Insights across trends

Despite challenging overall market conditions in 2023, continuing investments in frontier technologies promise substantial future growth in enterprise adoption. Generative AI (gen AI) has been a standout trend since 2022, with the extraordinary uptick in interest and investment in this technology unlocking innovative possibilities across interconnected trends such as robotics and immersive reality. While the macroeconomic environment with elevated interest rates has affected equity capital investment and hiring, underlying indicators—including optimism, innovation, and longer-term talent needs—reflect a positive long-term trajectory in the 15 technology trends we analyzed.

These are among the findings in the latest McKinsey Technology Trends Outlook, in which the McKinsey Technology Council identified the most significant technology trends unfolding today (to know more about the Council, see the sidebar "About the McKinsey Technology Council"). This research is intended to help executives plan ahead by developing an understanding of potential use cases, sources of value, adoption drivers, and the critical skills needed to bring these opportunities to fruition.

Our analysis examines quantitative measures of interest, innovation, investment, and talent to gauge the momentum of each trend. Recognizing the long-term nature and interdependence of these trends, we also delve into the underlying technologies, uncertainties, and questions surrounding each trend. (For more about new developments in our research, please see the sidebar "What's new in this year's analysis" on page 9; for more about the research itself, please see the sidebar "Research methodology" on pages 10–11.)

New and notable

The two trends that stood out in 2023 were gen AI and electrification and renewables. Gen AI has seen a spike of almost 700 percent in Google searches from 2022 to 2023, along with a notable jump in job postings and investments. The pace of technology innovation has been remarkable. Over the course of 2023 and 2024, the size of the prompts that large language models (LLMs) can process, known as "context windows," spiked from 100,000 to two million tokens. This is roughly the difference between adding one research paper to a model prompt and adding about 20 novels to it. And the modalities that gen AI can process have continued to increase, from text summarization and image generation to advanced capabilities in video, images, audio, and text. This has catalyzed a surge in investments and innovation aimed at advancing more powerful and efficient computing systems.

The large foundation models that power generative AI, such as LLMs, are being integrated into various enterprise software tools and are also being employed for diverse purposes such as powering customer-facing chatbots, generating ad campaigns, accelerating drug discovery, and more. We expect this expansion to continue, pushing the boundaries of AI capabilities. Senior leaders' awareness of gen AI innovation has increased interest, investment, and innovation in AI technologies and other trends, such as robotics, which is a new addition to our trends analysis this year. Advancements in AI are ushering in a new era of more capable robots, spurring greater innovation and a wider range of deployments.

About the McKinsey Technology Council

Technology is a catalyst for new opportunities, from inventing new products and services, expanding the productivity frontier and capturing more value in our day-to-day work. The McKinsey Technology Council helps business leaders understand frontier technologies and the potential application to their businesses.

We look at a spectrum of technologies, from generative AI, machine learning, and quantum computing to space technologies that are shaping new opportunities and applications. The McKinsey Technology Council convenes a global group of more than 100 scientists, entrepreneurs, researchers, and business leaders. We research, debate, and advise executives from all industries as they navigate the fast-changing technology landscape.

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

–26%

tech trends job postings from 2022 to 2023

–17%

global job postings from 2022 to 2023

+8%

tech trends job postings from 2021 to 2023

Electrification and renewables was the other trend that bucked the economic headwinds, posting the highest investment and interest scores among all the trends we evaluated. Job postings for this sector also showed a modest increase.

Although many trends faced declines in investment and hiring in 2023, the long-term outlook remains positive. This optimism is supported by the continued longer-term growth in job postings for the analyzed trends (up 8 percent from 2021 to 2023) and enterprises' continued innovation and heightened interest in harnessing these technologies, particularly for future growth.

In 2023, technology equity investments fell by 30 to 40 percent to approximately $570 billion due to rising financing costs and a cautious near-term growth outlook, prompting investors to favor technologies with strong revenue and margin potential. This approach aligns with the strategic perspective leading companies are adopting, in which they recognize that fully adopting and scaling cutting-edge technologies is a long-term endeavor. This recognition is evident when companies diversify their investments across a portfolio of several technologies, selectively intensifying their focus on areas most likely to push technological boundaries forward. While many technologies have maintained cautious investment profiles over the past year, gen AI saw a sevenfold increase in investments, driven by substantial advancements in text, image, and video generation.

