks among workers, and breaking up long sequences. This reduced training time and cost significantly compared with a single machine. Similarly, companies are moving to areas with better power availability or using edge computing to process data closer to its source.[14]

The following is a real-world example of the rise of specialized players:

— *CoreWeave, backed by Nvidia, has become a key player in cloud computing by offering specialized GPU-accelerated cloud services tailored for AI and machine learning workloads.* It caters to niche markets such as AI model training and inference for start-ups and research institutions with high-performance GPUs such as Nvidia H100. The company has grown quickly, with revenue surging to $1.9 billion in 2024, a 737 percent increase year over year that led to an IPO in March 2025.[15]

Real-world examples involving the rising demand for sovereign clouds include the following:

— *Oracle expanded its sovereign cloud in 2024 to cover the European Union.* This allows European companies to process data locally using Oracle's cloud infrastructure.[16]

— *Delos Cloud, founded by SAP, is working with Arvato Systems and Microsoft to deliver a sovereign cloud solution tailored to the German public sector.* The platform is designed to enable government agencies to distribute sensitive workloads securely across multiple data centers within Germany.[17]

Underlying technologies

The technologies that power cloud and edge computing include the following:

— *Virtualization.* Virtualization enables the creation of virtual instances of servers, storage, and networking, allowing for resource sharing and isolation.

— *Compute and serverless computing.* This technology provides on-demand computing resources, including serverless models with infrastructure managed by cloud providers, which frees up developers to focus on code.

— *Containers and Kubernetes.* Containers package applications and their dependencies to enable consistent deployment across environments, while Kubernetes manages container orchestration at scale.

— *APIs and microservices.* APIs facilitate communication between cloud applications and services, while microservices break down applications into smaller, independent components for greater scalability and flexibility.

— *Cloud storage.* This technology includes scalable and accessible storage solutions such as object storage and block storage, which help facilitate data management in the cloud.

— *Internet of Things (IoT) or device edge.* IoT devices such as sensors and video cameras collect and process data. These devices often come with basic computing and storage capabilities.

— *On-premises or "close to the action" edge.* These are computing and storage resources deployed within a premises or a remote or mobile location where data is generated.

— *Operator, network, and mobile edge computing (MEC).* These are private or public computing and storage resources deployed at the edge of a mobile or converged-services provider's network and are typically one network hop away from enterprise premises.

[13] "Theta EdgeCloud adds DeepSeek-R1 LLM—supporting efficient, high-performance AI in a decentralized network," Medium, January 28, 2025.
[14] *AWS Machine Learning Blog*, "End-to-end LLM training on instance clusters with over 100 nodes using AWS Trainium," blog entry by Jianying Lang et al., May 29, 2024.
[15] Billy Duberstein, "This Nvidia-backed IPO grew 737% last year and is about to go public: What investors should know about CoreWeave," The Motley Fool, March 9, 2025; and "CoreWeave shares soar past IPO price on third trading day," Reuters, April 1, 2025.
[16] "Organizations across Europe move to Oracle EU Sovereign Cloud to manage critical business data," Oracle press release, November 4, 2024.
[17] Axel Kannenberg, "SAP: Two billion euros for sovereign clouds—with and without Microsoft," Heise Medien, September 21, 2024.

— *Metro edge.* With this technology, data centers with smaller footprints (usually about three megawatts) are located in large metro areas that augment the public cloud with near-premises computing power and storage to provide lower latency and greater availability.

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

Key uncertainties

The major uncertainties affecting cloud and edge computing include the following:

— As chip technology advances, balancing faster performance with lower energy use in both hardware and software remains a key challenge.

— Regulatory scrutiny and data privacy concerns are spurring more emphasis on cloud governance and data sovereignty.

— The environmental and sustainability impact of accelerating data center expansions, power sourcing, water usage, and electronic waste could lead to additional regulations.

— Security remains a critical concern for cloud and edge computing in 2025. Organizations face escalating security risks due to limited visibility across multicloud environments and underinvestment in protection.

Big questions about the future

Companies and leaders can consider the following questions when moving forward with cloud and edge computing:

— How can cloud providers effectively reduce their energy consumption and carbon footprint?

— How can companies ensure data sovereignty and compliance with evolving regulations in multicloud environments? Will regionally dominant cloud providers emerge?

— What will define competitive advantage in the cloud over the next five years—scale, architecture, or ecosystem control?

— As cost curves, tariffs, and regulatory pressures evolve, how should organizations dynamically optimize their workloads across cloud, edge, and on-premises platforms?

06

Immersive-reality technologies

Immersive-reality technologies encompass augmented reality (AR) and virtual reality (VR) and include AR smart glasses, advanced haptic feedback, and AI-powered enhancements that improve rendering, tracking, and processing capabilities.

The trend—and why it matters

Immersive-reality technologies—including augmented reality (AR), which projects images into real-world settings, and virtual reality (VR), which enables interaction within fully virtual environments through spatial computing—have the potential to transform experiences across many industries. Such technologies continue to develop, with advances such as lighter, more affordable wearable devices, improved haptic technologies, and AI integration. While gaming and entertainment remain the sectors with the strongest adoption and most visible innovation, these technologies are also being used in other sectors for marketing, prototyping, and simulating high-risk scenarios to improve training and safety. Personalized learning and entertainment applications leverage immersive reality to tailor experiences to individual needs, enhancing outcomes and procedural knowledge acquisition. By providing safe, controlled environments, AR and VR allow users to practice skills and experiment without real-world risks. In healthcare, immersive technologies support medical training and patient treatments. The AR/VR market saw steady but modest growth in 2024, with headset shipments increasing by 10 percent, though forecasts suggest growth may slow in 2025.[1]

'Immersive reality is rapidly moving beyond its roots in gaming and entertainment to become a transformative force across industries. As the technology matures, organizations that thoughtfully integrate AR and VR into their operations will unlock new dimensions of productivity, creativity, and human connection. The next wave of innovation will be defined not just by technical advances but also by how seamlessly immersive experiences can be woven into the fabric of everyday business and life.'

— David Naney, senior specialist, Southern California

[1] Paul Hill, "The AR/VR market rebounded in 2024, but forecast suggests 2025 growth pause," Neowin, March 26, 2025.

COMPUTE AND CONNECTIVITY FRONTIERS

Immersive-reality technologies

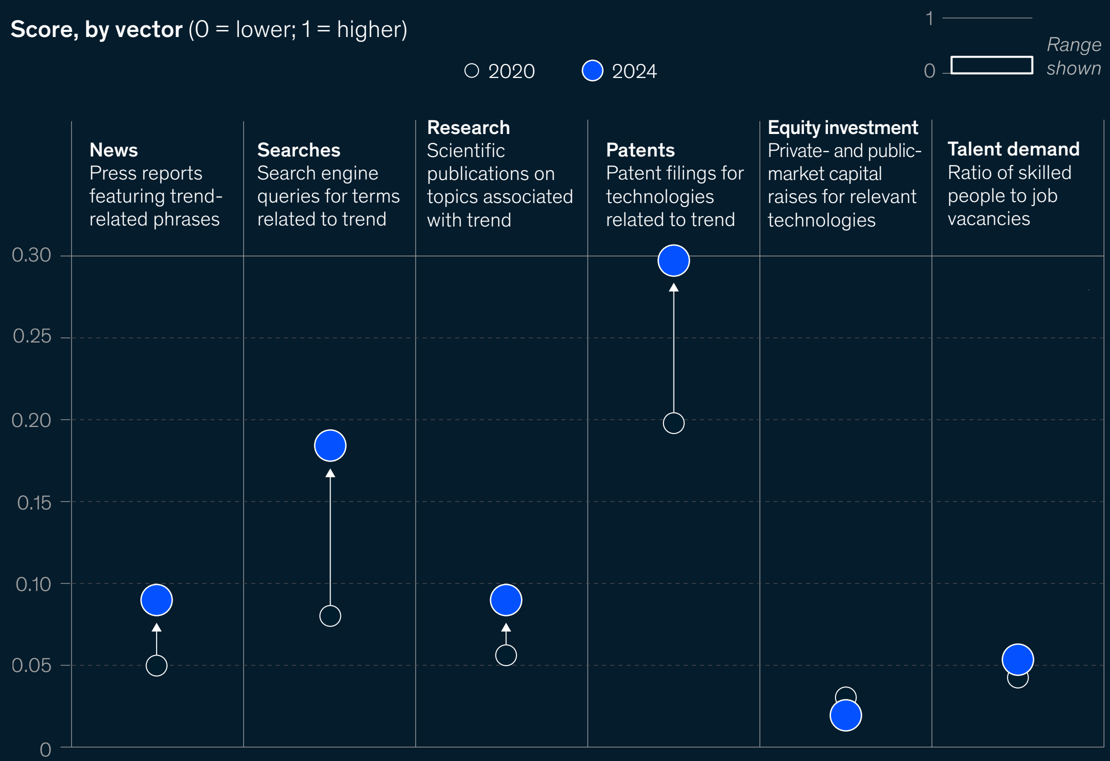
Scoring the trend

Even as equity investment has remained relatively flat, levels of interest (news, searches) and innovation (research, patents) in immersive reality have grown recently, driven by rising curiosity about smart glasses tied to notable product launches like the Apple Vision Pro and Ray-Ban Meta AI glasses.

Equity investment, 2024
$6 billion

Job postings, 2023–24, % difference
–11%

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



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

Recent developments involving immersive-reality technologies include the following:

— *Historically, AR and VR headsets have underperformed expectations.* This is due to high costs, limited consumer adoption, and technical limitations—although there is evidence of renewed investment, such as Meta's AI glasses and Google's Android XR glasses.[2]

— *Haptic advancements are blurring the line between reality and simulations.* The integration of haptic technology and advanced sensory feedback is creating more immersive and realistic virtual environments. Ultra-low-power haptic actuators and wearable gloves and suits provide precise tactile feedback, simulating sensations like raindrops or texture. Chemical sensors and wireless dispensers can replicate flavors. This multisensory approach can elevate user engagement across various applications.

— *AI integration is revolutionizing AR and VR technologies, enhancing rendering, tracking, and processing capabilities, especially in gaming and training simulations.* AI algorithms generate hyperrealistic environments and characters in games that respond dynamically to user interactions, creating more immersive experiences. AI techniques, including deep learning models, are improving the realism of 3D visualizations by training on vast data sets of real-world textures and lighting conditions.[3]

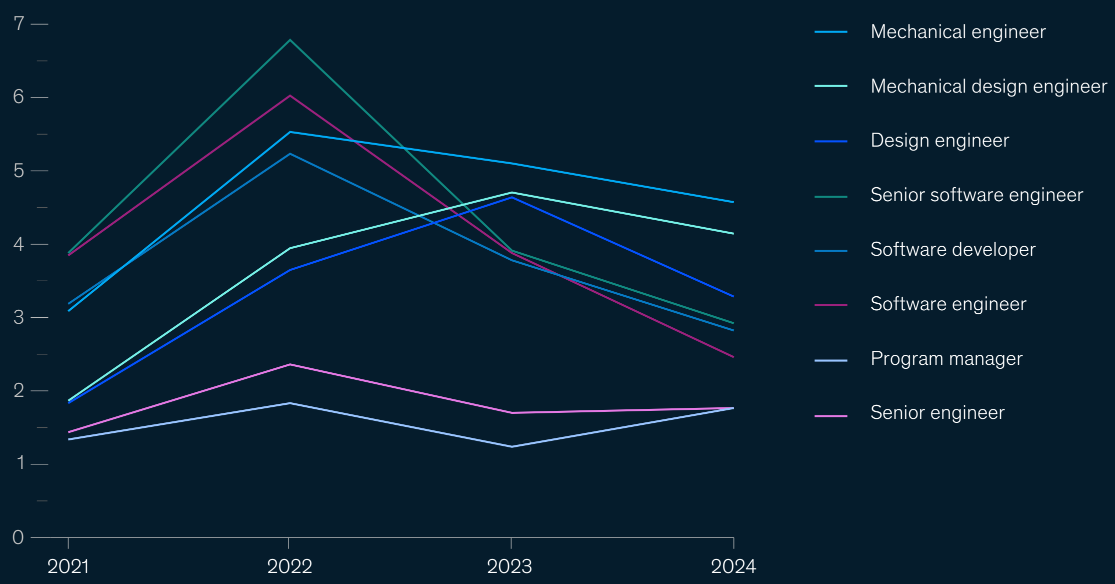
2 *Google Blog*, "A new look at how Android XR will bring Gemini to glasses and headsets," blog entry by Shahram Izadi, May 20, 2025.
3 "Creating realistic 3D models with AI-generated textures and materials," OpsMatters, December 22, 2024.

Immersive-reality technologies

Demand

Demand for mechanical engineering roles has been relatively stable compared with software-focused positions, reflecting the continued need for hardware expertise in the manufacturing and prototyping of AR and VR devices. The overall decline in talent demand for most job titles in 2024 indicates that the job market is recalibrating itself as the use cases and support structure for this area evolve.

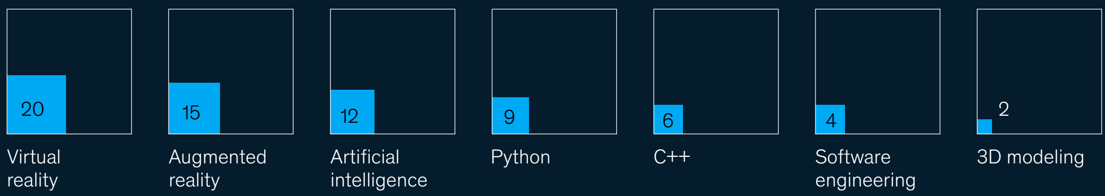
Job postings, by title, 2021–24, thousands



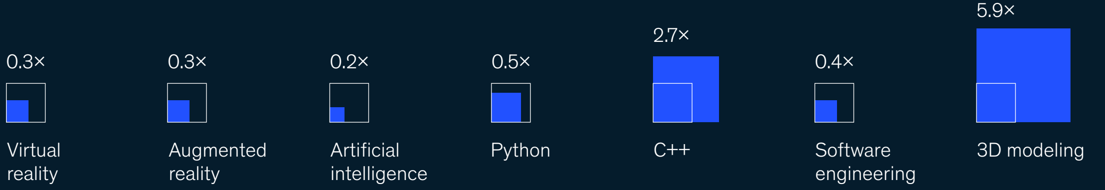
Skills availability

The immersive-reality sector faces shortages in VR, AR, and AI skills, driven by growing demand for adaptive simulations and AI-powered content creation. Programming skills, such as C++, are more readily available, and 3D-modeling expertise remains abundant.

Talent required, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Adoption score: 2—Experimentation. Organizations are testing the functionality and viability of the technology with small-scale prototypes, typically without a focus on a near-term ROI. Few companies are scaling or have fully scaled the technology.

The adoption of immersive-reality technologies is highly variable across geographies and use cases. While smart glasses have gained meaningful traction, headset adoption has been slower than anticipated. Momentum is building in sectors like healthcare and consumer goods, yet widespread scale remains constrained by usability issues, high costs, and regional disparities in infrastructure and innovation.

In real life

Real-world examples involving the use of wearable devices include the following:

— *Helping to bridge the gap between physical presence and digital interaction.* Despite the company's subsequent decision to discontinue production of the initial model, Apple's Vision Pro headset, first shipped in early 2024, marked a milestone in the immersive-reality technology market. Among its features is "Persona," which uses AI and AR to scan a user's face and create a realistic digital avatar for FaceTime calls, allowing users to communicate more naturally in virtual environments.[4]

— *Broadening the perspective of smart glasses.* Expanding the field of vision is considered important for the growth of AR, and the fifth generation of Snap's Spectacles, released in September 2024, makes progress in that direction. The product, which is primarily targeted at AR developers, has a more immersive display, with more intense colors and a wider 46° diagonal field of view, as well as extended battery life and enhanced processing power.[5] Despite these improvements, the category still faces challenges like relatively limited fields of view and heavy device weights.

— *Making VR more immersive and accessible to casual users and enterprise applications.* The ambitious visions of VR headsets have been limited by technical challenges. Products like the Meta Quest 3, a stand-alone headset launched in 2023, marked another step forward in the evolution of immersive hardware. In addition to not requiring a constant connection to external PCs or consoles, it features improved graphics, processing power, and rendering capabilities.[6]

— *Dr. Joaquin Sanchez-Sotelo performed the first-ever mixed-reality-navigated shoulder replacement surgery at the Mayo Clinic in 2024.* This innovative approach to surgery used specially designed tools and goggles to create a highly accurate hologram of the joint, allowing for greater precision in placing the implant.[7]

— *Reducing the time it takes to build a prototype.* Physical prototypes typically require 45 days, but New Balance used VR to shorten that process to just seven days or less. This VR-based approach enables decision-makers to view shoe designs from all angles in a virtual environment, comparable to handling physical samples. The use of VR in this context has made it easier to communicate design intent and enabled more informed decision-making.[8]

Real-world examples of how haptic and other sensory technology are enhancing virtual experiences include the following:

— *A more realistic and engaging gaming experience.* Virtuix has launched the Omni One, its consumer-focused, multidirectional VR treadmill that allows users to move in any direction within virtual spaces. This 360°

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4 Chris Velazco, "I lived inside a Vision Pro for two weeks. Here's what it was like," *Washington Post*, February 12, 2024; "Apple Vision Pro available in the U.S. on February 2," Apple press release, January 8, 2024; Mark Gurman, "Apple scraps work on Mac-connected augmented reality glasses," Bloomberg, January 31, 2025.

5 "Introducing new Spectacles and SNAP OS: The next frontier of AR glasses," Snap press release, September 17, 2024; Harry McCracken, "Snap's new AR spectacles are fun. Too bad they're not for consumers (yet)," *Fast Company*, September 17, 2024; Alex Heath, "Snap's new Spectacles inch closer to compelling AR," *Verge*, September 17, 2024.

6 Mitch Wallace, "Meta Quest 3 review: Mixed reality for the win," *Forbes*, January 24, 2025; *Meta Blog*, "Meta Quest 3: The first mass-market mixed reality headset is available now," October 9, 2023; David Heaney, "Quest 3 automatically renders at higher resolution in almost all apps & games," UploadVR, September 27, 2023.

7 Joel Streed, "Mayo Clinic Minute: Mixed reality provides precise path during shoulder surgery," Mayo Clinic, January 12, 2024.

8 *Metalitix Blog*, "Virtual reality use in product design & prototyping," July 15, 2024.

'The landscape of immersive technology is undergoing a profound transformation with the integration of robotics and world foundation models. Advances in AI-driven world foundation models have enabled machines to dynamically perceive and predict their 3D environments in real time. This breakthrough will reshape the role of immersive technology in bridging the digital and physical realms.'

— Ichiro Otobe, senior client development adviser, Tokyo

capability increases a sense of presence in VR environments.[9]

- *Bringing a sense of touch to VR.* Haptic gloves are meant to help wearers interact with virtual objects naturally and intuitively. Contact CI's Maestro EP, a lightweight, wireless model the company showcased at AWE 2024, represents an advance in that area. The US Air Force has used Contact CI's haptic technology since 2020 for VR training programs, a practical application of these gloves in a professional setting.[10]

- *Stronger flavor in virtual taste simulation.* Addressing and growing consumer demand for multisensory digital ecosystems is a major focus area in the immersive-reality-technology sector. One recent innovation models the work of taste buds. Developed by researchers at Ohio State University, e-Taste technology uses chemical sensors and wireless microfluidic actuators to replicate sweet, sour, salty, bitter, and umami tastes via a controlled release of ions and flavor compounds. Human trials achieved 70 percent accuracy in distinguishing taste intensities.[11]

Real-world examples of how AI is transforming immersive-reality applications include the following:

- *Skybox AI, developed by Blockade Labs, is an advanced AI-powered tool for creating immersive 360° panoramic environments.* Users can generate detailed 8K-resolution skyboxes from simple text prompts and remix existing environments, edit elements, and even convert 2D skyboxes into 3D models for use in various applications. This technology can be applied in gaming, VR, simulations, education, and more.[12]

- *Creating gaming NPCs reaches a new level with AI.* In 2023, Epic Games rolled out a new AI-driven feature for Unreal Engine (UE), its versatile 3D computer graphics game engine. Dubbed the Procedural Content Generation Framework,[13] it uses AI algorithms to automatically generate game assets such as landscapes, 3D objects, buildings, and even entire worlds. As one of the AI-enhanced follow-ups, the company introduced MetaHumans in Unreal Editor for Fortnite,

[9] Brian Heater, "Virtuix's VR treadmill is finally launching in September," *TechCrunch*, August 14, 2024; Rebekah Carter, "Virtuix Omni One review: An immersive VR platform," XR Today, September 20, 2024.
[10] "Contact CI to show haptic gloves at AWE 2024," LAVNCH [CODE], June 17, 2024.
[11] Tatyana Woodall, "New device could allow you to taste a cake in virtual reality," Ohio State News, February 28, 2025.
[12] Dean Takahashi, "Blockade Labs improves quality for AI-generated 3D art for 360-degree apps," VentureBeat, April 18, 2024.
[13] Evgeny Obedkov, "Epic launches Unreal Engine 5.2 with new procedural generation framework and shader compilation improvements," Game World Observer, May 12, 2023.

allowing creators to design and animate high-fidelity, digital "human" nonplayer characters (NPCs) for their Fortnite islands. UE's Behavior Trees asset can be used separately to enable smart AI behaviors for NPCs.[14]

Underlying technologies

The technologies that power immersive reality include the following:

— *Augmented reality.* AR enables partial immersion by adding information to real-world settings.

— *Virtual reality.* VR immerses users in entirely virtual settings.

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

— *Spatial computing.* This type of computing uses the perceived 3D physical space around the user as a canvas for a user interface.

— *Wearable and external sensors.* These sensors, embedded in handheld or wearable devices or mounted around users, detect objects and bodies for representation in virtual settings.

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

— *Location-based augmented reality.* This software integrates a user's real-time physical location and surroundings into AR to overlay the surrounding physical environment in the virtual environment.

— *Machine learning.* This term refers to models that make predictions after being trained with data rather than following programmed rules.

— *Artificial intelligence.* AI refers to the capability of machines to perform cognitive functions typically associated with human minds, such as perceiving, reasoning, learning, interacting with the environment, and problem-solving.

Key uncertainties

The major uncertainties affecting immersive-reality technologies include the following:

— *Data availability and data privacy.* Immersive technologies such as virtual and augmented reality collect large amounts of personal data, such as body movements, eye tracking, and how users interact with their surroundings. This raises serious privacy concerns. Some advanced AI systems can even interpret unconscious behavior, including eye movements, to guess what users are thinking or feeling—often without the user realizing it. There's a real risk that this information could be misused or exposed in data breaches, making it critical to protect user privacy.

— *Amplifying bias.* If not implemented carefully, immersive technologies can reinforce existing social biases. For example, candidates with reliable internet and access to newer devices or dedicated VR workspaces may benefit more from virtual hiring processes, education programs, or access to public services.

— *Physical safety.* Augmented and virtual reality systems often limit a user's vision of the real world. This creates safety concerns when they are used in environments that aren't tightly controlled.

— *Multiple device types.* There are many different types of immersive tech devices, from independent AR and VR platforms to peripheral AR accessories for mobile phones. This variety can make it unclear which devices are best suited for specific tasks. As new products continue to emerge, users face uncertainty in choosing the right tools for their needs.

— *Hardware development.* Advances in hardware in areas such as weight, heat management, battery life, field of view, and motion sickness reduction are progressing at a varying pace. Some areas are moving faster than others, due to technical challenges or market demand. While steady progress can be anticipated, the timeline for achieving substantial advances across all areas simultaneously remains uncertain.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with immersive-reality technologies:

— How will the pace of hardware breakthroughs—across cost, comfort, and performance—shape

[14] "MetaHuman now available for UEFN: Bring digital human NPCs to your islands," Fortnite Creator Portal, March 20, 2024.

the evolution of immersive reality from niche novelty to general-purpose platform?

— What's the tipping point for immersive reality to move from pilot projects to scaled deployment in specialized, high-value domains such as energy infrastructure, advanced manufacturing, or high-end media?

— How will immersive reality shift and adapt as more organizations embrace a return to office and less remote work?

— What kind of regulatory frameworks are needed to ensure the safety, security, and ethical use of VR technologies, including content moderation, data privacy, and cybersecurity?

— What impact will widespread adoption of AR/VR have on society and human behavior?

07

Digital trust and cybersecurity

Digital trust and cybersecurity covers technologies and practices designed to ensure secure, transparent, and trustworthy digital interactions. This includes identity verification, data protection, encryption, threat detection, and blockchain-based trust systems.

The trend—and why it matters

The digital trust and cybersecurity trend encompasses technologies across cybersecurity, AI trust, and blockchain. These technologies build, scale, and maintain stakeholders' trust. They help organizations mitigate technology and data risks, innovate, and safeguard assets, which contribute to enhanced organizational performance and stronger customer relationships.

Cybersecurity and artificial intelligence provide advanced defense mechanisms that protect against increasingly sophisticated cyberthreats. They can enhance threat detection, incident response, and overall digital resilience for any organization.

AI trust systems provide explainability, fairness, robustness, and security that build confidence among users and stakeholders. As AI is increasingly integrated into daily life and critical decision-making processes, the importance of trust cannot be overstated.

Blockchain-based tokenization systems, inherently built for transparency, security, and accessibility, could underpin innovative solutions in fields such as finance and healthcare.

These technologies share the common goals of building digital trust and safeguarding data integrity. Capturing the full benefits of digital trust and cybersecurity requires top-down leadership and deliberate changes across multiple spheres of activity, from strategy and technology to enterprise capabilities.

'The core foundations of cybersecurity—asset management, vulnerability management, and identity management—remain critical to securing a digital world where generative AI continues to unlock more and more value. Creating systems and processes in this period of gen AI that will provide secure customer and user experiences requires both maintaining foundational security capabilities and investing in leading technology to keep up with the pace of change.'

— Charlie Lewis, partner, Connecticut

COMPUTE AND CONNECTIVITY FRONTIERS

Digital trust and cybersecurity

Scoring the trend

As advances in AI and agentic AI underscore the necessity of comprehensively managing risks, interest in digital trust and cybersecurity has increased, leading to a 20 percent rise in Google searches for related terms from 2023 to 2024.

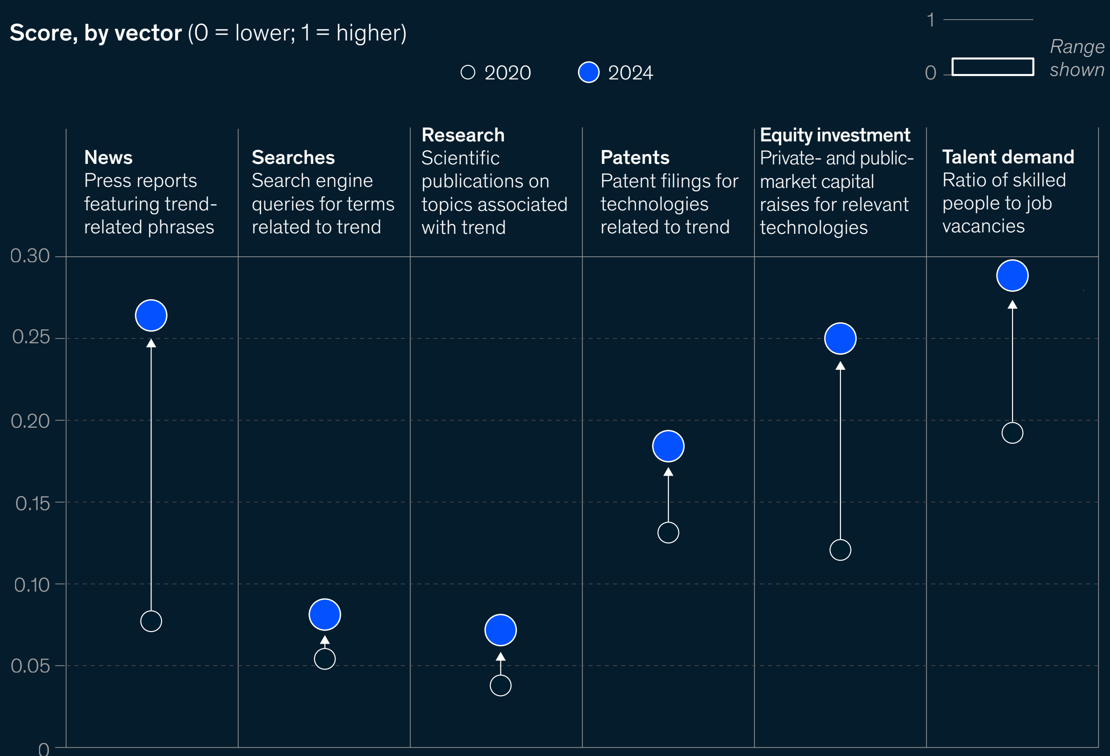
Equity investment, 2024

$77.8 billion

Job postings, 2023–24, % difference

+7%

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



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

Recent developments involving digital trust and cybersecurity include the following:

— *The rapid advance of AI technologies and disruptions across industries and in daily lives highlights the urgent need to establish AI trust across the value chain.* Trust in AI companies has declined, falling from 61 percent in 2019 to 53 percent today.[1] Failure to proactively implement responsible and safe AI practices could have significant consequences for companies and society at large. From 2017 to 2023, cumulative stock market returns for trusted brands outperformed those of untrusted brands by 245 percentage points,[2] illustrating how digital and operational resilience and trust pay dividends.

— *Attackers are increasingly exploiting gen AI and machine learning to target organizations—and doing so with greater effectiveness.* Meanwhile, organizations themselves are adopting these technologies to bolster threat detection and

1 Ina Fried, "Exclusive: Public trust in AI is sinking across the board," Axios, March 5, 2024.

2 McKinsey research methodology: sample of companies identified as trusted or untrusted based on equally weighted scores of consumer trust (Trustpilot rating); financial stability (credit rating); sustainability (Sustainalytics ESG rating and CDP climate rating); workforce trust (Indeed employee rating); investor trust (shareholder board approval rate); and data integrity (score on the Privacy 100 list).

response capabilities. These tools enable systems to swiftly analyze extensive data sets, identify patterns, and detect anomalies, improving threat detection and prevention.

— *The exploitation of vulnerabilities in third-party software and capabilities highlights the broader impact of system risks.* As industries increasingly rely on third-party software and capabilities, risks become concentrated across various business processes, increasing the need to design and implement software bills of materials to enhance transparency and manage vulnerabilities.

— *Focus has increased on regulatory oversight, transparency, and security in the digital realm.* Governments around the world have taken significant steps to institute more comprehensive and stringent regulations as concerns about digital trust have highlighted the need for clear governance frameworks.

— *Geopolitical risks have intensified, posing significant threats to digital trust and cybersecurity.* In this uncertain environment, countries are increasingly weaponizing technology to achieve strategic objectives, raising concerns about the resilience of critical infrastructure and data security. Critical infrastructure, such as satellites and undersea cables, have become targets, which could disrupt global communications, commerce, and security. Organizations can take proactive and adaptive approaches to cybersecurity by incorporating geopolitical factors into risk assessments and mitigation strategies.

— *Tokenization is increasing in sectors like finance as institutions look to expand offerings.* Blockchain technology's ability to provide an interoperable, immutable ledger is enabling applications such as tokenized assets.

'Trust is no longer a soft issue; it's a business-critical asset. In a world of AI-generated content, cross-border data flows, and rising cyber risk, digital trust is the license to operate. The companies that build it in by design will be the ones customers choose—and the ones that earn the backing of societal stakeholders.'

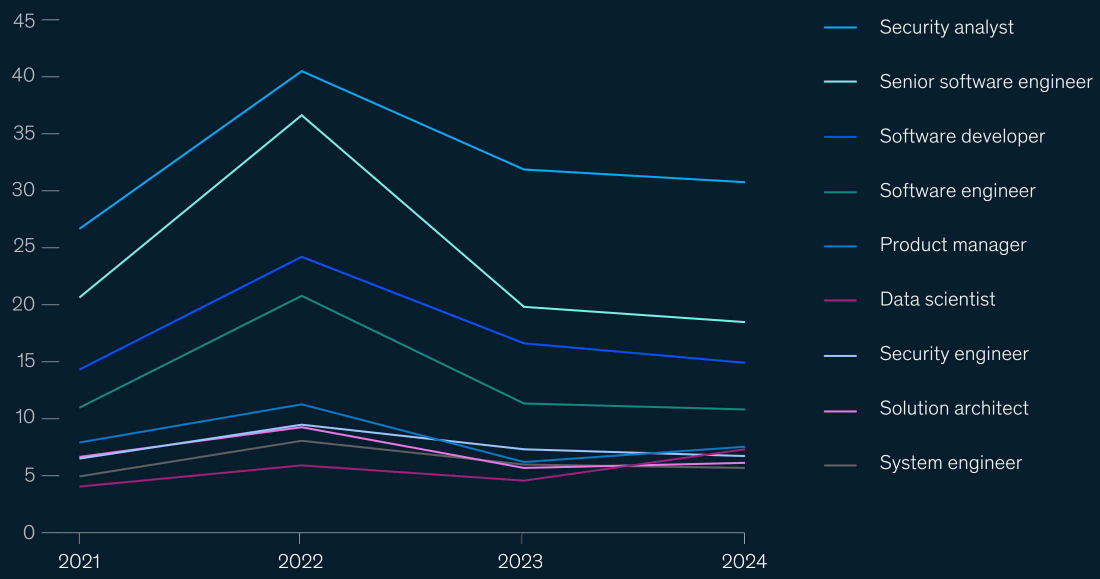
— Roger Roberts, partner, Bay Area

Digital trust and cybersecurity

Demand

Software-related roles remain central to digital trust and cybersecurity, with software engineering and software development maintaining relatively steady demand despite slight declines from 2023 levels. Security analyst roles, while down significantly from their 2022 peak—as with most job titles in this trend—still lead overall postings, reflecting the ongoing need for threat monitoring and compliance expertise.

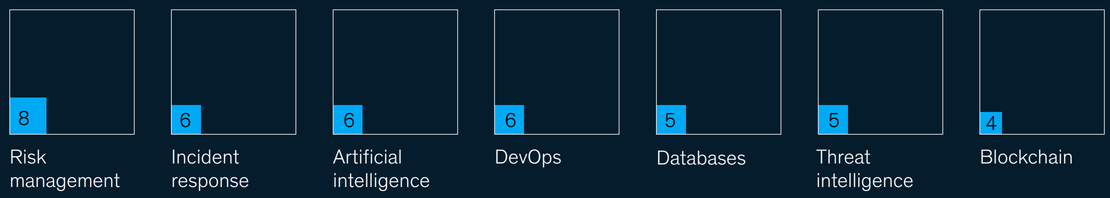
Job postings, by title, 2021–24, thousands



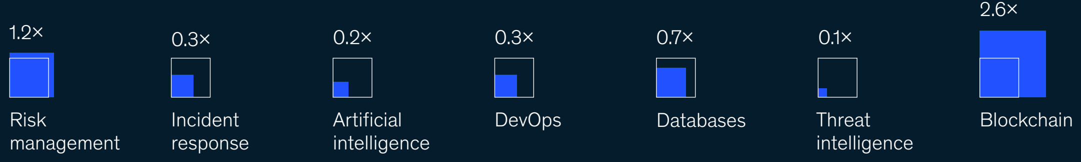
Skills availability

In-demand skills such as incident response, threat intelligence, and DevOps (software development and IT operations) face substantial shortages, reflecting urgent industry needs for threat mitigation and automation expertise. AI is increasingly critical as companies integrate AI-driven security tools for threat detection and response, yet talent remains scarce. Conversely, risk management shows a slight talent surplus, suggesting alignment with current training pipelines. Regulatory uncertainties and market volatility have led to fluctuations in the talent market for blockchain and distributed ledger skills.

Talent required, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Adoption score: 4—Scaling in progress. Organizations are scaling the deployment and adoption of these technologies across an enterprise.

Even when cybersecurity is fully scaled across an organization, technological advances mean it must continue to evolve. AI trust technologies, for example, remain in the early piloting stage despite the rapid rollout of gen AI. A small number of organizations are developing bespoke cybersecurity solutions but most depend on providers to scale. The European Union has gotten a jump on strengthening data security and sovereignty with the AI Act, which imposes strict regulations on high-risk AI systems, requires transparency, and protects consumer rights.[3]

In real life

Real-world examples involving initiatives and developments that support safe and responsible AI usage include the following:

— *The AILuminate v1.0 benchmark, introduced by MLCommons last December, is a tool that evaluates the propensity of large language models (LLMs) to respond hazardously to prompts.* It helps identify risks such as child exploitation, hate speech, and indiscriminate weapons such as chemical, biological, radiological, nuclear, and explosives violations, providing an independent analysis of LLM risk to inform decision-making. MLCommons is currently expanding AILuminate to address risks in agentic AI across correctness, safety and control, and security.[4]

— *Consolidation is enabling technology companies to respond to consumer demands for more comprehensive solutions.* For example, Cisco made its largest acquisition ever in March 2024, when it acquired Splunk for $28 billion, enhancing what it can offer its customers to improve threat detection and response by integrating Splunk's machine data analytics platform into its existing cybersecurity portfolio.[5] Five months later, Cisco acquired Robust Intelligence, a pioneer in AI application security.[6]

The following is a real-world example of AI-driven attacks targeting organizations:

— *Voice phishing—or "vishing"—is another wrinkle in phishing attacks that uses voice.* Vishing phone calls or voice messages trick people into giving up sensitive personal or financial information. According to the *CrowdStrike 2025 global threat report*, vishing attacks increased 442 percent in just six months, from the first half of 2024 to the second half.[7] Organizations can deploy a multilayered defense strategy that combines employee education, technological safeguards, and proactive monitoring to combat vishing.

Real-world examples of growing regulatory focus include the following:

— *The US Department of Defense (DOD) established the CMMC (Cybersecurity Maturity Model Certification) 2.0 framework in 2024 to enhance cybersecurity among its defense contractors and subcontractors.* DOD contractors and subcontractors will need to attain a CMMC certificate to win new defense contracts.

— *Regulatory bodies are increasingly focusing on the fintech and blockchain sectors to address consumer protection and financial stability.* The European Union's Markets in Crypto-Assets (MiCA) regulation came into effect at the end of 2024, aiming to provide a comprehensive legal framework for digital assets, including stablecoins. This regulation is expected to standardize the issuance and trading of tokenized assets, fostering innovation while mitigating risks associated with digital finance.[8]

Real-world examples involving geopolitical risks affecting digital trust include the following:

— *Salt Typhoon, a foreign-state-sponsored cyberattack group, has been responsible*

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3 Deborah Margolis and Hannah Drury, "The first requirements of the EU AI Act come into force in February 2025," Littler Mendelson, December 13, 2024.
4 "MLCommons launches AILuminate, first-of-its-kind benchmark to measure the safety of large language models," Business Wire, December 4, 2024.
5 "Cisco completes acquisition of Splunk," Cisco Systems, March 18, 2024.
6 "Cisco acquires Robust Intelligence," SC Media, August 27, 2024.
7 Jordyn Alger, "Vishing attacks increased by 442% in the second half of 2024," *Security*, March 5, 2025.
8 "Markets in Crypto-Assets Regulation (MiCA): MiCA implementing measures," ESMA, accessed March 26, 2025.

‘Blockchain-based tokenization platforms are laying the foundation for greater digital trust by making transactions more transparent, secure, and accessible. As we see real-world adoption accelerate in sectors like finance and healthcare, the challenge is not just technical; it’s about building interoperable platforms to increase adoption and navigating evolving regulations to deliver meaningful, trusted innovation.’