Despite an overall downturn in private equity investment, the pace of innovation has not slowed. Innovation has accelerated in the three trends that are part of the "AI revolution" group: generative AI, applied AI, and industrializing machine learning. Gen AI creates new content from unstructured data (such as text and images), applied AI leverages machine learning models for analytical and predictive tasks, and industrializing machine learning accelerates and derisks the development of machine learning solutions. Applied AI and industrializing machine learning, boosted by the widening interest in gen AI, have seen the most significant uptick in innovation, reflected in the surge in publications and patents from 2022 to 2023. Meanwhile, electrification and renewable-energy technologies continue to capture high interest, reflected in news mentions and web searches. Their popularity is fueled by a surge in global renewable capacity, their crucial roles in global decarbonization efforts, and heightened energy security needs amid geopolitical tensions and energy crises.

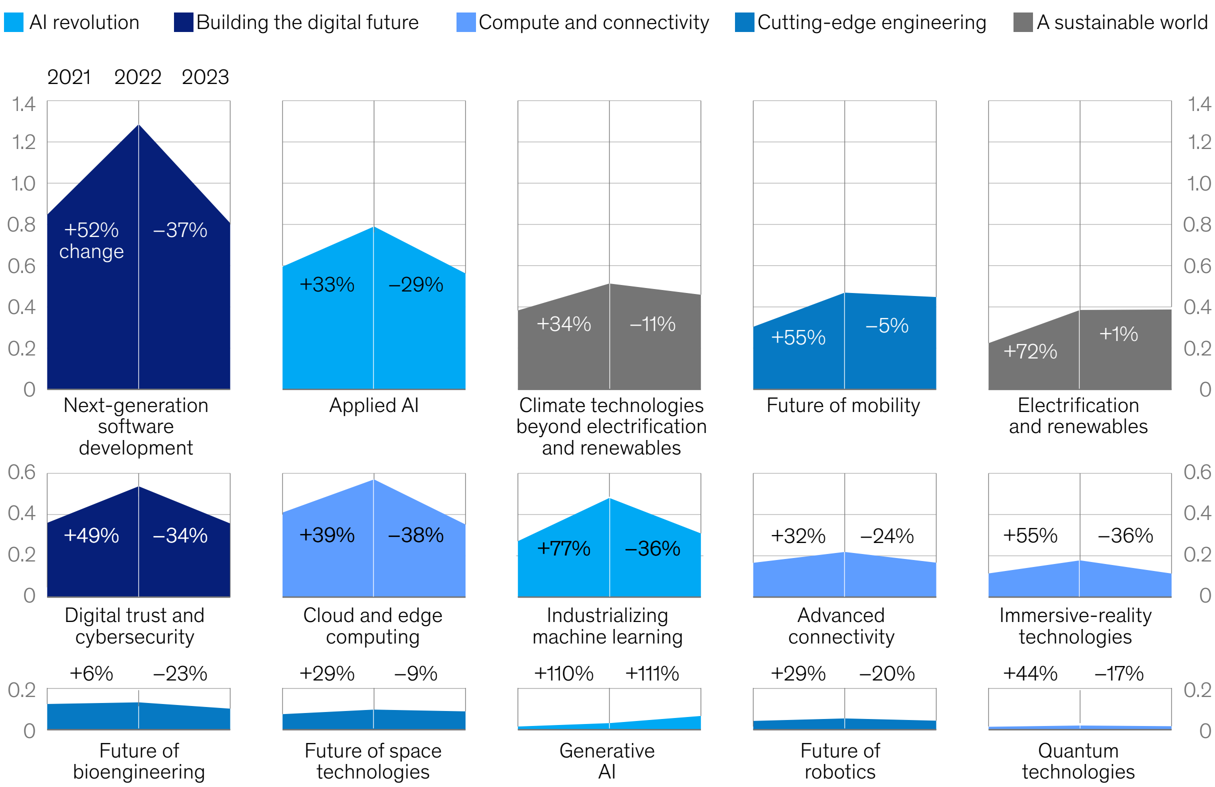
The talent environment largely echoed the investment picture in tech trends in 2023. The technology sector faced significant layoffs, particularly among large technology companies, with job postings related to the tech trends we studied declining by 26 percent—a steeper drop than the 17 percent decrease in global job postings overall. The greater decline in demand for tech-trends-related talent may have been fueled by technology companies' cost reduction efforts amid decreasing revenue growth projections. Despite this reduction, the trends with robust investment and innovation, such as generative AI, not only maintained but also increased their job postings, reflecting a strong demand for new and advanced skills. Electrification and renewables was the other trend that saw positive job growth, partially due to public sector support for infrastructure spending.