— Matt Higginson, partner, Boston

for a series of high-profile cyberattacks targeting telecommunications companies and other critical infrastructure. Several North American telecommunications operators were compromised in 2024, highlighting vulnerabilities across the global telecommunications infrastructure.[9]

- *In recent years, several sea cable outages seemingly aimed at disrupting internet and external communications have raised concerns about sabotage amid geopolitical tensions.* In the past 15 months, 11 Baltic Sea cables have been damaged, causing major outages, prompting NATO to launch a program called Baltic Sentry to protect critical undersea infrastructure.[10] Sea cables are costly to build and carry roughly 99 percent of all transcontinental internet traffic.[11]

Real-world examples of companies deploying tokenization include the following:

- *JPMorgan integrated Kinexys Digital Payments.* This digital-first blockchain solution was integrated with JPMorgan FX Services to handle foreign exchange settlements.[12]
- *BlackRock introduced BUIDL.* This tokenized fund now represents over 40 percent of the tokenized US Treasury market.[13]

Underlying technologies

Digital trust and cybersecurity technologies include the following:

- *Digital identity.* An identity consists of all the digital information that characterizes and distinguishes an individual or an entity. Self-sovereign identity enables users to control the identifying information they share and with whom they share it. Users of passwordless identities can verify and authenticate themselves with alternatives to alphanumeric passwords, such as biometrics, devices and applications, and documents. Businesses are developing “converged identity” solutions, which bring together different dimensions of identity into a single platform, enabling, for example, continuity as a person shifts from employee to business partner to customer.
- *Privacy engineering.* This practice governs the implementation, operations, and maintenance of privacy to reduce privacy risks and enable purposeful decision-making about resource allocation and effective implementation of privacy controls in information systems.
- *Technology resilience.* This is the sum of practices and technical foundations necessary to architect, deploy, and operate technology safely across an enterprise environment,

[9] Milind Gunjan, “Salt Typhoon: A wake-up call for strengthening telecom cybersecurity,” *Forbes*, March 5, 2025.
[10] “NATO launches ‘Baltic Sentry’ to increase critical infrastructure security,” NATO, January 14, 2025; John Leicester and Emma Burrows, “At least 11 Baltic cables have been damaged in 15 months, prompting NATO to up its guard,” AP News, January 28, 2025.
[11] Alex Capri, “The new geopolitics of undersea cables,” Hinrich Foundation, April 30, 2024.
[12] “JPMorgan to integrate on-chain FX settlement into Kinexys blockchain platform,” PYMNTS, November 6, 2024.
[13] Liam Wright, “BlackRock $1.9B BUIDL fund’s 183% growth puts it behind just four stablecoins in tokenized dollar assets,” CryptoSlate, April 2, 2025.

including components such as immutable backup and self-healing networks.

— *Blockchains.* These digitally distributed, decentralized ledgers exist across a computer network and facilitate the secure, transparent, and immutable recording of transactions.

— *Smart contracts.* Established in immutable code on a blockchain, these software programs are automatically executed when specified conditions, such as terms agreed on by a buyer and seller, are met.

— *Tokens and digital assets.* These intangible items include native cryptocurrencies, governance tokens, stablecoins, nonfungible tokens, and tokenized real-world and financial assets, including cash.

— *Decentralized applications.* These applications operate on peer-to-peer networks, eliminating reliance on centralized servers. They use blockchain technology for data storage and security and cryptocurrencies for transactions and user engagement.

— *Artificial intelligence.* AI refers to computer systems that use advanced algorithms and data analysis to perform tasks that typically require human intelligence, such as learning, problem-solving, and decision-making.

— *Explainable AI.* This deploys methods and approaches to increase transparency and interpretability of inputs, weightings, and reasoning of machine learning algorithms to build trust and confidence in them.

— *Automation for governance, risk, and compliance (GRC).* GRC tools are software applications and platforms designed to help organizations manage and streamline governance, risk management, and compliance processes.

Key uncertainties

The major uncertainties affecting digital trust and cybersecurity include the following:

— *The trade-off between security and usability is a constant challenge.* Stronger security measures can reduce vulnerability to attacks but often come at the cost of slower, less user-friendly systems. Consumer preferences and actual adoption patterns add another layer of complexity.

— *Currently, there is no one-size-fits-all approach to explainability that can open the black box of large AI models to provide meaningful explanations for their outputs.* Explainability tools need to be tailored to specific contexts and data, but compatibility challenges can interfere with efforts to update or migrate technologies, especially when integrating with legacy systems like the many fragmented point solutions still in use.

— *Even as demand for computing power continues to rise, business doubts about the increasing use of data fueling that growth persist.* Many companies have concerns about their confidential data being used to train LLMs, leading to risks of data and IP leakage, which can cause them to adopt more expensive, in-house training solutions. To mitigate these risks, vendors are making stronger commitments to data protection, including offering various forms of indemnity against IP claims.

— *Recent advances in quantum technology have increased concerns about the cryptographic systems that underpin security in blockchain networks.* As quantum computing advances on an uncertain timeline, it will pose a significant threat to the integrity and confidentiality of data protected by current cryptographic algorithms.

— *Regulation of blockchain technology and tokenization is fragmented across jurisdictions, posing compliance challenges.* The European Union has established frameworks such as the Markets in Crypto-Assets Regulation, but other regions, including the United States, are still developing regulatory approaches.[14] A lack of global standardization extends to trust architecture techniques and cybersecurity regulations, necessitating ongoing monitoring and adaptation of local company policies to ensure compliance.[15] The evolving nature of these regulations across jurisdictions requires continuous vigilance from blockchain and tokenization companies.

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[14] "EU set to lead crypto sector with 2024 MiCA regulations," AInvest, June 22, 2025.
[15] *Asset tokenization in financial markets: The next generation of value exchange*, World Economic Forum, May 21, 2025.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with digital trust and cybersecurity:

— What is required to secure the growing number of connected devices, such as the Internet of Things and operational technology, in consumer homes? What frameworks will ensure user privacy in a hyperconnected world?

— What role should governments play in maintaining digital trust and cybersecurity?

— How much will insurance incentives factor into enterprise decisions to invest in cyber resilience and digital trust?

— How can AI be leveraged to help develop advanced security mechanisms that stay ahead of emerging threats (geopolitical, AI-related, quantum)?

— How will evolving regulations and shifts in enterprise attitudes influence the pace and scale of blockchain-based tokenization?

08

Quantum technologies

Quantum-based technologies make use of the unique properties of quantum mechanics to execute certain complex calculations exponentially faster than classical computers, secure communication networks, and produce sensors with higher sensitivity levels than their classical counterparts.

The trend—and why it matters

Quantum technologies represent a fundamental leap beyond traditional computing by harnessing the unique principles of quantum mechanics to solve some difficult problems. One pillar, quantum computing, has the potential to enable solutions to specific classes of problems that are infeasible using classical computers, such as simulating quantum phenomena in chemistry or breaking some commonly used encryption techniques. The second pillar, quantum communication, could play a pivotal role in ensuring secure communication. Quantum sensing, the third pillar, enhances sensitivity, enabling a broader range of capabilities for specific use cases than conventional sensors.

Thus far, 2025 has been an eventful year for quantum computing, with major players like Amazon Web Services (AWS), Google, IBM, and Microsoft announcing breakthroughs in quantum chips and capabilities. Developments such as Google's Willow chip, Microsoft's Majorana 1 processor, IBM's Quantum Heron, and AWS's Ocelot have addressed key challenges like error correction and scalability, marking important steps toward more practical quantum systems. While practical applications of quantum computing have yet to be realized, significant strides are being made. These developments reflect ongoing progress in the field, as companies continue to explore the path from experimental research to potential real-world applications. Quantum technologies could have an economic impact across the chemicals, life sciences, finance, and mobility industries.

To truly unlock the transformative benefits of quantum technologies, however, a series of technical challenges must be overcome, perhaps through collaboration between the private and public sectors. Companies can position themselves to capitalize on future breakthroughs by monitoring developments in quantum technologies and thoughtfully investing based on their potential relevance to challenges in their industries.

COMPUTE AND CONNECTIVITY FRONTIERS

Quantum technologies

Scoring the trend

The visibility of quantum technologies is rising as industry leaders announce advancements in quantum research and development.

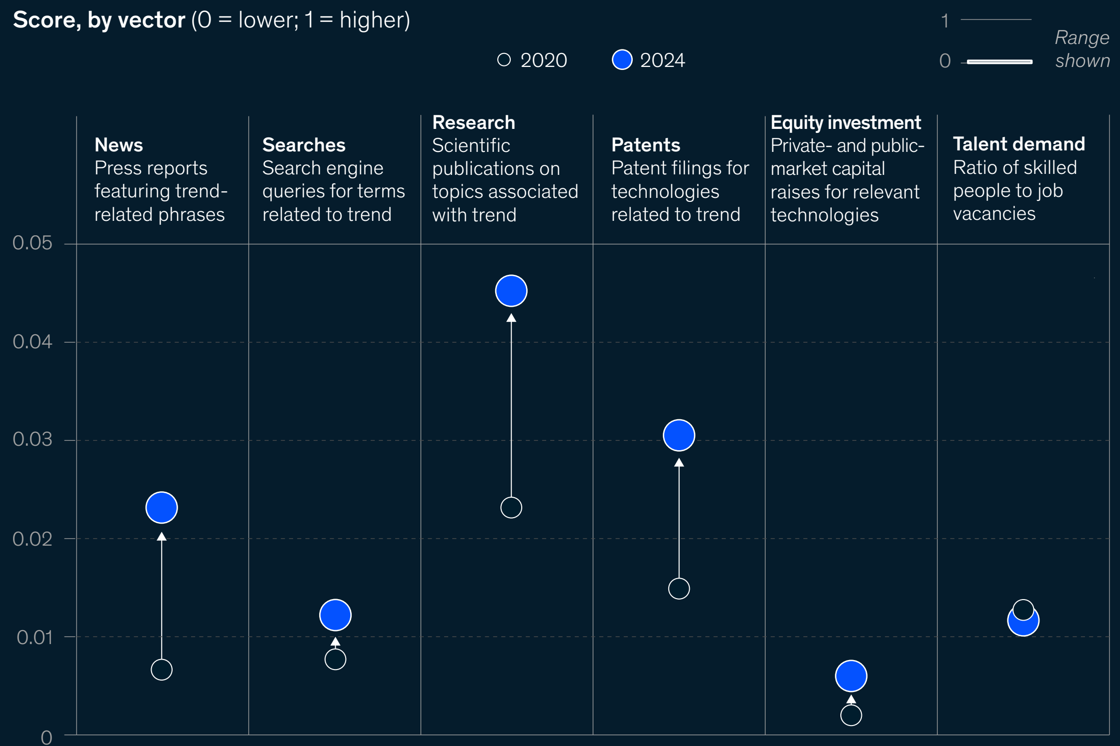
Equity investment, 2024

$2 billion

Job postings, 2023–24, % difference

–15%

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



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

Recent advances in quantum technologies have focused on overcoming key technical barriers, such as error correction and scalability. Meanwhile, heightened competition among major tech companies and start-ups, the expansion of global quantum programs, and early signs of commercialization all signal growing momentum across the field.

Recent developments in quantum technologies include the following:

— *Innovations have improved error correction and enabled scaling.* Qubit reliability has increased, and real-time error mitigation has improved, contributing to more robust fault-tolerant systems.

— *Quantum computing is rapidly becoming a highly competitive field.* Hyperscalers, large-scale tech companies that provide cloud computing services, are making notable advances in technology releases, marking a new era in which traditional computing giants not only participate but also aggressively pursue leadership in quantum computing innovation. Smaller players, including start-ups, are working to differentiate themselves by focusing on riskier innovations.

— *Innovation hubs for quantum technologies grew significantly in 2025, reflecting the increasing interest in quantum technologies and related regulatory frameworks.* Thirty-four countries now have national quantum programs, and the United Nations has declared 2025 the International Year of Quantum Science and Technology, shining a global spotlight on quantum innovation. As the quantum landscape evolves, regulators recognize the important role that international standards will play in complementing regulatory frameworks and driving innovation in quantum technologies.

'Quantum advantage requires a dual focus: groundbreaking innovation on the hardware side and further innovation on the error correction side. Together, such achievements will enable a fault-tolerant quantum computer much earlier than projected.'

— Henning Soller, partner, Frankfurt

'In recent years, significant investments have been made to address quantum technical challenges, but momentum is now shifting toward the corporate sphere. Forward-thinking organizations are exploring how to harness quantum potential to drive tangible value with impactful business applications.'

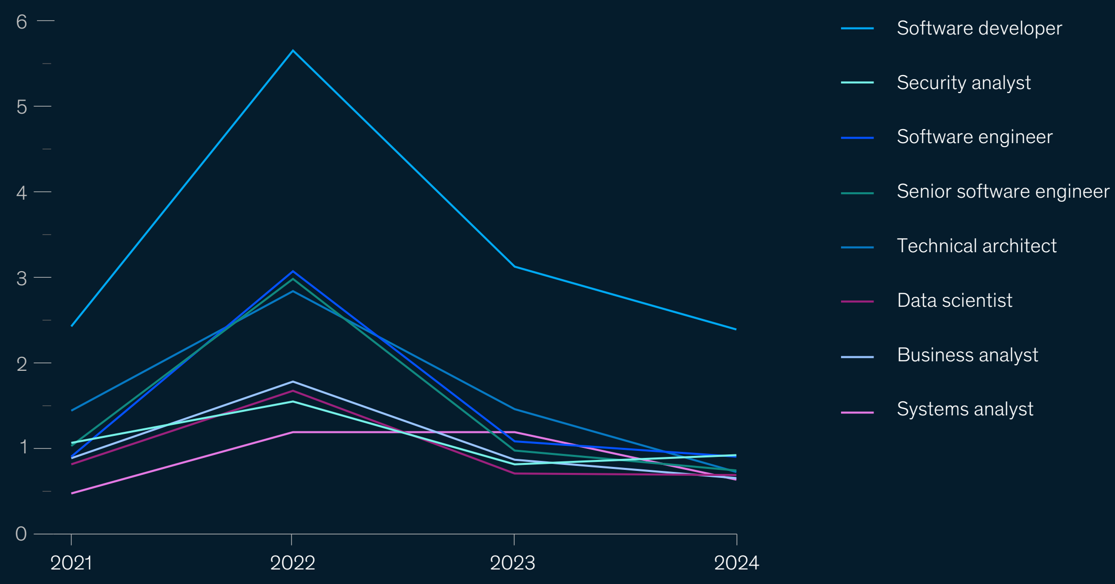
— Anna Heid, associate partner, Zurich

Quantum technologies

Demand

Quantum-technology job postings peaked in 2022 across key roles such as software developers, software engineers, senior software engineers, and technical architects before declining steadily throughout 2023 and 2024. Security analysts and systems analysts showed more modest fluctuations, with postings stabilizing at lower levels by 2024. Overall, talent data indicates that hiring activity surged and then consolidated, with software development and engineering leading the demand throughout the period.

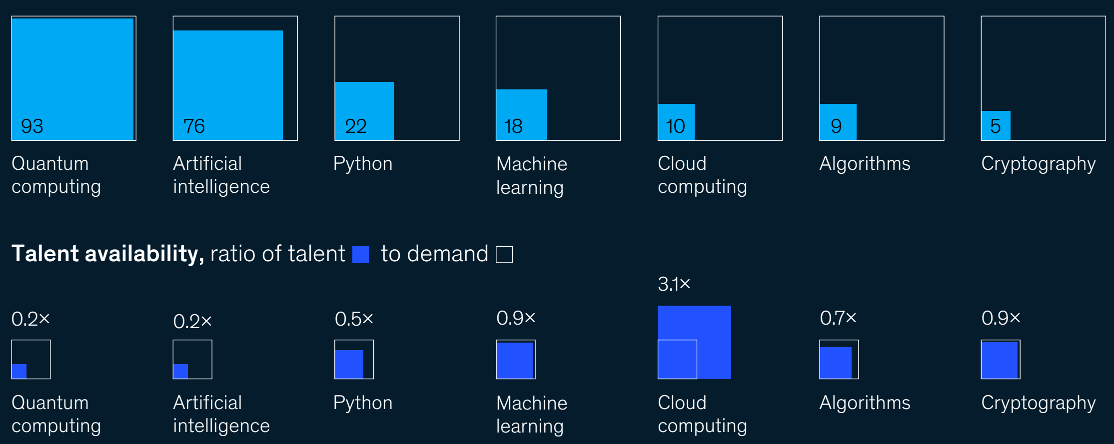
Job postings, by title, 2021–24, thousands



Skills availability

The quantum technology sector faces significant shortages in quantum computing and AI skills, which are required in the majority of job postings. In contrast, talent is readily available for cloud computing, a skill required by just 10 percent of job postings.

Talent required, % share of postings requiring skill



Adoption developments across the globe

Adoption score: 1—Frontier innovation. This technology is still nascent, and few organizations are investing in or applying it. It is largely untested and unproven in a business context.

The quantum-technology landscape is evolving rapidly, with both innovative start-ups and established tech giants announcing more investments and advancements. Despite this momentum, users remain in the exploratory phase, running proofs of concept and small-scale prototypes to assess potential applications and limitations. In particular, quantum computing is still largely focused on research and development, with early-stage systems primarily used for testing and algorithm development. Investments and strategic focus vary by region, supported by initiatives like the €1 billion Quantum Technologies Flagship in Europe and growing investment in places like the United Arab Emirates.[1]

In real life

Real-world examples of error correction and enabled scaling include the following:

— *Atom Computing recently achieved 99.6 percent two-qubit gate fidelity, the highest fidelity of neutral-atom qubits in a commercial system and a significant advancement in error correction capability.*[2] The company's technology can be combined with Microsoft's qubit virtualization system to detect and correct errors in real time, not just in the postprocessing period. However, the current limits of two-qubit gate fidelity and correction facility constrained computational strength in the demonstration. Scaling to run larger and more complex algorithms will therefore require additional improvements.[3]

— *Rigetti Computing and Riverlane passed a significant milestone in quantum error correction with their demonstration of real-time, low-latency error correction on Rigetti's 84-qubit Ankaa-2 system.* Their experiment marked the first successful demonstration of low-latency quantum error correction, enabling the rapid feedback essential for fault-tolerant quantum computing.

Real-world examples involving competition and advances in scaling include the following:

— *Google announced Willow, its latest quantum chip, which can reduce errors exponentially when scaling by adding more qubits.* Reducing errors is a key challenge in quantum computing. Willow also performed a benchmark computation that would take one of today's fastest supercomputers 10 septillion years—vastly longer than the universe has existed—in just five minutes. However, the benchmark computation has no known real-world applications.[4]

— *AWS's Ocelot uses "cat qubit" technology, which speeds up and significantly reduces the hardware needed for quantum error correction.* Cost is a major hurdle to scaling quantum computing, and Ocelot could cut costs by as much as 90 percent. AWS predicts Ocelot could accelerate the arrival of practical quantum computing by five years.[5]

— *Microsoft unveiled Majorana 1, the world's first quantum processor powered by topological qubits, which are more stable than other qubits, at least theoretically.* Microsoft says Majorana 1 will enable quantum computers to solve meaningful, industrial-scale problems in years rather than decades.[6]

Real-world examples involving quantum hubs include the following:

— *IBM inaugurated its first European quantum data center in Ehningen, Germany.* There, advanced processors like Eagle and Heron provide quantum computational power. The center aims to foster research and innovation across Europe, offering cloud-based access to quantum computing resources while adhering to regional data protection regulations.[7]

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1 "Quantum Technologies Flagship," European Commission, accessed March 31, 2025; Mai Barakat, "Capacity Middle East 2025: Growth in data centers and AI," S&P Global, March 12, 2025.
2 *Microsoft Azure Quantum Blog*, "Microsoft and Atom Computing offer a commercial quantum machine with the largest number of entangled logical qubits on record," blog entry by Krysta Svore, November 19, 2024.
3 Matt Swayne, "A closer look into the Microsoft-Atom Computing Logical Qubit Study," Quantum Insider, November 23, 2024.
4 *Google Blog*, "Meet Willow, our state-of-the-art quantum chip," blog entry by Hartmut Neven, December 9, 2024.
5 "AWS unveils Ocelot, its first quantum computing chip," Quantum Insider, February 27, 2025; "Amazon Web Services announces a new quantum computing chip," Amazon, February 27, 2025.
6 "Microsoft's Majorana 1 chip carves new path for quantum computing," Microsoft, February 19, 2025.
7 "First IBM quantum data center in Europe opens; will include IBM's most performant quantum systems," IBM, October 1, 2024.

- *Nvidia announced that it is building a quantum computing research center, the NVIDIA Accelerated Quantum Research Center (NVAQC), in Boston.* This initiative plans to advance quantum computing by integrating leading quantum hardware with AI supercomputers, a concept referred to as accelerated quantum supercomputing. NVAQC hopes to overcome some of the most pressing challenges in quantum computing, including qubit noise and the transformation of experimental quantum processors into practical devices, as well as developing techniques like quantum error correction and hybrid quantum algorithms.