Even with the short-term vicissitudes in talent demand, our analysis of 4.3 million job postings across our 15 tech trends underscored a wide skills gap. Compared with the global average, fewer than half of potential candidates have the high-demand tech skills specified in job postings. Despite the year-on-year decreases for job postings in many trends from 2022 to 2023, the number of tech-related job postings in 2023 still represented an 8 percent increase from 2021, suggesting the potential for longer-term growth (Exhibit 1).

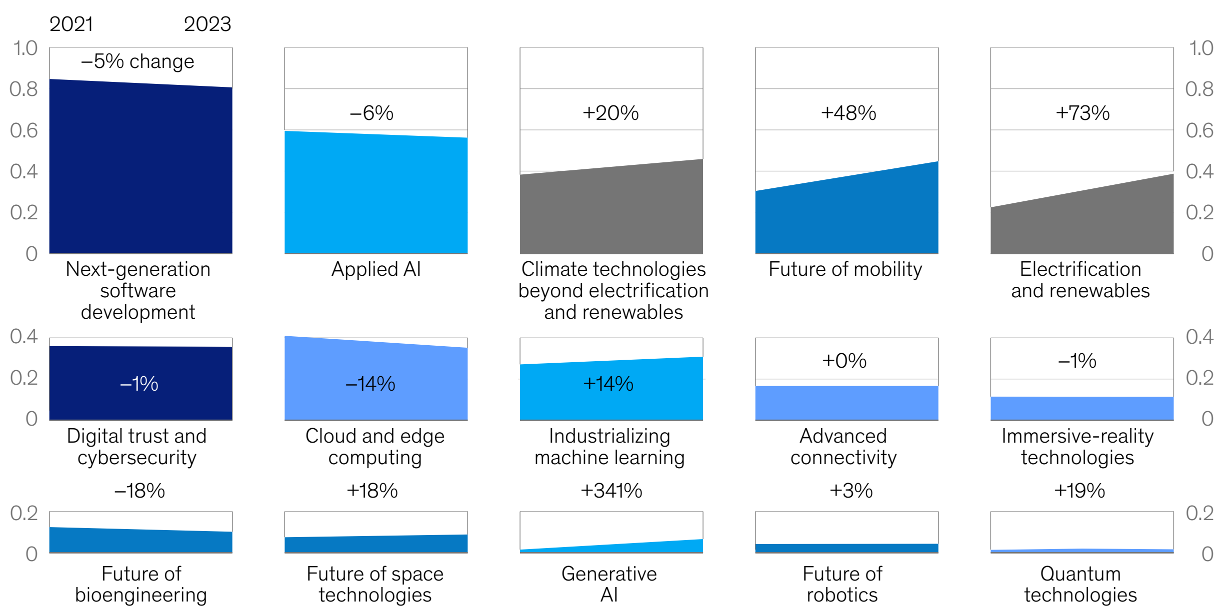
Exhibit 1

Despite a one-year drop in job postings, demand for jobs in many technology trends has increased over two years.