Underlying technologies

Quantum technologies encompass the following:

- *Quantum computing.* Quantum computing is a computing paradigm leveraging the laws of quantum mechanics to significantly improve the performance of certain applications and to enable new territories of computing.
- *Quantum communication.* Quantum communication is the secure transfer of quantum information across distances.
- *Quantum key distribution (QKD).* QKD is the use of quantum technology to securely share a secret key that can be used with classical encryption algorithms.
- *Quantum sensing.* Quantum sensing uses a new generation of sensors based on quantum systems that provide measurements of various quantities—for example, electromagnetic fields, gravity, and time. Quantum sensors may be orders of magnitude more sensitive than classical sensors.

Key uncertainties

The major uncertainties affecting quantum technologies include the following:

- Technical challenges include achieving the ability to manage a sufficient quantity and quality of qubits over a long enough period to derive meaningful computational results while navigating potential regulatory, technological, and financial barriers to adoption that are not yet apparent.
- Cost-effectiveness may take time to achieve. Most of the calculations that businesses require can be performed by traditional supercomputers reasonably well and at a much lower cost than for quantum computers. Once quantum advantage is achieved, costs may come down, but it is currently unclear which quantum computing components will become more cost-effective.
- Quantum computing ecosystems are nascent. Innovation outside quantum hubs is hindered by limited awareness and adoption of quantum technologies, varying levels of technology maturity and applicability for different industries, the need for increased interdisciplinary coordination (for example, between academia and industry) to bring technologies to market, and continued work among quantum companies to find and develop talent in quantum theory, hardware, and software development.
- Countries leading in quantum technology could revolutionize industries like pharmaceuticals, logistics, and cybersecurity, potentially widening the economic gap among nations.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with quantum technologies:

- When is quantum technology likely to reach major milestones over the next decade, including full error correction, quantum advantage, and making feasible the defeat of current RSA encryption?
- How can companies prepare now for quantum technology, particularly the security threats posed by quantum computing?
- What impact will quantum computing have on decentralized finance?
- Will the quantum talent supply catch up to demand? How can the private and public sectors help fill the talent gap?
- How will geopolitical dynamics and emerging regulatory frameworks shape the global race to develop, commercialize, and control quantum technologies?

Cutting-edge engineering

09

Future of robotics

The future of robotics covers the advancement of robotics capable of performing tasks autonomously or semi-autonomously, adapting to new, real-life inputs with increasing degrees of autonomy and dexterity, including autonomous mobile robots and humanoid robots.

The trend—and why it matters

Over the past six decades, robots have become a familiar presence in advanced manufacturing. Today, more than four million industrial robots work in settings such as automobile plants. Interest in physical robotics, enabled by advances in AI, surged beyond industrial settings in 2024. A growing number of companies are developing robots with different form factors, from robotic arms and quadrupeds to humanoid machines that navigate and operate in physical spaces designed for humans. The same kinds of AI foundation models that enable the creation of chatbots are being trained to control robots to respond flexibly in novel situations. The combination of new form factors and more flexible control systems could put more multipurpose or even general-purpose robots to work.

Robots are increasingly being designed and deployed in environments beyond manufacturing, including airports, large-format stores, and restaurants. While annual industrial-robot installations are forecast to grow in the mid-single-digit percentages annually for the next few years, with half of the new installations in China, the market for service robots in areas such as logistics, hospitality, and agriculture has been growing many times faster—20 to 35 percent annually. Although interest in "humanoid" robots is growing, many robots do not resemble humans at all. For example, autonomous mobile robots (AMRs) that transport materials within a warehouse resemble a robotic household vacuum more than a person. An increasing number of robots are being designed to operate safely side by side with human workers. Known as cobots, short for collaborative robots, they expand the number of tasks and situations in which robots can be deployed beyond industrial settings, where safety walls often separate them from human workers.

Despite significant advancements, challenges persist. Untethered humanoid robots are constrained by power: A state-of-the-art humanoid robot can operate for about four hours before needing to be recharged, which takes roughly two hours. Humanoid robots also fall down—the balance needed to stay atop two feet is harder to achieve than one might expect. Handlike devices are often much slower than human hands when it comes to grasping objects, and other devices, such as suction cups, can be more effective for certain tasks. Other critical priorities to address are workforce reskilling, physical safety of human coworkers, and robust cybersecurity frameworks.[1]

1 Future of robotics insights provided by the Stanford Robotics Center.

CUTTING-EDGE ENGINEERING

Future of robotics

Scoring the trend

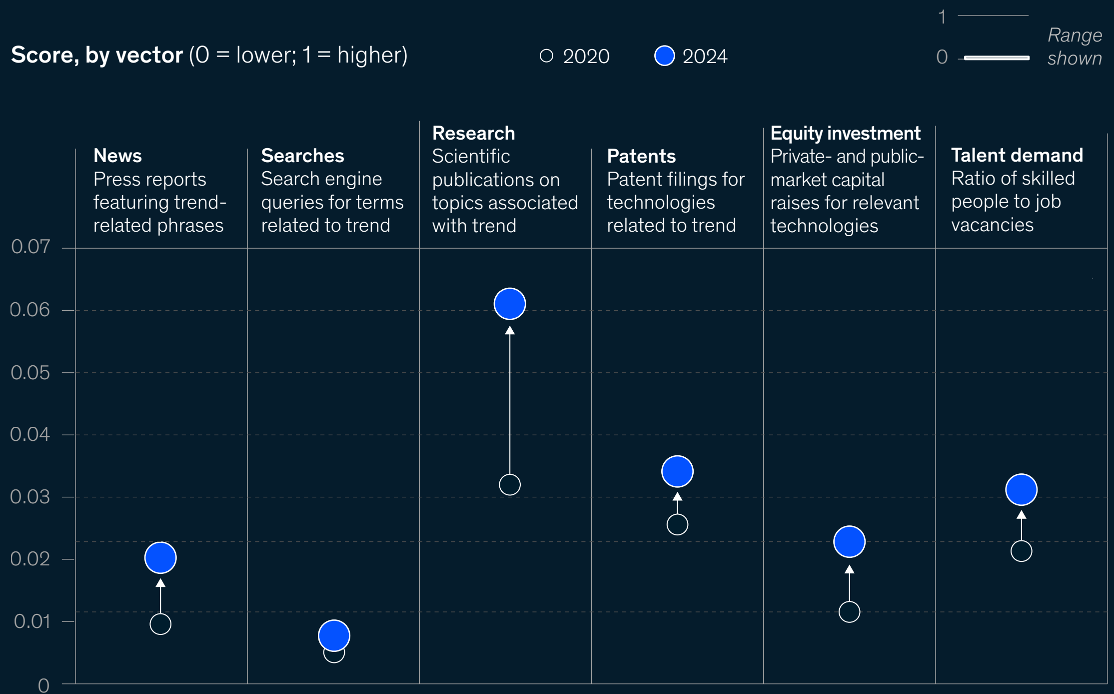
Compared with other trends, robotics has a smaller overall footprint. Nonetheless, interest and innovation metrics for robotics increased by double digits from 2023 to 2024. Media attention to humanoid robots partly explains the increased interest, but real technological innovations are being incorporated into robots, including equipping them with AI-driven capabilities like natural-language programming and advanced sensing. The market for robots is also expanding, with adoption in emerging sectors like agriculture and healthcare, the development of cobots, and broader deployment in manufacturing and logistics.

Equity investment, 2024

$7 billion

Job postings, 2023–24, % difference

–2%



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

Recent developments involving robotics include foundation models for robotics and humanoid robots:

— *An increasing number of robot developers are building "foundation models" to control robots in the physical world—the same AI solution that underpins progress in the virtual world.* These models are giant, simulated neural networks trained on immense quantities of varied unstructured data to generate unstructured output data, for example, large language models (LLMs). In the context of robotics, the goal is for foundation models to generate robot behaviors rather than language. Additionally, the industry hopes that, like LLMs, foundation models for robots will be able to generalize from their training data and generate appropriate responses to a wide range of inputs, even those they were not explicitly trained on.

— *The volume of training data is a limiting factor for using foundation models to control robots.* LLMs are trained on all the language data on the internet, but finding enough data to train robot foundation models on how to move is not easy. Researchers are getting creative by collaborating to collect bigger real-world training data sets, creating simulated worlds, teaching robots to watch videos, and paying workers to perform tasks repeatedly while being recorded, among other efforts.

- *Multiple companies are developing humanoid robots, which have vaguely human shapes—two arms, two legs, a body, and sometimes a head.* The practical reason for developing robots with human forms is to deploy them in physical spaces designed for human beings; after all, legs are more suitable than wheels for climbing stairs. These robots are designed for flexible applications, as they can be deployed for multipurpose or even general-purpose use.
- *Robotics has expanded into more sectors, particularly into services, including cobots working safely alongside human workers.* For example, robots are now working in the food service sector, preparing food. The healthcare sector has also expanded its use of robots, using them to deliver items in hospitals.

'The moment for AI-driven robotics has arrived. In the face of labor shortages and escalating production costs, the technology will soon become a dimension of competitive differentiation and a CEO-level agenda topic. The market opportunity is massive—up to approximately $900 billion by 2040—but adoption still requires addressing challenges around capability development, operating model, IT/OT [information technology/operational technology] infrastructure, and a playbook for automation at scale.'

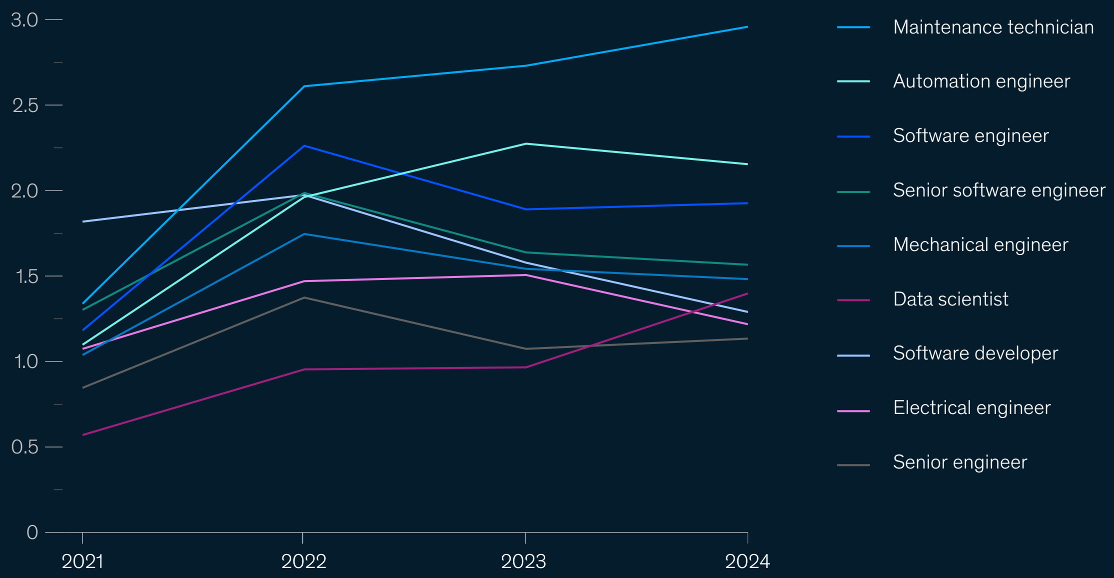
— Ani Kelkar, partner, Boston

Future of robotics

Demand

Although the number of jobs in robotics remains small compared with other sectors, demand increased across almost all job titles between 2021 and 2024. Positions such as maintenance technician, data scientist, and automation engineer had especially strong growth, reflecting expanded automation needs in manufacturing, logistics, and healthcare that require skilled technicians; the integration of AI systems demanding more data scientists to develop machine learning (ML) models for robotic decision-making; and the adoption of technologies necessitating automation engineers to implement cobots and Internet of Things–connected systems.

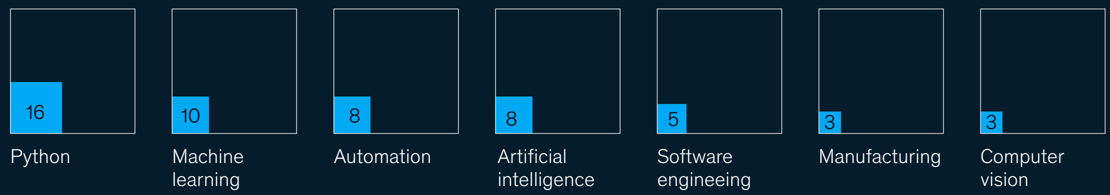
Job postings, by title, 2021–24, thousands



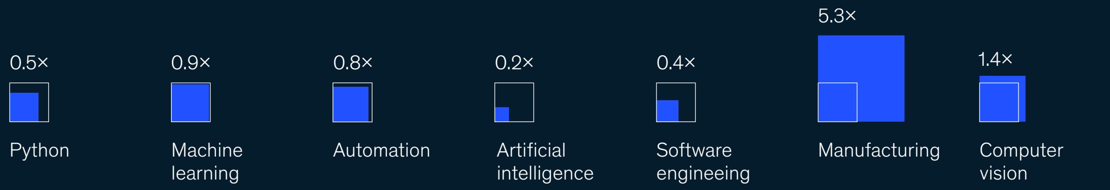
Skills availability

As robotics increasingly incorporates AI-powered systems, the demand for expertise in ML, AI, automation, and computer vision is growing, yet the talent pool remains constrained. Companies will need to bridge these skill gaps to fully unlock robotics technologies' transformative potential.

Talent required, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Adoption score: 2—Experimentation. Organizations are testing the functionality and viability of the technology using small-scale prototypes, typically without a focus on a near-term ROI. Few companies outside of manufacturing and e-commerce are scaling or have fully scaled the technology.

Although adoption varies across robotic technologies, several piloting initiatives are underway in warehouses, manufacturing, and general-purpose use cases.

In real life

Real-world examples involving the use of foundation models in robotics include the following:

— *Covariant introduced RFM-1, a robotics foundation model that gives robots human-like reasoning.* This model helps robots understand how objects move and interact in the real world, follow language-based instructions, and reflect on their own actions.[2]

— *Figure AI introduced Helix, a vision-language-action (VLA) model that enables humanoid robots to perform complex tasks, such as putting away groceries.* According to Figure AI, Helix is a step toward adaptable, real-world robotic applications, enabling dynamic object recognition and collaboration without prior training.[3]

Real-world examples involving the development of humanoid robots include the following:

— *Boston Dynamics introduced Electric Atlas, a fully electric humanoid robot with enhanced strength and a range of motion that can handle heavy objects in industrial settings.* Hyundai plans to deploy Electric Atlas in automotive manufacturing as a cobot.[4]

— *Tesla's Optimus is a humanoid robot designed for general-purpose tasks in industrial and domestic environments.* Standing five feet, eight inches tall and weighing 125 pounds, Optimus is equipped with advanced AI and 22 degrees of freedom in its hands. The company envisions deploying Optimus in various sectors, including manufacturing, healthcare, and home services.[5]

— *GXO Logistics has a multiyear agreement with Agility Robotics to deploy the Digit humanoid robot in its facilities, the first industry agreement of its kind.* Digit will automate tasks like moving totes and managing palletization, which can enhance operational efficiency and safety. Digit has performed successfully in a GXO pilot program, maximizing capacity and keeping up with demand in sectors like manufacturing, third-party logistics, retail, and e-commerce.[6]

Real-world examples involving expanded industry applications of robotics include the following:

— *Amazon has deployed AI-driven cobots across its warehouses to automate both pick-and-place and palletization tasks, significantly boosting throughput and accuracy.* These robots can handle a wide range of items, leveraging force sensors and AI-powered vision systems. This combination enables them to pick up and place objects with dexterity and tactile sensitivity.[7]

— *Launched in October 2023, BotBob is KFoodtech's advanced-robotic-kitchen solution that addresses labor shortages and operational costs in restaurants.* BotBob can cook up to six servings of traditional Korean stew in just 3.5 minutes, improving efficiency and reducing wait times.[8]

— *Tortuga AgTech's robots can identify and pick ripe fruit with 98 percent accuracy, requiring only one human supervisor.* These robots address labor shortages and reduce crop damage during harvesting.[9]

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2 Andrew Sohn et al., "Introducing RFM-1: Giving robots human-like reasoning capabilities," Covariant, March 11, 2024.
3 "Helix: A vision-language-action model for generalist humanoid control," Figure, February 20, 2025.
4 "An electric new era for Atlas," Boston Dynamics, April 13, 2024.
5 Niamh Ancell, "Optimus' new hand upgrade includes 22 degrees of freedom: What does it mean?," Cybernews, November 29, 2024; Jijo Malayil, "Watch: Tesla Optimus robot catches high-speed tennis balls with new hand upgrade," Interesting Engineering, November 29, 2024.
6 "GXO signs industry-first multi-year agreement," GXO Logistics press release, June 27, 2024.
7 "How AI-powered cobots transform the logistics industry," Techman Robot, accessed March 26, 2025; Dominic Preston, "Amazon develops a robot that 'feels' touch, just like its human workers," *Verge*, May 7, 2025.
8 Daehyun Song, "KFoodtech Inc. introduces BotBob – a next generation robotic kitchen solution for restaurant industry," KoreaTechDesk, September 13, 2023.
9 Jennifer Strailey, "Oishii acquires robotics company Tortuga AgTech, extends harvesting capabilities," *Packer*, March 24, 2025.

— *Sanctuary AI's advanced haptics tactile sensors*[10] *and Meta AI's*[11] *Digit 360 improved robotic dexterity to enable tasks like blind picking and slippage detection.* Digit 360 can detect spatial details as fine as seven microns and forces as small as one millinewton, which provides a foundation for more versatile and sensitive robotic applications across industries.

Underlying technologies

The technologies that power robotics include the following:

— *Advanced AI and ML.* These sophisticated algorithms and models enable robots to learn, adapt, and make complex decisions based on data and experience.

— *Sensor and vision systems.* Robotic sensing and vision technologies are hardware and software combinations that allow robots to perceive and interpret their environment, enabling tasks like object recognition and navigation.

— *Advanced actuators and motion control.* These are components and systems that precisely control robot movements, enabling complex and accurate physical interactions.

— *Human–robot collaboration.* Collaborative technologies allow robots to work safely and effectively alongside humans, enhancing productivity in various industries.

— *Robotics as a service (RaaS).* RaaS is a business model that provides robotic solutions on a subscription or pay-per-use basis, increasing access to advanced robotics for more businesses.

— *Autonomous navigation and decision-making.* These capabilities allow robots to move and operate independently in various environments and make real-time decisions based on their surroundings.

— *Tactile sensing.* Sensing technologies enable robots to detect and respond to physical contact, improving their ability to handle objects and interact with their environment.

— *Purpose-built batteries.* These batteries are specialized power sources designed to meet the specific energy requirements and operational demands of robotic systems.

Key uncertainties

The major uncertainties affecting the future of robotics include the following:

— *Uncertainties about the risk and trust framework for robotics emerge as they mix into our labor force beyond the traditional manufacturing use cases.* For example, the liability and safety protocols for autonomous robots may need to be redefined, as existing frameworks have difficulty addressing AI-driven decision-making. Establishing international standards for human–robot collaboration safety remains an important challenge.

— *The fascination, fear, and uncertainty surrounding humanoid robots have given rise to concerns that they may develop to meet and exceed the capabilities of certain employees.* As robots take on more advanced tasks, the nature of human work is evolving. For example, autonomous robots are increasingly being used to handle tasks like room service and cleaning in hospitality. While these systems improve efficiency, they also spur public fears about job displacement.

Big questions about the future

Businesses and leaders may want to consider a few questions when moving forward with robotics:

— When does it make strategic and financial sense to retrofit robotics into existing brownfield environments versus starting from a clean slate?

— Which untapped industries or service sectors are poised for a breakthrough in robotics implementation?

— Where do cobots create real value—and where do they get in the way?

— What new ethical and regulatory challenges will emerge with the rapid advancement of AI in robotics?

— What will it take to build employee and customer trust in robotics?

[10] "Sanctuary AI new tactile sensors enable richer sense of touch," Sanctuary AI press release, December 19, 2024.
[11] Chris McKay, "Meta is developing a robot hand that can touch and feel," Maginative, October 31, 2024.

10

Future of mobility

Mobility technologies include autonomous vehicles, electric vehicles, drones, urban air mobility solutions, such as electric vertical takeoff and landing aircraft, and micromobility, such as e-scooters and e-bikes, that have the goal of improving efficiency, safety, and sustainability of transportation systems.

The trend—and why it matters

The future of mobility in 2025 is rapidly evolving, driven by technological advancements and emerging demands for sustainability across autonomous vehicles (AVs), electric vehicles (EVs), drones, air travel, and micromobility. The integration of AI, advanced sensors, and connectivity is improving vehicle safety and efficiency, while shared-mobility models are reshaping urban transportation. These developments could revolutionize transportation, urban planning, energy systems, and the overall quality of life globally, with potential economic impacts through the creation of new markets and job opportunities.

However, challenges remain in regulatory frameworks, infrastructure development, and public acceptance. As these technologies mature, they promise transformative changes, but innovators must still navigate technological, regulatory, and consumer sentiment issues. For instance, EU battery regulations have set stricter standards for battery design, production, and end-of-life management, reflecting the growing emphasis on sustainability in the mobility sector.[1]

'We are now at a point where several groundbreaking new technologies are getting close to scaling, including, for example, autonomous-vehicle applications and next-generation battery chemistries. The critical next step will be moving from developing the technology to building new ecosystems.'

— Andreas Breiter, partner, Bay Area

[1] "The future of mobility," TÜV SÜD, accessed March 31, 2025.

CUTTING-EDGE ENGINEERING

Future of mobility

Scoring the trend

Despite a continued decline in equity investment, innovation metrics for mobility, including patents and research publications, continue to increase in line with broader trends across the tech sector. Overall interest in mobility rose 6 percent from 2023 to 2024, reflecting breakthroughs in AI-driven autonomous systems and expanding EV infrastructure.

Equity investment, 2024

$131.6 billion

Job postings, 2023–24, % difference

+6%

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

Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

Recent developments involving the future of mobility include the following:

— *Growth in sales of EVs has been uneven globally.* Growth in EV sales in the United States slowed in 2024 to a little over 7 percent, a marked decline from the almost 33 percent growth seen from 2022 to 2023. High production costs and the impending elimination of tax credits in 2025 in the United States contributed to lower demand.[2] Conversely, EV sales in China jumped nearly 36 percent, driven by strong consumer demand, expanding charging infrastructure, and government incentives.[3] In Europe, the average cost of battery electric vehicles (BEVs) has dropped to about $44,000, undercutting comparable gasoline-powered vehicles that cost $45,000 on average.[4] Automakers plan to release more affordable EV models globally, although affordability improvements remain slower in the United States, hampering widespread adoption.

2 Dan Grossman, "Electric vehicle sales slow in the US: What's behind the decline?," Scripps News, February 25, 2025.
3 Chris Randall, "China hits 12.9 million new energy vehicle sales in 2024," *Electrive*, April 23, 2025.
4 Jake Lingeman, "Experts predict a major shift in the US car market in 2025," *Newsweek*, February 18, 2025.

- *AVs are making progress but still face hurdles.* Shared autonomous vehicles are already operating in multiple cities, including Los Angeles, Phoenix, and San Francisco. The adoption timeline has, on average, slipped by two to three years across all autonomy levels relative to past predictions, stymied by ongoing technical obstacles, high operational costs, and public skepticism. Unit costs are expected to lower significantly by 2035, as companies achieve greater vehicle utilization, make operational improvements, and reduce R&D needs. However, about 50 percent of respondents surveyed believe safety remains one of the key bottlenecks to widespread AV adoption.[5] Nonetheless, industry leaders should continue to collaborate with regulators and establish standard frameworks for continuous improvements to safety, accessibility, and affordability of autonomous-driving systems.

- *Drones continue to expand their role in commercial operations.* Delivery drone services are expected to reach $29 billion by 2034, a CAGR of 40 percent.[6] Consumer interest remains high, particularly for the convenience drone delivery offers, though safety and privacy remain concerns. Companies are customizing drones to meet specific delivery needs and integrating them with AVs for seamless last-mile delivery solutions. Additionally, underwater drones have gained prominence for intelligence, surveillance, and reconnaissance missions in maritime environments, displaying extended endurance for real-time intelligence gathering.

- *The industry for electric vertical takeoff and landing (eVTOL) aircraft is advancing toward regulatory certification for carrying paying passengers, marking a critical step toward commercial urban air mobility.* Multiple manufacturers are progressing through certification stages with aviation authorities globally, while regulators are working to harmonize safety standards and operational guidelines. Although infrastructure and air traffic integration challenges remain, the sector is poised to begin limited commercial-passenger operations within the next year, signaling a transformative shift in short-distance urban transportation.

- *Micromobility is showing resilience after previous oversupply issues.* The introduction of new products like micro-EVs and declining e-bike costs have spurred renewed demand. Major players, such as e-scooter companies Bird and Lime, have consolidated their positions through acquisitions and partnerships, as cities increasingly integrate micromobility options into public transportation systems. Personal e-mobility devices such as e-scooters and e-bikes are gaining mainstream acceptance globally, and infrastructure adaptations in many cities support their growth. In Asia and Europe, two-wheelers are increasingly electrified in response to environmental concerns and supportive policies.

- *Innovative technologies are advancing water mobility and electrification.* Autonomous barge systems equipped with advanced crane technologies are in development to streamline loading and unloading processes at ports, with the goal of reducing handling times and improving efficiency.[7] Additionally, computer-controlled hydrofoil technology has begun to lift vessels above water surfaces, significantly reducing drag and energy consumption.

5 "Getting on board with shared autonomous mobility," McKinsey, January 3, 2025.

6 "Delivery drone market to register a CAGR of 40.3% from 2025 to 2034 to reach USD 29,417.91 million by 2034: Report by Polaris Market Research," GlobeNewswire, December 18, 2024; "Delivery drone market share, size, trends, industry analysis report, 2024–2032," Polaris Market Research, December 2024.

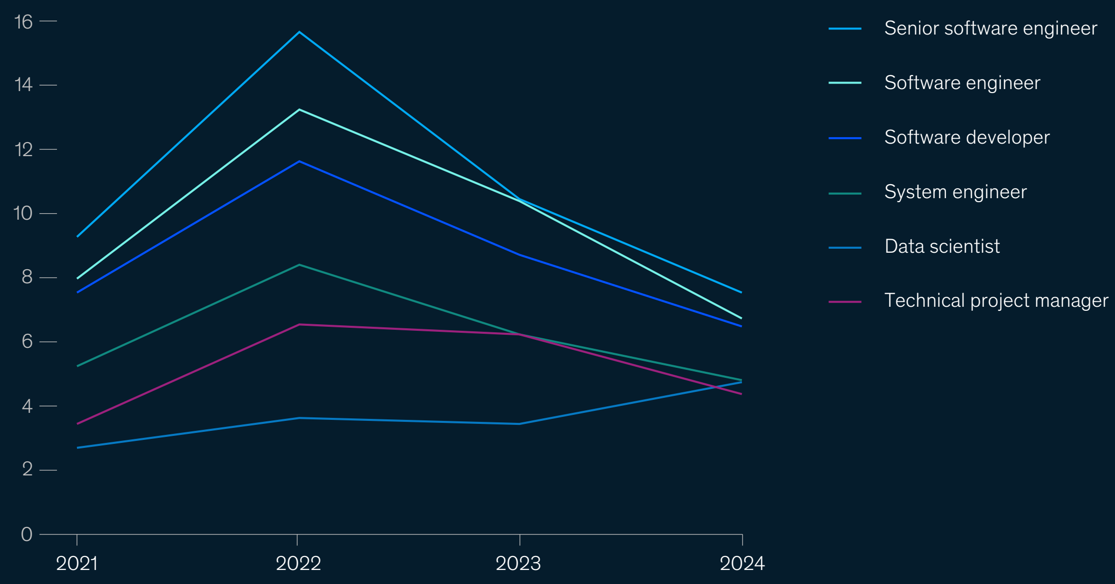
7 Waseem Al Rousan, "Smart ports: Optimizing operations with AI and automation," Datahub Analytics, October 8, 2024.

Future of mobility

Demand

Software roles peaked in 2022 before declining more recently, potentially related, in part, to AI streamlining the coding process for autonomous systems. Job postings for data scientists have grown steadily, reflecting rising demand for battery analytics and AI-driven logistics. The sector's pivot toward data-centric mobility solutions and AI-augmented workflows underscores a broader shift away from traditional software roles, as the industry prioritizes sustainability and autonomy.

Job postings, by title, 2021–24, thousands



Skills availability

Even as available roles in software engineering decline, the mobility sector faces deficits in software engineering and Python skills, and user experience talent remains in significant shortage. Fleet management and C++ skills show surpluses, and data analysis talent is oversupplied.

Talent required, % share of postings requiring skill

Talent availability, ratio of talent to demand

‘Executives and investors are very confident that the volumes invested in mobility firms in 2025 are going to be higher than in recent years. The valuations won’t necessarily increase at the same time, but more and more investors are excited about the opportunities that exist. This newfound optimism can partly be explained by the more positive news coming out of the mobility space.’

— Kersten Heineke, partner, Frankfurt

Adoption developments across the globe

Adoption score: 3—Piloting. Organizations are deploying the technology in the first few business use cases, via pilot projects or limited implementation, to test its feasibility and effectiveness.

Despite some regional fluctuations in demand, the global market remains robust, driven by sustainability efforts and technological advancements. However, some areas of the globe lag behind in mobility innovation and adoption. For example, Africa is a slow adopter of EVs, as its nations struggle with reliable and continuous electricity access. The Middle East is also a slower adopter due to the low cost of fuel in the region.

In real life

Real-world examples involving progress in autonomous vehicles include the following:

— *Waymo expanded its fully autonomous ride-hailing service to Los Angeles and Austin, Texas, in 2024, going from 12,000 rides in August 2023 to 312,000 one year later.*[8] The company is exploring global expansion and plans to enter the Japanese market in 2025, offering rides in Tokyo’s complex urban environment.[9]

— *In December 2024, Kodiak Robotics launched its first commercial driverless operations in West Texas in partnership with Atlas Energy Solutions.* Robo-trucks equipped with Kodiak’s proprietary self-driving system, the Kodiak Driver, were used on private roads in the Permian Basin. These trucks autonomously transported fracking sand for Atlas, delivering 100 loads by early 2025. This operation showcased the ability of AVs to navigate harsh conditions such as extreme heat and dust storms while maintaining safety and efficiency.[10]

The following is a real-world example of the expanding role of drones in commercial operations:

— *Several companies are actively advancing pilot programs for commercial drone delivery in 2025.* Amazon Prime Air has resumed drone deliveries in some US markets, and Walmart is expanding its drone delivery services through partnerships with providers like Wing and Zipline. Other companies are also scaling autonomous-delivery operations, supported by growing Federal Aviation Administration (FAA) approvals and increasing demand for faster, contactless logistics.

The following is a real-world example involving the eVTOL industry:

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8 Yiwen Lu, “Waymo’s had a quiet—but huge—increase in ridership,” *Sherwood News*, November 4, 2024.
9 Sharon Feldman, “What we know about Waymo’s 2025 expansion plans,” *Ars Technica*, February 27, 2025.
10 “Kodiak delivers first customer-owned autonomous robotrucks to Atlas Energy Solutions, completes 100 loads of proppant with first-ever driverless commercial semi-truck service,” Businesswire, January 24, 2025.

— *Urban air mobility players are making steady progress toward commercialization.* Archer Aviation's Midnight air taxi, designed for short-distance urban transportation, is preparing to launch in its first market commercially.[11] Joby Aviation has made progress toward FAA certification and aims to begin operations soon.[12]

The following is a real-world example of micromobility:

— *In 2024, Lime expanded to more than 20 new cities globally, including Tokyo and Athens, Greece.* The company also surpassed 750 million lifetime rides, a notable shift toward more sustainable urban transportation options. Lime's expansion reflects the growing interest in micromobility solutions as cities explore ways to reduce congestion and emissions.[13]

The following is a real-world example of innovative water mobility technologies:

— *Launched in 2024, the Candela P-12 Nova is the world's first electric hydrofoil ferry.* Candela says that *Nova* reduces energy consumption by 80 percent compared with conventional vessels by cutting water friction. Powered by renewable electricity, Nova emits minimal noise and has no wake, allowing for high-speed operation within city limits.[14]

Underlying technologies

The technologies that power the future of mobility include the following:

— *Autonomous technologies.* Advanced sensor fusion systems, edge AI processors, and fail-safe architectures enable vehicles to perceive their environment, make decisions, and operate safely without human intervention.

— *Connected-vehicle technologies.* 5G vehicle-to-everything (V2X) communications, robust cybersecurity protocols, and over-the-air update capabilities enable vehicles to interact with infrastructure, other vehicles, and networks to enhance safety, efficiency, and user experience.

— *Electrification technologies.* Solid-state batteries, bidirectional charging systems, and hydrogen fuel cells can improve vehicle powertrains by extending range, reducing charging times, and enabling integration with smart grids.

— *Shared-mobility solutions.* Mobility-as-a-service platforms and dynamic fleet rebalancing algorithms optimize the use of shared vehicles, reducing congestion and emissions and improving urban mobility.

— *Materials innovation.* Biobased composites, fire-resistant battery materials, and recyclable aerogels are enhancing vehicle performance, safety, and sustainability through lightweight, durable, and environmentally friendly components.

— *Value chain decarbonization.* Green-methanol shipping, circular supply chains, and carbon capture in manufacturing processes are reducing the environmental impact of vehicle production and logistics.

— *Software-defined vehicle architectures.* Centralized computing platforms enable modular hardware upgrades and continuous software improvements, enhancing vehicle functionality and longevity.

— *Digital-twin technologies.* AI-driven simulations to predict maintenance needs and optimize fleet operations improve efficiency and reduce downtime across mobility ecosystems.

— *Advanced battery management systems.* AI algorithms optimize charging cycles and extend battery life, improving the long-term viability and performance of EVs.

Key uncertainties

The major uncertainties affecting the future of mobility include the following:

— *Global energy supply expansion.* In 2025, global lithium demand is expected to outpace supply, reflecting the surge in EV production.[15] If the EV market continues to grow, significant

[11] Joe Macey, "Archer reveals Launch Edition program for Midnight eVTOL in Abu Dhabi," *Advanced Air Mobility*, March 5, 2025; Hanneke Weitering,"Abu Dhabi Aviation will be first Archer eVTOL aircraft operator in the UAE," AINonline.com, February 28, 2025.
[12] "Joby reports record certification progress and delivery of second aircraft to US Air Force at Edwards Air Force Base," Joby Aviation, February 26, 2025.
[13] "Lime delivers record revenue and profitability, positive free cash flow in 2024," Business Wire, February 18, 2025.
[14] "World's first electric hydrofoil ferry line takes off in Stockholm," Candela press release, October 29, 2024.
[15] "Facing the tightening lithium supply challenge in 2025," Fastmarkets, February 6, 2025.

investments in battery manufacturing capacity will be needed.

— *Safety and accountability concerns.* As AV technology advances, safety remains a top priority among industry leaders and innovative players. For example, the scale and public visibility of the autonomous-trucking sector depend on rigorous safeguards. Self-driving freight company Aurora plans to deploy driverless trucks in Texas in 2025, underscoring the need for robust safety regulations and public trust-building measures.

— *Equipment and infrastructure costs.* EV-charging infrastructure costs vary widely, from $2,000 for basic Level 1 chargers to more than $100,000 for direct current fast-charging stations. Installation expenses often exceed equipment costs, requiring site preparation, electrical upgrades, and permits that increase the total investment.[16]

— *Public acceptance and trust.* Building trust in AVs through increased transparency and public education is essential for widespread adoption. The J.D. Power 2024 US Mobility Confidence Index showed a modest increase in consumer confidence in AVs, although it remains low at 39 out of 100.[17]

— *Cybersecurity and privacy.* As vehicles become more connected and software defined, addressing cybersecurity threats and protecting user data has become increasingly critical. This includes securing V2X communications and safeguarding personal information collected by smart vehicles.

Big questions about the future

Companies and leaders can consider a few questions when moving forward with mobility technologies:

— How will changing geopolitics affect the mobility supply chain?

— In what ways will the expansion of central-mobility hubs, such as train and bus terminals and shared-micromobility depots, and connected transport networks reshape urban landscapes and commuting patterns?

— What are the implications of public infrastructure versus private investment in shaping the future of mobility?

— How will public trust and acceptance of autonomous vehicles evolve?

— How will shifts in regulation determine the speed and scale of adoption for autonomous vehicles, drones, and next-generation transport systems?

[16] "EV charging infrastructure costs: What's behind the price tag for electrification," Clean Current, March 6, 2025.
[17] "AV readiness increases after a two-year decline, J.D. Power finds," J.D. Power press release, October 22, 2024.

11

Future of bioengineering

Bioengineering is the application of engineering principles to biology, utilizing technological advancements (for example, gene editing, synthetic biology) to improve health and human performance, transform food value chains, and create innovative offerings.

The trend—and why it matters

The convergence of biological sciences and advanced computing technologies is setting the stage for the next wave of innovation in bioengineering. This intersection drove innovations across multiple sectors in 2024, with advancements in bioengineering affecting industries such as healthcare, agriculture, pharmaceuticals, and environmental management. Breakthroughs in gene editing, personalized medicine, and synthetic biology promise to improve human health and longevity while offering more environmentally friendly solutions for food production and security. The use of AI in bioengineering is accelerating R&D and reducing costs, allowing researchers to identify new materials, create more optimized bioroutes to production, and prototype more products. As a particularly notable example of AI's enabling role in bioengineering, the 2024 Nobel Prize in Chemistry was shared by three researchers who have used AI to predict the structure of existing proteins and design new proteins.[1]

The rapid evolution of these technologies, however, brings new ethical, regulatory, and societal challenges. Successful adoption of bioengineering innovations depends on ensuring public acceptance and creating robust frameworks for responsible development and application. While the science underpinning many of these advancements is proved, achieving commercial viability and addressing societal concerns remain crucial for realizing the full potential of bioengineering technologies.

'Bioengineering is finally at the stage where we are starting to see some level of maturity—such as more ubiquitous use of AI in chemical and biologic design, on-market bioengineered precision medicines, and 3D bioprinting. No one doubts the scientific and economic impact of this space anymore.'

— Erika Stanzl, partner, Zurich

[1] "Nobel Prize in Chemistry 2024," Nobel Prize Outreach 2025 press release, October 9, 2024.

CUTTING-EDGE ENGINEERING

Future of bioengineering

Scoring the trend

Although equity investment has fallen since 2020, the trend holds an overall strong innovation score due to AI-fueled advancements in the field and a growing number of published research papers.