Annual change in tech trend job postings, 2021–23, millions of postings[1]



Cumulative change in tech trend job postings, 2021–23, millions of postings[1]



[1]Out of 130 million surveyed job postings (extrapolated Jan–Oct 2023). Job postings are not directly equivalent to numbers of new or existing jobs.
Source: McKinsey's proprietary Organizational Data Platform, which draws on licensed, de-identified public professional profile data

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Enterprise technology adoption momentum

The trajectory of enterprise technology adoption is often described as an S-curve that traces the following pattern: technical innovation and exploration, experimenting with the technology, initial pilots in the business, scaling the impact throughout the business, and eventual fully scaled adoption (Exhibit 2). This pattern is evident in this year's survey analysis of enterprise adoption conducted across our 15 technologies. Adoption levels vary across different industries and company sizes, as does the perceived progress toward adoption.

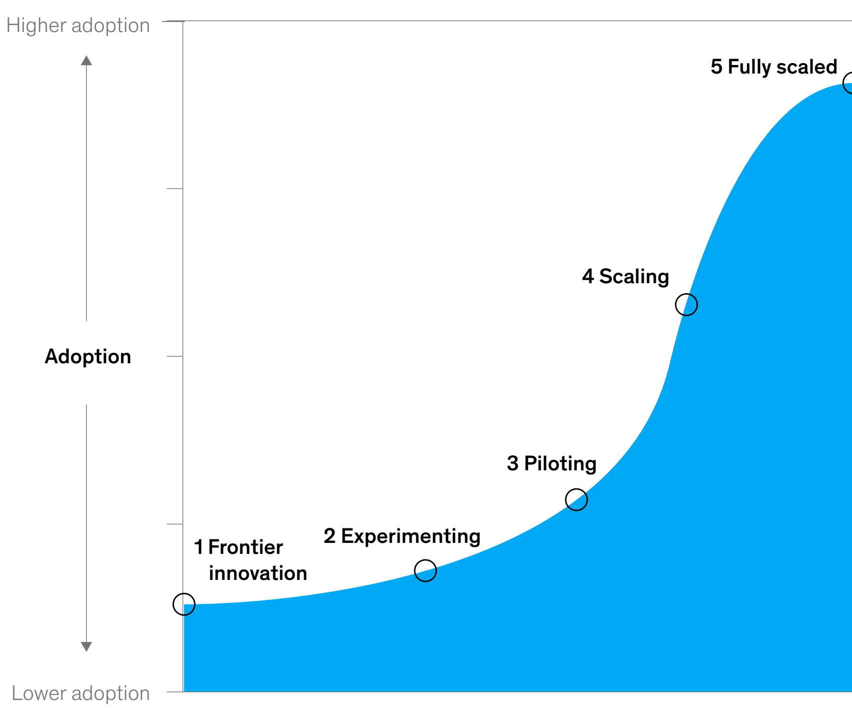
We see that the technologies in the S-curve's early stages of innovation and experimenting are either on the leading edge of progress, such as quantum technologies and robotics, or are more relevant to a specific set of industries, such as bioengineering and space. Factors that could affect the adoption of these technologies include high costs, specialized applications, and balancing the breadth of technology investments against focusing on a select few that may offer substantial first-mover advantages.

As technologies gain traction and move beyond experimenting, adoption rates start accelerating, and companies invest more in piloting and scaling. We see this shift in a number of trends, such as next-generation software development and electrification. Gen AI's rapid advancement leads among trends analyzed, with about a quarter of respondents self-reporting that they are scaling its use. More mature technologies, like cloud and edge computing and advanced connectivity, continued their rapid pace of adoption, serving as enablers for the adoption of other emerging technologies as well (Exhibit 3).

Exhibit 2

Technologies progress through different stages, with some at the leading edge of innovation and others approaching large-scale adoption.

Adoption curve of technology trends, adoption score



4
Advanced connectivity
Applied AI
Cloud and edge computing
Generative AI

3
Digital trust and cybersecurity
Electrification and renewables
Industrializing machine learning
Next-gen software development

2
Climate technologies beyond electrification and renewables
Future of bioengineering[1]
Future of mobility[1]
Future of robotics[1]
Immersive-reality technologies