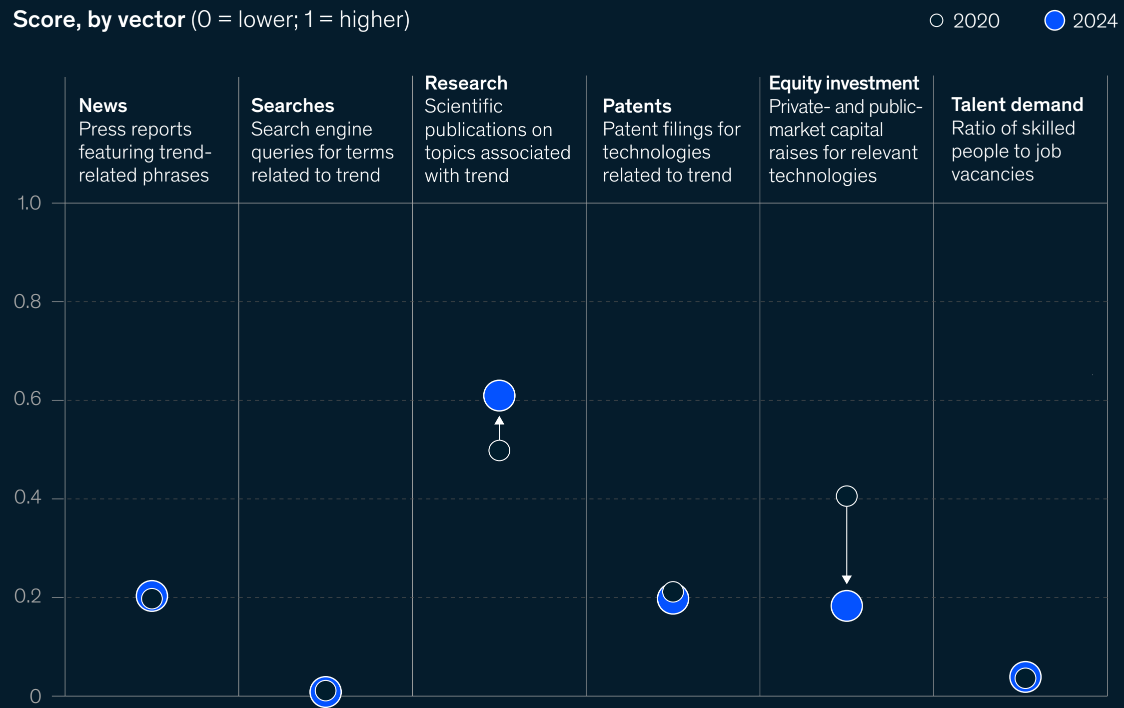
Equity investment, 2024

$57.3 billion

Job postings, 2023–24, % difference

–17%

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



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

Recent developments involving the future of bioengineering include the following:

— *Biomaterials and tissue engineering continue to advance rapidly.* Significant progress in 3D bioprinting and regenerative therapies is increasing the potential for lab-grown organs and advanced treatments for complex diseases.[2]

— *Manufacturing capacity is beginning to scale to match scientific progress.* The bioengineering industry is expanding production capacity by installing large-scale infrastructure, such as 2,000-liter bioreactors, to support growing demand and enable broader clinical translation.[3]

— *AI is accelerating R&D in both pharmaceuticals and biomaterials.* In drug development, AI is streamlining tasks like data processing and candidate screening, helping reduce trial

[2] "Progress in organ bioprinting for regenerative medicine," *Engineering Journal*, August 2, 2024.
[3] "Cytiva broadens Xcellerex X-platform to include 500L and 2 000L bioreactors," Cytiva, March 25, 2025.

preparation time and increase efficiency. In biomaterials, AI supports the rapid design and testing of novel compounds by modeling unique molecular structures. These advances are shortening innovation cycles and lowering development costs across the life sciences.[4]

— *CRISPR-based therapies are moving beyond clinical trials into approved treatments.* This milestone in precision medicine has ushered in a new era for treating genetic disorders at their root and is already catalyzing further innovation in gene-editing delivery systems and expanding the scope of treatable diseases.[5]

— *Breakthroughs in bioengineering—including advances in 3D cell culture systems that enhance tissue architecture modeling and injectable biomimetic hydrogels that improve regenerative microenvironments—propelled stem cell research forward in 2024.*[6] These innovations addressed critical challenges in reproducibility, immune rejection, and clinical scalability, accelerating the translation of stem cell therapies into advanced therapeutic medicinal products like tissue-engineered grafts and gene-edited cell formulations.[7]

‘Significant progress has been made in the lab, making new molecules and materials more effectively, and continues to accelerate. But to achieve commercial viability, efficient production is required; to really scale, we’ll also need advances in how we design, build, and operate commercial-scale production assets. This is a massive opportunity for engineers, manufacturers, and construction firms who can crack this problem.’

— Tom Brennan , partner, Philadelphia

[4] “Matmerize, CJ Biomaterials team up to harness AI technology driving sustainable polymer solutions,” Bernama, May 4, 2024; Adam Bluestein, “How this company is helping researchers identify potential new drugs,” *Fast Company*, March 19, 2024.

[5] “In another win for CRISPR, FDA approves Casgevy for beta thalassemia,” *Inside Precision Medicine*, January 17, 2024; Hope Henderson, “CRISPR clinical trials: A 2024 update,” Innovative Genomics Institute, March 13, 2024; Gorm Palmgren, “CRISPR partnerships propel precision medicine,” CRISPR Medicine News, February 20, 2024.

[6] José Mauro Granjeiro et al., “Bioengineering breakthroughs: The impact of stem cell models on advanced therapy medicinal product development,” *World Journal of Stem Cells*, October 16, 2024; “Top 5 latest advances in stem cell applications for tissue engineering,” MTM Lab, accessed April 18, 2025.

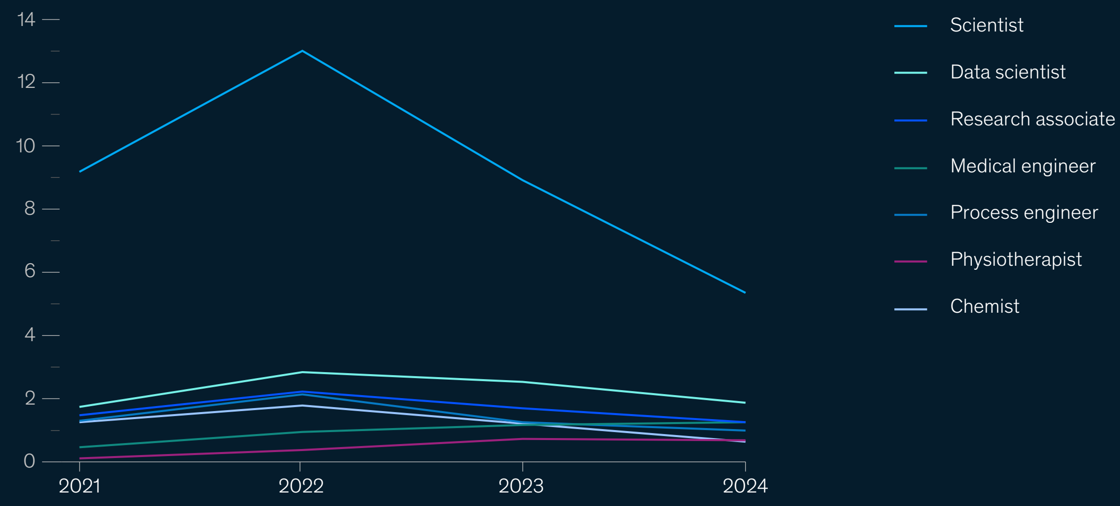
[7] Bashdar M. Hussen et al., “Revolutionizing medicine: Recent developments and future prospects in stem-cell therapy,” *International Journal of Surgery*, December 2024, Volume 110, Issue 12.

Future of bioengineering

Demand

The job market for bioengineering roles has shown some signs of contraction since 2022. Key positions such as scientists, chemists, and researchers have seen declines in postings, with most top job categories relevant to bioengineering experiencing a drop from 2023 to 2024. This trend indicates a cooling in hiring demand within the bioengineering sector, likely driven by a combination of funding slowdowns in biotech, consolidation across the pharmaceutical and research landscape, and delayed commercialization of emerging bio-based technologies.

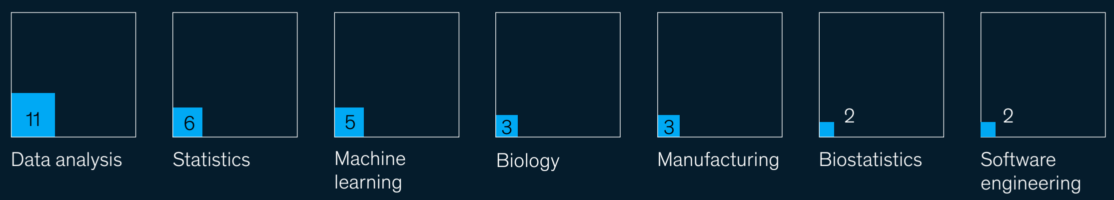
Job postings, by title, 2021–24, thousands



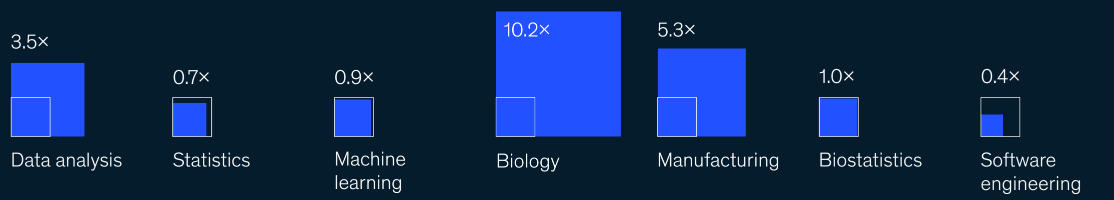
Skills availability

In some areas of bioengineering, there is sufficient talent to meet the demand. For example, there are more people with broadly applicable skills such as biology and data analysis in the talent pool than open roles requiring those skills. Conversely, more specialized skills like machine learning, statistics, and biostatistics are more proportionally represented, with talent availability more closely aligned to job market demand. These skills, along with software engineering, are increasingly important as bioengineering integrates more computational and data-driven approaches, requiring professionals who can bridge biology with advanced analytics and AI techniques.

Talent required, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Adoption score: 4—Scaling in progress.
Organizations are scaling deployment and adoption of the technology across the enterprise.

Biotechnology is rapidly scaling across diverse industries, moving beyond limited deployments. Breakthroughs like the US Food and Drug Administration (FDA) approval of Casgevy and advancements in precision fermentation and biomaterials demonstrate the technology's transformative potential. Bolstered by AI-driven solutions that accelerate drug discovery and material design, the commercial impact is growing. The combination of technological maturity, commercial viability, and AI-driven acceleration positions biotechnology for scaling across enterprises.

In real life

Real-world examples involving advances in biomaterials and tissue engineering include the following:

— *Kyoto University and Shinobi Therapeutics are using biologically derived scaffolds, including collagen, in regenerative-medicine applications.* This innovation optimizes scaffold stability and reduces immunogenicity for soft-tissue repair. Shinobi's collaboration with Panasonic on closed-system manufacturing devices could incorporate AI-powered systems to optimize automated systems.[8]

— *A landmark bioengineering advancement in 2024 centered on mRNA-lipid nanoparticle technology to reprogram adult cells into induced pluripotent stem cells.* Researchers used engineered lipid nanoparticles—tiny, fat-like carriers—to deliver synthetic mRNA instructions into skin cells, temporarily activating genes that "reset" them into versatile stem cells without altering their DNA. This method, refined by teams at Harvard and uBriGene Biosciences, could enable scalable, patient-specific stem cell production for repairing damaged tissues, modeling diseases, and testing therapies.[9]

Real-world examples of companies scaling production to match scientific progress include the following:

— *21st.BIO, a Danish biotech company, specializes in precision fermentation to enable large-scale production of sustainable proteins and biomaterials.* In 2024, 21st.BIO launched a pilot facility to scale fermentation and entered the US market.[10]

— *The LYCRA Company, in collaboration with Dairen Chemical Corporation (DCC), is working to produce renewable spandex on a large scale.* DCC has developed a process with a markedly lower carbon footprint, using corn to create a material used in making spandex.[11]

The following is a real-world example of how AI accelerates research and development in pharmaceuticals and biomaterials:

— *Adaptyv Biosystems launched a protein-engineering foundry.* The facility leverages gen AI, open-source software, and synthetic biology to develop new medicines, enzymes, and sustainable materials. The company's platform combines robotics and microfluidics to validate AI-based protein designs, accelerating the drug discovery process.

Additional real-world examples of breakthroughs in bioengineering include the following:

— *GOOD Meat received regulatory approval to sell cultivated chicken in the United States, and UPSIDE Foods, which gained FDA and USDA approval,*[12] *served cultivated chicken at a Michelin-star restaurant in San Francisco as part of a limited release.* Both companies are pursuing scaled production but have faced technical and regulatory challenges with ramping up operations.[13]

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8 "Panasonic and Shinobi Therapeutics partner to develop efficient and cost-effective iPS cell therapy manufacturing technology," Shinobi Therapeutics press release, April 18, 2024.
9 "uBriGene Biosciences submits drug master file for iPSC Reprogramming mRNA-LNP Kit," BioSpace, March 4, 2025; "HSCI researchers achieve major breakthrough in cell reprogramming," Harvard Stem Cell Institute, accessed April 18, 2025.
10 "21st.BIO unveils a new pilot plant facility to accelerate impact of biotech innovations globally," 21st.BIO press release, May 6, 2024.
11 Daniela Castillo Monagas, "LYCRA Company partners with Dairen for world's first large-scale, bio-derived spandex," World Bio Market Insights, May 9, 2024.
12 "GOOD Meat and UPSIDE Foods approved to sell cultivated chicken following landmark USDA action," Good Food Institute, June 21, 2023.
13 "Upside's cultivated chicken debuts at Bar Crenn: 'The first meat that I feel good about serving,'" Green Queen, July 3, 2023; "Upside Foods struggles with lab-grown chicken despite $600 million - Bloomberg," SOSV, December 14, 2023.

— *The EVERY Company produces animal-free egg proteins with precision fermentation.* Its signature product is the EVERY Egg, and it makes ingredients for food and beverage products, such as coffees, juices, syrups, and baked goods. In 2024, the company received a foundational patent for recombinant ovalbumin production and expanded partnerships with Unilever, Grupo Nutresa, and Grupo Palacios.[14]

Underlying technologies

Advancements in the following technologies will define the future of bioengineering in 2025:

— *Omics.* Single-cell sequencing is emerging as a transformative approach for integrating data from DNA, RNA transcripts, and methylation, providing a comprehensive view of cellular function and regulation. Building on this foundation, single-cell proteomics is advancing as a tool for characterizing protein expression at the individual cell level. When combined, these technologies offer insights into cellular heterogeneity and intricate biological processes. Additionally, integrating multiomics into multimodal AI models is addressing long-standing challenges related to differences in format and structure that are faced when combining diverse multiomic data sets. Deep learning techniques, a subset of AI, have enabled analyses that are more sophisticated than traditional statistical approaches.

— *Gene editing.* The FDA approved a CRISPR-based therapy for the first time. In vivo gene-editing programs to combat rare diseases are advancing to clinical trials, increasing the potential to treat larger patient populations.

— *3D bioprinting and tissue engineering.* Novel high-throughput bioprinting techniques using spheroids have accelerated the creation of complex tissues with high cell viability. The technology, which produces tissue ten times faster than existing methods, is advancing the development of functional tissues and organs for transplantation and drug testing.

— *Biomaterials.* Eco-friendly raw materials derived from vegetable oils are being developed for various applications, including cosmetics, superabsorbent polymers, and adhesives. Biologically derived scaffolds, such as collagen, are being optimized for regenerative-medicine applications.

— *Synthetic biology and metabolic engineering.* Precision fermentation is advancing, with companies producing nature-equivalent proteins through fermentation that are more environmentally friendly alternatives to traditional proteins derived from dairy and other sources.

— *Precision medicine technologies.* AI-powered solutions are accelerating target identification in drug discovery, reducing clinical trial costs and R&D time. Personalized treatment strategies based on specific protein signatures are being developed to treat cancer and other diseases.

Key uncertainties

The major uncertainties affecting the future of bioengineering include the following:

— *Regulation of bioengineering.* Regulatory frameworks are evolving to address rapid advancements in bioengineering. For example, the National Defense Authorization Act for fiscal year 2025 requires the US Department of Defense to create an annual biotechnology road map and assess barriers to adoption, workforce needs, and international collaboration. Similarly, the FDA's 2025 guidance agenda includes new recommendations for evaluating biologics and therapeutic products, reflecting the growing need for oversight in this field. Yet there is uncertainty about how Europe and China will regulate bioengineered food and crops. While Europe debates easing restrictions on certain genomic techniques, China is expanding approvals for genetically modified crops but faces public skepticism about their safety, creating a complex global regulatory landscape.[15]

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14 "EVERY secures foundational patent for ovalbumin produced via precision fermentation," Business Wire, September 2, 2024; "The Every Co. eliminates the chicken from egg production," *Food Business News*, January 2, 2024.

15 Robert Hodgson, "Governments agree to ease regulation of new-generation GMOs," Euronews, March 14, 2025; Zhitao Du, Yuqi Xiao, and Jinghong Xu, "How does information exposure affect public attitudes toward GMO in China? The mediating and moderating roles of conspiracy belief and knowledge," *Frontiers in Psychology*, September 19, 2022, Volume 13.

- *Public perceptions and ethical concerns.* Public attitudes toward bioengineering remain mixed, with concerns about safety, equitable access, and ethical implications. Issues such as the “blurring of boundaries” between natural and artificial systems persist, particularly when it comes to synthetic-biology applications. During the COVID-19 pandemic, skepticism about these technologies increased, including concerns about bioengineered organisms’ ability to self-replicate or persist in ecosystems.
- *Unintended consequences.* Bioengineered systems are inherently interconnected, meaning small changes can have cascading effects. This is particularly relevant in light of the self-replicating nature of engineered organisms and the potential for unintended consequences, including horizontal gene transfer, biodiversity loss, or ecological disruption when these organisms interact with natural ecosystems. Modified agricultural organisms, for example, may face challenges related to survival and propagation in the environment, with some failing while others persist unexpectedly.
- *Biosecurity and dual-use risks.* The dual-use nature of biotechnology is another growing concern because tools designed for beneficial purposes can also be misused in harmful applications like bioterrorism. The intersection of AI and bioengineering amplifies these risks by lowering technical barriers to advanced bioengineering. Initiatives such as the Biological Weapons Convention and AI safety summits aim to mitigate these threats through international collaboration.
- *Effectiveness of technologies versus traditional approaches.* While bioengineering technologies have transformative potential, their effectiveness compared with traditional methods is still under evaluation. For example, synthetic biology-based therapies must demonstrate cost-effectiveness and scalability to compete with established treatments—and meet rigorous safety standards.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with bioengineering:

- How will society balance the potential benefits of genetic-editing technologies with medical-ethics concerns?
- What factors will influence public acceptance and adoption of genetically engineered crops and other bioengineered products?
- How will regulatory frameworks evolve to address safety and trust issues around emerging bioengineering technologies?
- How will geopolitical divergence in clinical research and regulation determine the global balance of power in bioengineering?

12

Future of space technologies

Space technologies cover satellite systems, launch vehicles, habitation modules, and exploration missions, including low-Earth-orbit satellite constellations, direct-to-device connectivity integrating space assets with terrestrial networks, and Earth observation.

The trend—and why it matters

Space technologies are rapidly reshaping our world, unlocking new levels of connectivity and data-driven insights that are attracting broad interest beyond traditional aerospace. Companies have joined countries in global launch activity and investment in space exploration. Japan had a successful moon landing, and NASA has hired private companies to develop lunar landers for its Artemis program. Businesses are also working on end-to-end solutions that integrate space technologies with terrestrial infrastructure to provide seamless services across various sectors.

Since 2024, expanding use cases in areas such as remote sensing and Earth observation have attracted attention and investment from a number of high-profile tech companies. The latest trends in this technology include constellations of low-Earth-orbit (LEO) satellite communications, most notably SpaceX's Starlink, which has more than 7,000 LEO satellites in orbit.[1] Potential competitors such as Project Kuiper by Amazon, which launched 27 LEO satellites in April 2025, have also entered the market.[2] In the mobile phone sector, direct-to-device (D2D) satellite connectivity is being rolled out, as illustrated by Apple's emergency connection feature for iPhones.

Looking forward, the industry could face questions surrounding ownership and access rights to space, establish governance structures for safe operations, and coordinate efforts to manage space debris and traffic effectively. Additionally, the industry will likely have to navigate growing cyber risks and define the future landscape of satellite distribution across different orbits.

'Space is quickly becoming an essential platform for innovation, security, and economic growth. The dramatic reduction in launch costs, the rise of commercial satellite constellations, and new in-orbit capabilities are transforming what's possible across industries. The organizations that will lead in this new era are those that embed space-based data and connectivity into their core strategies, forging partnerships and building the talent needed to navigate a rapidly evolving ecosystem.'

— Ryan Brukardt, senior partner, Miami

1 Tereza Pultarova, "Starlink satellites: Facts, tracking and impact on astronomy," Space.com, June 4, 2025.
2 Joey Roulette, "Amazon launches first Kuiper internet satellites, taking on Starlink," Reuters, April 29, 2025.

CUTTING-EDGE ENGINEERING

Future of space technologies

Scoring the trend

Online searches for the future of space technologies declined somewhat from 2023 to 2024, likely linked to fluctuations in interest surrounding specific events such as asteroid discoveries and rocket launches. Nonetheless, searches increased overall from 2020 to 2024. Patents increased by 7 percent in 2024 from the previous year.

Equity investment, 2024

$9.3 billion

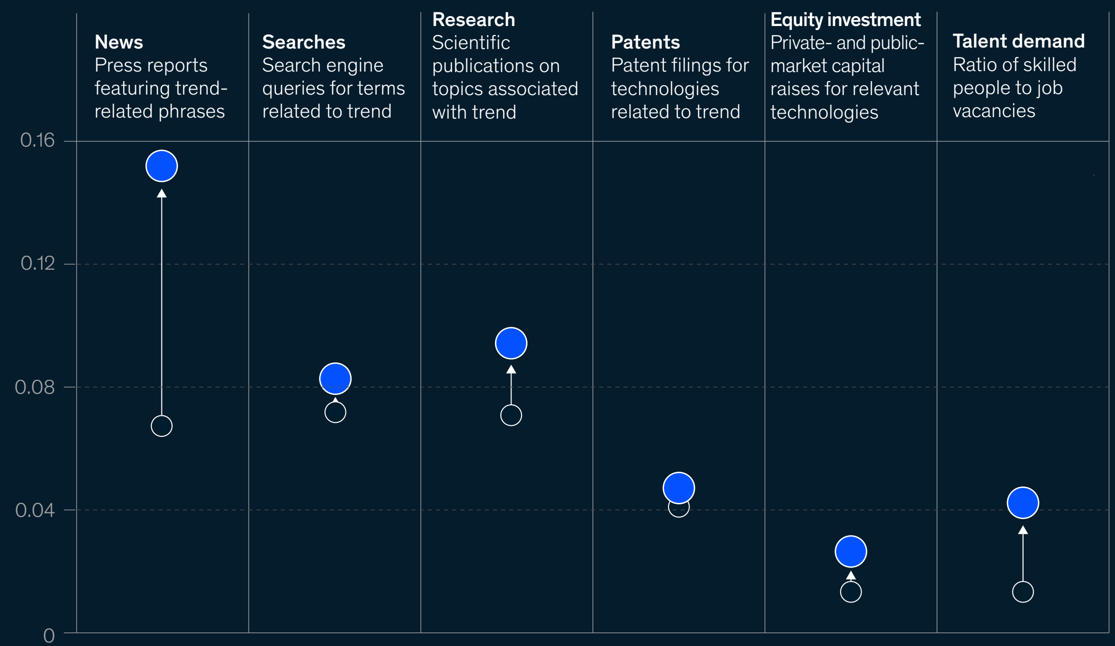
Job postings, 2023–24, % difference

–9%

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

○ 2020 ● 2024

1 0 *Range shown*



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

Advances in reusable rockets, satellite technology, and AI-driven data analysis are rapidly transforming space access and Earth observation. These enable faster, lower-cost launches and real-time insights that affect fields from environmental monitoring to global communications.

Recent developments involving space technologies include the following:

— *The cost to launch payloads into LEO has fallen, driven by reusable rockets and innovations in satellite miniaturization.* For example, SpaceX's *Falcon Heavy* launches at approximately $1,400 per kilogram, while SpaceX's *Starship* aims to reduce this to $10 to $30 per kilogram through full reusability and high launch cadence.[3]

— *Advances in space communication are expanding options for global connectivity and data transmission.* Very-low-Earth-orbit (VLEO) satellites, laser communications, and

[3] *Next Big Future*, "SpaceX Starship roadmap lower launch costs by 100 times," blog entry by Brian Wang, January 20, 2025; James Pethokoukis, "Moore's law meet Musk's law: The underappreciated story of SpaceX and the stunning decline in launch costs," American Enterprise Institute, March 26, 2024; *Next Big Future*, "How will SpaceX bring the cost to space down to $10 per kilogram from over $1000 per kilogram?," blog entry by Brian Wang, January 19, 2024.

5G networks also are transforming space communication. Integrating 5G with satellite systems has extended high-speed, low-latency internet coverage to remote areas and improved global telecommunications. Developments in propulsion, material science, and solar-power technologies have increased efficiency and cost-effectiveness, attracting growing investment in VLEO satellites.[4] These satellites enable new possibilities for industries such as Internet of Things (IoT), aviation, and remote broadband access, paving the way for a more connected future.

— *Companies continue to integrate space-based data with terrestrial data sets to enhance environmental monitoring and disaster response.* This convergence is particularly important in addressing wildfires because satellite imagery combined with infrared sensors can detect heat signatures and track fire behavior in real time, despite smoke or adverse weather conditions. These advances ensure faster, more accurate decision-making to mitigate wildfire impacts based on diverse data sources and a seamless flow of actionable insights.

— *Advanced Earth observation systems are transforming data collection and analysis.* Satellites using hyperspectral imaging and hundreds of spectral bands now provide more than half of climate data. Combined with machine learning algorithms, these systems enable real-time analysis for applications ranging from detecting pipeline leaks to identifying crop diseases. In the defense sector, these technologies are revolutionizing geospatial intelligence by drastically reducing the time to process, exploit, and disseminate imagery. Satellite photos that used to take as much as 57 minutes to analyze can now be parsed in seconds, thanks to advances in AI, enabling faster decision-making for critical defense operations. Rapid deployment of as many as 70,000 LEO satellites over the next five years should further improve such capabilities.[5]

— *AI's growing role in supporting space operations is increasing efficiency in mission planning, anomaly detection, and resource optimization.* While not fully autonomous, AI can now help improve situational awareness and assist with tasks such as collision avoidance and on-orbit logistics, enabling smarter and more reliable spacecraft operations.

'After years of continuous technological improvements and cost reductions, space is making headlines, from space tourism to defense systems. We collectively must use this technology, in particular paired with AI, to make humanity flourish.'

— Giacomo Gatto, partner, London

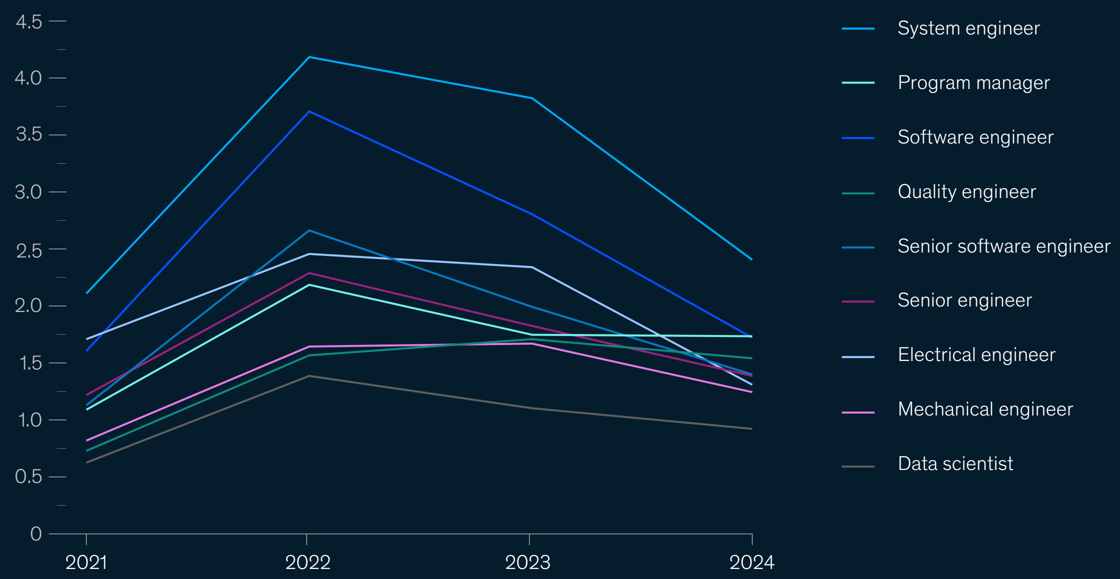
[4] Juniper Research's new Future Leaders Index reveals VLEO satellite vendors to watch as market develops," Juniper Research press release, June 18, 2024.
[5] "The global satellite market is forecast to become seven times bigger," Goldman Sachs, March 5, 2025.

Future of space technologies

Demand

Engineering roles continue to dominate the space technology job market, but demand for every major role has declined from 2022 to 2024. Quality engineers, program managers, and senior technical positions remain important, but overall job postings reflect a broader industry shift toward efficiency and automation.

Job postings, by title, 2021–24, thousands

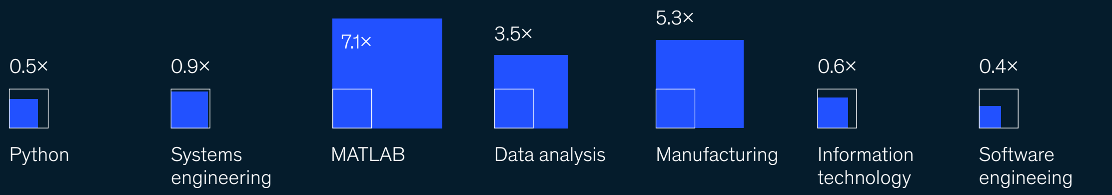


Skills availability

The space technology sector faces shortages in software engineering and Python expertise, possibly driven by the growing need for AI-driven mission automation and processing of satellite data. In contrast, skills in data analysis, the programming platform MATLAB, and manufacturing are more readily available, reflecting established training pipelines and lower relative demand.

Talent required, % share of postings requiring skill

Talent availability, ratio of talent to demand



Adoption developments across the globe

Adoption score: 2—Experimentation. Organizations are testing the functionality and viability of the technology with small-scale prototypes, typically without a focus on a near-term ROI. Few companies are scaling or have fully scaled the technology.

While space technology has tremendous potential, its adoption varies widely across sectors. Many private sector organizations remain in the experimentation and piloting phases, testing small-scale prototypes and exploring functionality. Given their reliance on connectivity and remote sensing, sectors such as energy, materials, and telecommunications are further along the adoption curve.

Space is now widely recognized as a critical domain for defense, and the defense sector is scaling space technologies as advances in satellite constellations, geospatial intelligence, and real-time data processing drive their strategic importance.[6] Adoption and innovation of various technologies vary globally, with the space economy concentrated in China, Europe, and the United States.[7] Interest in space technology is increasing in the Middle East, where companies in real estate and construction, in particular, are seeking to create value from Earth observation and geospatial data, for example, through monitoring construction progress via satellite imagery.[8]

In real life

Real-world examples involving reduction in rocket launch costs include the following:

— *SpaceX's 2024 Starship flight tests, including the booster catch, have shown major steps toward making space travel far more affordable.* By mastering fully reusable rockets, SpaceX aims to reduce the cost of reaching orbit, potentially opening new possibilities for lunar missions, satellite internet constellations, and even future space tourism. While the company's charges for commercial flights are not public, these tests demonstrate the company's ambition to make space accessible to a wider range of industries and governments.

Real-world examples of companies integrating space-based and terrestrial data for environmental monitoring and disaster response include the following:

— *Thales Alenia Space has undertaken the GREAT and GROOVE projects for the Italian Space Agency.* These projects aim to demonstrate the benefits of satellite navigation for environmental monitoring, including natural disaster forecasting and climate change impact assessment.[9]

— *Companies such as Pole Star Global and Spire Maritime provide advanced satellite systems that track ship positions and monitor engine performance.* These technologies enhance maritime safety, optimize fuel efficiency, and support predictive maintenance.

Real-world examples involving Earth observation systems include the following:

— *Since their debut in 2013, Planet now has a fleet of more than 150 satellites capturing three-meter-resolution imagery daily, covering 350 million square kilometers of Earth's surface each day.*[10] Initially experimental, it now delivers multispectral data (RGB [red, green, and blue] plus near-infrared) for precision agriculture, deforestation tracking, and disaster response, with upgrades to improve revisit rates and spectral capabilities.[11]

— *The US Department of Defense is shifting the way it tracks moving targets on the ground, reducing its reliance on aircraft by using space-based systems.* Known as a ground moving target indicator (GMTI), this capability monitors activity on the ground with persistent,

6 Gabriel Honrada, "US arming up to zap China, Russia in space," Asia Times, March 19, 2025.
7 Robert Murray, "The NewSpace market: Capital, control, and commercialization," Atlantic Council, April 27, 2023.
8 *Middle East geospatial analytics market*, Credence Research, May 12, 2025.
9 "GREAT and GROOVE: 2 satellite navigation projects for environmental monitoring," Thales Alenia Space press release, September 3, 2024.
10 "Our constellation," Planet Labs, accessed June 17, 2025; "Real-time satellite monitoring with Planet," Planet Labs, accessed June 17, 2025; "CSDA vendor – Planet," NASA Earthdata, accessed June 17, 2025.
11 "Data driven precision agriculture with Planet," Planet Labs, accessed March 31, 2025; Christopher Anderson, "Forest carbon monitoring: A dove's-eye view of global forest change," Planet Labs, September 27, 2024.

video-like surveillance previously provided by planes. Space-based satellites provide real-time tracking and reduce the time needed to process data from nearly an hour to just seconds, using artificial intelligence and on-orbit processing.

Additional real-world examples of the latest technological advancements in space operations are as follows:

— *LeoLabs uses AI-driven radar networks to track and predict space debris movements.* It aims to improve the ability of satellites and spaceships to avoid collisions in the increasingly crowded low-Earth orbit.[12]

— *The US Space Force plans to demonstrate as yet unproven advanced in-space refueling technology in 2026.* This initiative, supported by companies including Astroscale and Northrop Grumman, aims to extend the lifespan and maneuverability of satellites by enabling them to adapt to dynamic and contested environments.[13]

— *Northwood Space has demonstrated phased-array antenna technology.* It uses improved connectivity to optimize ground infrastructure for satellite communications.

Underlying technologies

The technologies that power space-related advancements include the following:

— *Small satellites.* Customizable, cost-effective modular satellites, often built using CubeSat architectures, enable a wide range of missions.

— *Remote sensing.* Full-spectrum imaging and monitoring technologies observe Earth's features and phenomena, including oceanography, weather patterns, and geological formations.

— *SWaP-C advances.* Reductions in the size, weight, power, and cost (SWaP-C) of satellites and launch vehicles improve the viability of space technology.

— *Launch technology advances.* Innovations such as reusable boosters, advanced materials, and lower-cost heavy-lift launch vehicles reduce launch costs and increase launch rates, making space more accessible.

— *Advanced-connectivity technologies.* Technologies such as laser communications, electronically scanned antennas, and automated satellite operations improve data transmission rates, enhance connectivity, and enable more efficient satellite operations.

— *LEO constellations.* Large groups of satellites in LEO enhance communications, internet access, and Earth observation, driving advances in various sectors.

— *5G from space.* Integrating 5G technology with satellite communications enables ubiquitous connectivity, especially in remote and underserved areas.

— *Superheavy-lift launchers.* Rockets with significantly increased payload capacity, such as SpaceX's Starship, access space to deploy larger satellites and infrastructure and support deep-space missions.

— *Manned space systems.* Spacecraft designed to carry human crews, including the *Orion* spacecraft in NASA's Artemis program, are critical for space exploration and scientific research and establishing a human presence beyond Earth.

Key uncertainties

Uncertainties surrounding space technology include the following:

— *Cost-effectiveness of space technologies.* Economic viability remains a challenge for space-based technologies, particularly as mega-constellations such as Starlink scale up. Innovations in reusable rockets and satellite manufacturing will reduce costs, as Starship has already demonstrated the potential for significant savings.

— *Governance mechanisms for spectrum and orbit usage rights.* The proliferation of satellites, particularly LEO satellites, increases the risks of overcrowding or interference in orbital slots and

12 "Real-time conjunction alerts for safety of flight," LeoLabs, accessed June 12, 2025.
13 Garrett Reim, "Astroscale to attempt U.S. Space Force satellite refueling in 2026," Aviation Week Network, April 8, 2025; Sandra Erwin, "Northrop Grumman's orbital refueling port selected for U.S. military satellites," *SpaceNews*, January 29, 2024; "Astroscale U.S. to lead the first-ever refueling of a United States Space Force asset," Astroscale, April 9, 2025.

highlights the need for international regulatory frameworks to address spectrum and orbit usage rights. Disputes over spectrum allocation, including those involving the International Telecommunications Union and private operators, underscore the potential benefits of establishing equitable rules.

— *Cyber risks.* Space assets face increasing threats from cyberattacks such as jamming and satellite spoofing, including recent incidents targeting commercial and defense systems. Developing quantum-resistant encryption and robust cybersecurity protocols is essential for safeguarding critical infrastructure.

— *Geopolitical tensions.* Rising space aspirations and security concerns among nations have led to the conducting of tests for antisatellite weapons, which could undermine years of international collaboration in space. Cooperative governance initiatives like the Artemis Accords lack universal support, making it harder to maintain governance stability in space.

Big questions about the future

Companies and countries may want to consider the following questions as they explore opportunities related to space technologies:

— How will the space technologies industry address the growing challenges of space debris and traffic management?

— Could breakthroughs in heavy-lift launch capabilities and lower-cost access to orbit fundamentally reshape satellite economics and force incumbents to reinvent their business models?

— How will the rise of commercial space stations and in-orbit manufacturing change the economic landscape of space exploration?

— Will the future of space be defined more by international collaboration or by geopolitical divergence? How should organizations position themselves amid this period of geopolitical uncertainty?

13

Future of energy and sustainability technologies

Energy and sustainability technologies encompass a broad spectrum of innovations aimed at transforming the global energy landscape toward a more sustainable and resilient future. This includes the spectrum of technologies transforming the global energy value chain, particularly focusing on clean electrons, electrification, and clean molecules.

The trend—and why it matters

Energy is the backbone of modern society, powering everything from industry and transportation to digital infrastructure and daily life, so the transformation of its production, storage, and distribution systems is one of the most consequential challenges and opportunities of our time. Our analysis of this trend examines the spectrum of technologies transforming the global energy value chain, particularly clean electrons, electrification, and clean molecules. While the broader trend encompasses everything from grid infrastructure to carbon management, our research primarily focuses on the innovations that enable the generation and use of low-carbon electricity and fuels. Additionally, energy and sustainability technologies are far from uniform, having substantial variation in their cost profiles, maturity, adoption rates, and potential for future cost reductions.

The energy transformation is unfolding against a backdrop of rising geopolitical tensions, shifting policies, and macroeconomic uncertainty, all of which shape investment decisions and technology deployment. Tariffs on clean-energy technologies, such as solar panels and electric vehicles, could increase costs and complicate global supply chains, while competition for critical minerals and components is intensifying among major economies. Policy support for transforming energy systems is shifting in various countries, and infrastructure gaps are significant. At the same time, the explosive growth of data centers is driving up electricity demand, putting additional pressure on grids. As a result, the energy transition is a question of not only decarbonization but also ensuring that new systems are affordable, reliable, and globally competitive—objectives now at the forefront of policy and industry strategy.

Key uncertainties are also shaping the trajectory of the energy transition. Beyond the “adoption problem,” defined as the complex set of barriers to scaling and commercializing new climate technologies, fundamental innovation challenges pose obstacles to developing breakthrough technologies that are cost-effective, reliable, and scalable. The need to rapidly build out critical infrastructure amid supply chain bottlenecks, labor shortages, and regulatory delays compounds these challenges. The availability and sustainable sourcing of key materials such as lithium, rare earth elements, and other critical minerals also pose potential obstacles to achieving global net-zero commitments. Finally, energy transitions differ regionally, with the “global north” working to manage rising energy demand and scale low-emission technologies while the “global south” faces the dual challenge of expanding energy access and decarbonizing across diverse, country-specific contexts.

CUTTING-EDGE ENGINEERING

Future of energy and sustainability technologies

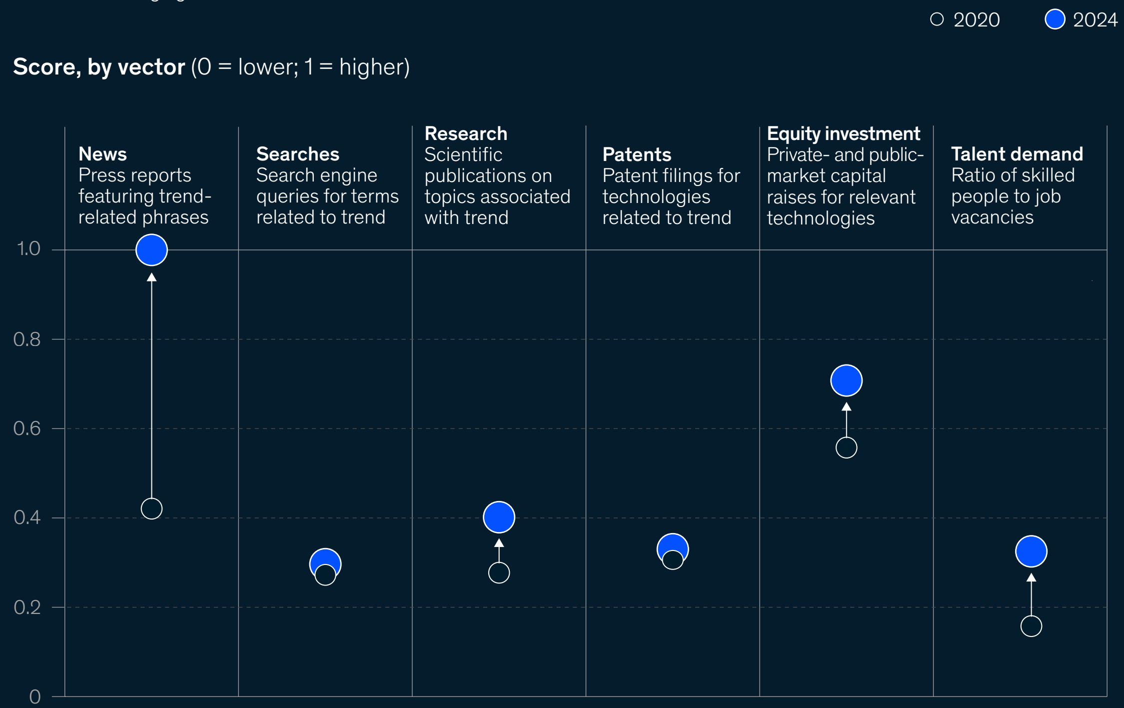
Scoring the trend

The future of energy and sustainability technologies remains the most widely covered trend in the news media, fueled by persistent environmental challenges and concerns and demand for solutions. However, growth in news coverage from 2023 to 2024 lagged the attention devoted to AI, a sector experiencing exponential advances. Equity investment in energy and sustainability technologies has fluctuated since 2020, growing by 79 percent from 2020 to 2021 to a high of $315 billion, then falling in 2022 and 2023 before increasing again from 2023 to 2024.

Equity investment, 2024
$223.2 billion

Job postings, 2023–24, % difference
–6%

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



Note: For each vector, we used a defined set of data sources to find occurrences of keywords associated with each of the 13 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.

Latest developments

Recent developments in energy and sustainability technologies include the following:

— *The demand for electricity has surged significantly.* Data centers alone have become one of the largest drivers of rising global power consumption, highlighting the urgent need to deploy low-emission power systems capable of meeting this growing demand. However, achieving decarbonization goals requires addressing several critical challenges, including ensuring flexibility in production and demand to balance baseload requirements, managing the intermittency of renewables such as wind and solar, and tackling economic hurdles such as falling capture prices for renewable-energy sources. In Texas, for example, gas peaker plants and engines are springing up alongside battery energy storage systems to ensure energy availability during peak periods. Additionally, investments in renewable-energy sources increasingly rely on power purchase agreements backed by strong balance sheets to remain viable amid market volatility. Without systemic fixes—such as new market mechanisms, streamlined permitting and construction timelines, enhanced peak power solutions, better optimization of existing infrastructure through smart-grid and time-based contracts, and improved operational flexibility—electric systems risk becoming a bottleneck in broader decarbonization efforts.

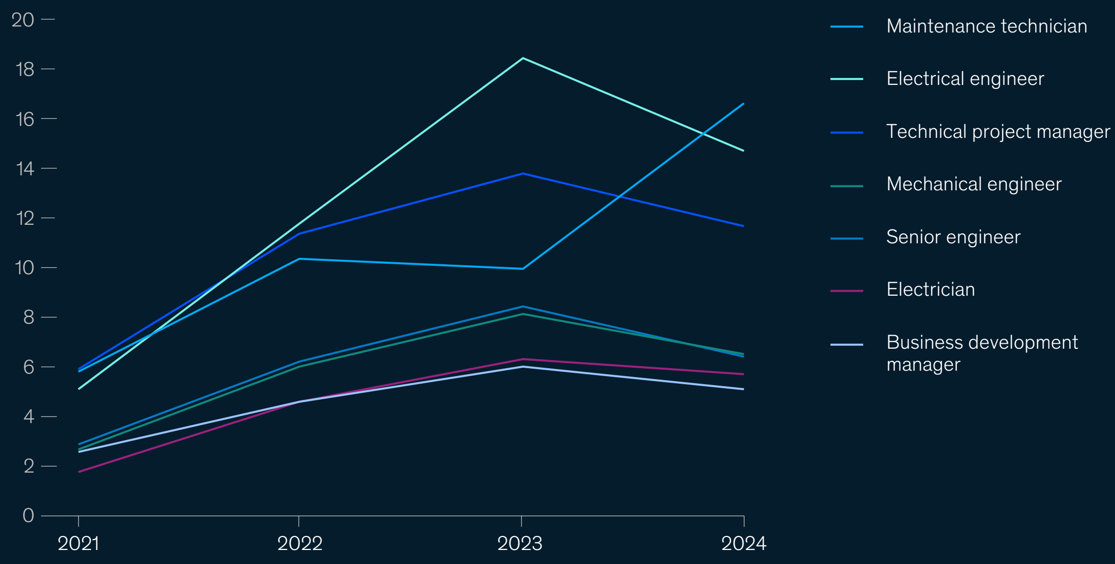
- *Advances in measurement technologies, such as satellite imagery and light detection and ranging (LiDAR), have enhanced the ability to monitor and model environmental impacts with greater precision and lower costs.* These tools enable more accurate emission tracking, land use changes, and ecosystem health, which supports better decision-making for climate initiatives and regulatory compliance. For start-ups developing climate technologies, these innovations provide critical proof points that validate environmental benefits, helping to secure long-term contracts and improve projections of technology performance and impact.
- *Hydrogen is increasingly viewed as an important option for decarbonizing hard-to-abate sectors, with ongoing technological advances and policy support laying the groundwork for future growth.* Although high production costs and slow project progression continue to present challenges, innovations in electrolyzer technology and integration with low-cost renewables are gradually improving the outlook. Europe remains at the forefront in developing the hydrogen market, and China is rapidly expanding its electrolyzer manufacturing capacity, signaling growing momentum even as the sector works to overcome key barriers to large-scale adoption.
- *Advanced biofuels and e-fuels are gaining traction, though challenges remain.* Innovations in biofuel production, such as fuel from agricultural waste, are improving efficiency and reducing costs. Uncertainties remain in scaling production and reducing the gap between the costs of biofuels and conventional fossil fuels, which underscores the need for continued investment and supportive policies to accelerate adoption.
- *Nuclear power is attracting attention because of its ability to provide stable baseload electricity.* Several countries have initiated or expanded their nuclear fission programs, and 31 countries have committed to tripling global nuclear energy capacity by 2050. However, the sector faces persistent challenges, including high capital expenditures, lengthy construction timelines, and ongoing public concerns about safety and nuclear waste. Advances in small modular reactors (SMRs) and improved economies of scale could help lower costs and accelerate deployment, but the future role of nuclear remains highly uncertain. Depending on decarbonization pathways, policy support, and the pace of technological progress, nuclear power could account for anywhere from 8 to 43 percent of global electricity by 2040, with market revenues varying widely, potentially reaching $400 billion, though only under the most optimistic scenarios. In addition to proven fission technologies, the promise of nuclear fusion for power generation is attracting investment, but significant technical challenges need to be overcome to make this technology a reality.

Future of energy and sustainability technologies

Demand

The job market for energy and sustainability technologies has expanded significantly since 2021, with strong growth in roles directly supporting the sector's transition. Maintenance technicians specializing in renewable-energy systems, electrical engineers working on grid modernization, and project managers overseeing decarbonization initiatives are in demand. While many of these job titles are common across industries, the surge in postings reflects increasing specialization within energy and sustainability contexts. Although demand in all categories of jobs—with the exception of maintenance technicians—declined in 2024 compared with 2023, the decrease likely reflected broader economic factors rather than reduced demand for skills critical to advancing electrification and clean-energy deployment.

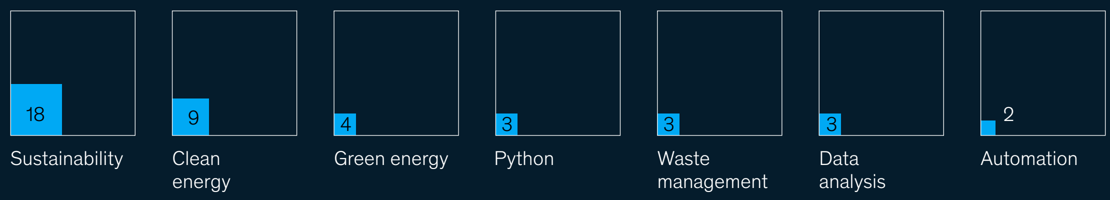
Job postings, by title, 2021–24, thousands



Skills availability

The energy and sustainability sector faces talent shortages in clean-energy and sustainability expertise, with the availability of candidates falling short of demand. Automation and other technical skills, including Python, are increasingly important as AI technologies are integrated into energy systems. Addressing these gaps through targeted training will be essential to support the ongoing energy transition and decarbonization efforts.

Talent required, % share of postings requiring skill



Talent availability, ratio of talent to demand

Adoption developments across the globe

Adoption score: 3—Piloting. Organizations are deploying the technology in the first few business use cases, via pilot projects or limited implementation, to test its feasibility and effectiveness.

But adoption rates of energy and sustainability technologies vary significantly, reflecting differences in technological maturity, economic viability, and enabling infrastructure. Some, such as solar-photovoltaic (PV) and wind power, are scaling rapidly in certain regions. Currently, China leads globally in solar PV manufacturing capacity, while India is scaling its production capacity and is expected to become the second-largest solar PV manufacturer by 2026. Other technologies, including green hydrogen and synthetic fuels, are in earlier stages of development. For some use cases, adoption is complicated because established low-emission technologies can't deliver the same performance as high-emission alternatives. Furthermore, the lack of established track records and other constraints have impeded deployment. Challenges beyond the technological include supply chain readiness, labor availability, and construction complexities. Without addressing these interconnected challenges holistically, achieving widespread adoption and maximizing the potential of various energy technologies will remain difficult.

In real life

Real-world examples involving the increasing demand for power and innovations in green electricity include the following:

- *British solar-technology company Oxford PV achieved a milestone in 2024 by commercializing its perovskite tandem solar technology, shipping the first panels to a US-based customer.* These panels provide as much as 20.0 percent more energy production than standard silicon panels and have a module efficiency of 24.5 percent, marking a significant advancement in solar technology.
- *Enpal, a leading German solar-energy company, is investing in workforce development to scale solar-energy adoption.* In June 2024, it launched Europe's largest Heat Pump Academy in Blankenfelde-Mahlow, investing several million euros to train installers and specialists in heat pump technology. This initiative aims to create more than 1,000 additional jobs in the German heat pump sector to support Enpal's ambition to become the market leader in heat pump installation.
- *Boston Metal, a Massachusetts-based start-up, is using molten oxide electrolysis technology to revolutionize steel production and high-value metals extraction.* Its process uses electricity instead of fossil fuels, with the potential to reduce by as much as 10 percent

'The AI boom is driving an unprecedented surge in compute demand, requiring massive infrastructure growth powered sustainably. Success hinges on rapid innovation in clean-energy integration, advanced cooling systems, and grid modernization. These challenges reflect the need to respond to rapidly growing energy demand and a desire for energy security.'

— Bernd Heid, senior partner, New York

of global carbon emissions linked to traditional steelmaking. In 2025, the company successfully operated its largest reactor yet, producing more than a ton of steel in a single run.

— *KoBold Metals uses AI and data analytics to explore critical battery metals such as cobalt, nickel, copper, and lithium.* By integrating large data sets from geological, geophysical, and geochemical sources, the company aims to improve the efficiency and accuracy of identifying potential mineral deposits. KoBold collaborates with mining partners across various regions to support the sourcing of materials essential for electric vehicles and renewable-energy technologies. Its approach can address some challenges in mineral exploration, though the long-term impact on supply chains and sustainability continues to evolve.

— *Electrified heat solutions, such as Coolbrook's RotoDynamic Heater, are gaining traction.* These systems use electricity to generate very high heat to decarbonize industrial processes. The technology demonstrated its capabilities for use in high-temperature process heating, completing its first phase of large-scale pilot testing. Coolbrook says its RotoDynamic Technology could reduce global CO_2 emissions by as much as 30 percent by replacing fossil fuels in energy-intensive industries such as steel, cement, and petrochemicals.

The following is a real-world example of advances in measurement technologies:

— *Carbon Mapper, a not-for-profit coalition leveraging advanced satellite technology, launched the Tanager-1 satellite in 2024 to detect, pinpoint, and track methane and CO_2 "superemitters" worldwide with unprecedented precision.* The coalition makes facility-level emissions data publicly accessible to empower rapid mitigation and support global climate goals. By combining NASA JPL's cutting-edge imaging spectrometer with Planet Labs' agile satellite platform, Carbon Mapper's open data helps governments, industry, and the public identify leaks and verify reductions.

The following is a real-world example of advances in hydrogen:

— *China's rapid expansion of electrolyzer manufacturing capacity, now accounting for about 60 percent of global output, has driven down equipment costs and positioned the country as a key supplier for the world's emerging hydrogen economy, with projects expected to exceed national targets by the end of 2024.* This surge is enabling more affordable green-hydrogen production globally and attracting international project developers, even as the sector continues to face challenges with project financing, infrastructure build-out, and alignment of renewable-energy supply with hydrogen demand.

The following is a real-world example of advances in biofuels and e-fuels:

— *E-fuels—synthetic fuels made from renewable electricity—are emerging as a promising technology for decarbonizing sectors such as aviation, shipping, and heavy-duty road transport.* The Swiss company Synhelion and others are developing e-fuel production processes that skip traditional steps, potentially reducing costs. In 2024, Synhelion inaugurated DAWN, the world's first industrial-scale plant that produces synthetic fuels using solar heat, in Jülich, Germany. Synhelion's process uses concentrated solar energy to achieve temperatures as high as 1,200°C in a thermochemical reactor that produces synthetic gas directly from CO_2 and water. This could reduce production costs and improve overall efficiency.

Real-world examples of advances in nuclear power include the following:

— *Small modular reactors (SMRs) promise to lower costs and accelerate deployment for nuclear fission plants, with efforts underway in both the United States and Europe.* In the United States, companies such as Oklo, X-energy, TerraPower, and Kairos Power are racing to develop commercially viable SMRs and secure domestic fuel supply chains. Microsoft, Google, and Amazon have announced agreements with operators and developers of nuclear power plants to help meet the growing demand by data centers for power.

— *A new wave of companies and public initiatives is racing to make nuclear fusion a practical source of clean energy.* Commonwealth Fusion Systems and UK-based Tokamak Energy are building different designs of tokamak-based reactors using powerful superconducting magnets, while Helion is developing a linear, pulsed system. Government-backed projects such as ITER in France, KSTAR in South Korea, and EAST in China are pushing the boundaries of plasma science. However, all these efforts remain experimental, and fusion's promise of abundant, carbon-free power is uncertain until the technical challenges are overcome.

Underlying technologies

The technologies that power energy and sustainability technologies include the following:

— *Nuclear fission.* This low-carbon energy source provides baseload power, contributing to grid stability and emissions reduction.

— *Renewables.* Clean-energy sources such as solar, wind, and hydropower are essential for decarbonizing the electricity sector.

— *Advanced solar-PV systems.* These are next-generation solar technologies that improve efficiency and reduce costs.

— *Hydrogen.* As a versatile energy carrier produced from renewable sources, hydrogen could decarbonize hard-to-abate sectors.

— *Sustainable fuels.* These are low-carbon alternatives to conventional fossil fuels, including biofuels and synthetic fuels, for reducing emissions in transportation and industry.

— *Batteries.* Energy storage devices enable the integration of intermittent renewable-energy sources and support electrification of transportation.

— *Energy storage.* These technologies store energy for later use, thus balancing supply and demand in renewable-energy systems.

— *Heat pumps.* These efficient heating and cooling systems transfer heat from one location to another, reducing energy consumption in buildings.

— *Smart-grid technologies.* Advanced electrical-grid systems optimize energy distribution, enable integration of distributed energy resources, and incorporate demand-side flexibility solutions to balance supply and consumption patterns.

— *Measurement, reporting, and verification (MRV) systems.* These tools and processes accurately quantify and track emissions and removals, ensuring the effectiveness of climate mitigation efforts.

— *Energy-efficiency technologies.* This set of technologies comprises technologies and practices that reduce energy consumption while maintaining or improving the level of service provided. Examples include high-efficiency appliances, improved insulation, smart systems for building management, and optimized industrial processes.

— *Carbon capture or direct air capture (DAC).* These technologies are designed to capture CO_2 emissions either from point sources (for example, power plants or industrial facilities) or directly from the ambient air. The captured CO_2 can then be stored permanently underground or used in various industrial processes.

— *Long-duration storage.* These energy storage technologies can store energy for extended periods (ranging from several hours to days or even weeks), addressing the variability of renewable-energy sources and ensuring grid reliability. Examples include advanced batteries, pumped hydro storage, compressed air energy storage, and hydrogen storage.

— *Thermal energy storage.* These technologies store energy in the form of heat or cold for later use. This can include storing heat from solar thermal collectors, industrial-waste heat, or excess electricity for heating or cooling applications.

— *Adaptation solutions.* These are measures taken to adjust to the actual or expected effects of climate change. Adaptation encompasses a wide range of actions, from building more resilient infrastructure and developing drought-resistant crops to implementing early-warning systems for extreme weather events and managing coastal retreat.

Key uncertainties

The major uncertainties affecting energy and sustainability technologies include the following:

— *Grid resilience and flexibility.* The ability of power grids to handle increasing amounts of variable renewable energy while maintaining stability and reliability is a major uncertainty in the energy transition.

‘Decarbonizing hard-to-abate sectors requires more than engineering breakthroughs. It demands coordinated action across industries, governments, and communities to ensure that innovation is accessible, affordable, and resilient in the face of global uncertainties.’

— Sebastian Mayer, partner, Munich

- *Infrastructure development.* The scale of infrastructure upgrades required for the energy transition, including transmission lines, charging stations, and hydrogen pipelines, is vast and faces potential delays and funding challenges.
- *Supply chain and resource constraints.* The availability and sustainable sourcing of critical materials for clean-energy technologies, such as rare earth elements and lithium, could limit the speed of deployment.
- *Market dynamics.* The interplay between traditional and emerging energy markets, including the future role of fossil fuels and the competitiveness of renewable-energy sources, remains a key area of uncertainty.
- *Pace of innovation and cost reductions.* The speed at which technologies such as green hydrogen electrolyzers, advanced batteries, and synthetic fuels improve cost and performance (for example, achieve cost parity with fossil fuel alternatives) remains uncertain, which affects their scalability and adoption in hard-to-abate sectors.
- *Systemic market and regulatory evolution.* The ability of electricity market designs and regulatory frameworks to rapidly adapt and incentivize flexibility, resilience, and low-emission investments is uncertain, posing risks to grid stability and affordability.
- *Labor and talent availability.* The capacity to scale workforce development and training programs to close acute talent shortages in clean energy, sustainability, and digital skills essential for energy transition technologies is uncertain, risking project delays and innovation bottlenecks.
- *Macroeconomic impacts on investment.* Inflation, rising interest rates, and global trade disruptions create uncertainty about financing costs and investment flows for large-scale clean-energy projects.

Big questions about the future

Companies and leaders may want to consider a few questions when pursuing energy and sustainability technologies:

- What will it take to accelerate the transition of promising climate technologies from lab to market, particularly in hard-to-abate sectors such as steel and cement?
- How can digital innovations—like AI, sensors, and advanced analytics—accelerate the deployment and integration of renewables and climate technologies across fragmented energy systems?
- As global electrification surges, how will energy systems adapt to rising demand, more distributed ownership of generation and storage, and the need for next-generation grid governance?
- How can nations and companies secure resilient, diversified supply chains for critical clean-energy materials amid rising geopolitical tensions?
- What regulatory frameworks and market mechanisms might unlock the investment and coordination required to scale next-generation energy technologies while maintaining affordability and reliability?

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