1
Future of space technologies[1]
Quantum technologies

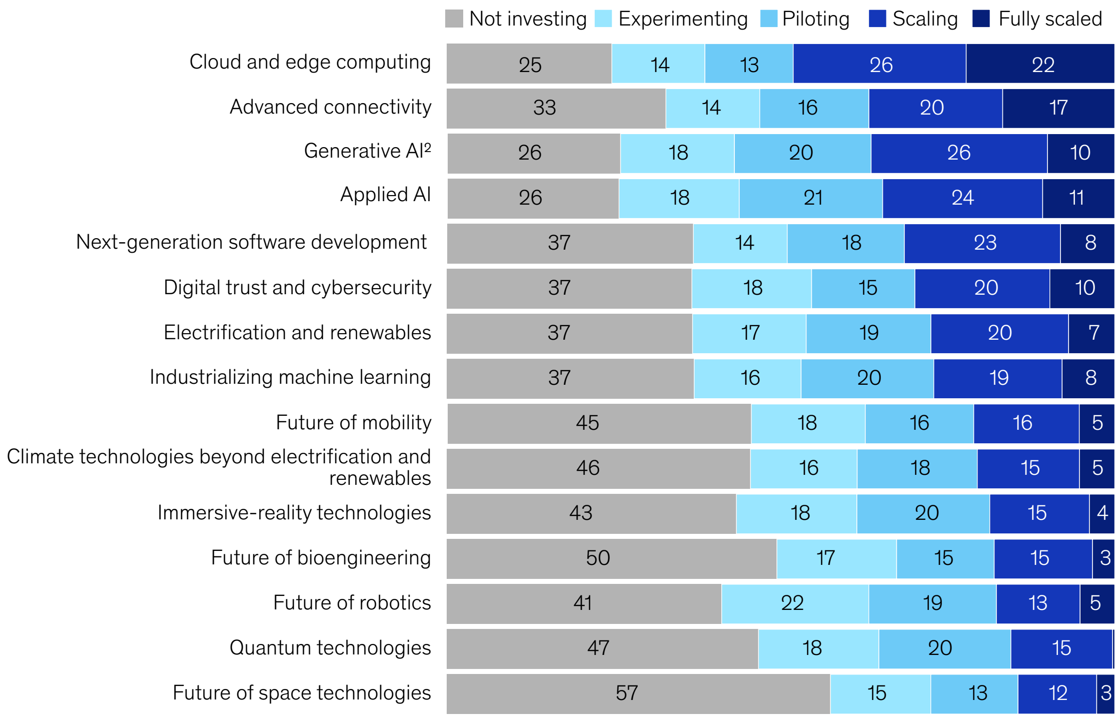
[1]Trend is more relevant to certain industries, resulting in lower overall adoption across industries compared with adoption within relevant industries.
Source: McKinsey technology adoption survey data; McKinsey analysis

McKinsey & Company

Exhibit 3

More-mature technologies are more widely adopted, often serving as enablers for more-nascent technologies.

Self-reported adoption level by tech trend, 2023,[1] % of respondents



[1]Respondents may interpret these categories differently based on their organizations. As such, the results should be considered as indicative of organizations' self-assessments, rather than precise measurements. [2]For a deeper look at our AI-related trends, see "The state of AI in early 2024: Gen AI adoption spikes and starts to generate value," McKinsey, May 30, 2024.
Source: McKinsey technology adoption survey data

McKinsey & Company

The process of scaling technology adoption also requires a conducive external ecosystem where user trust and readiness, business model economics, regulatory environments, and talent availability play crucial roles. Since these ecosystem factors vary by geography and industry, we see different adoption scenarios playing out. For instance, while the leading banks in Latin America are on par with their North American counterparts in deploying gen AI use cases, the adoption of robotics in manufacturing sectors varies significantly due to differing labor costs affecting the business case for automation.

As executives navigate these complexities, they should align their long-term technology adoption strategies with both their internal capacities and the external ecosystem conditions to ensure the successful integration of new technologies into their business models. Executives should monitor ecosystem conditions that can affect their prioritized use cases to make decisions about the appropriate investment levels while navigating uncertainties and budgetary constraints on the way to full adoption (see the "Adoption developments across the globe" sections within each trend that showcase examples of adoption dimensions for the trends or particular use cases therein that executives should monitor). Across the board, leaders who take a long-term view—building up their talent, testing and learning where impact can be found, and reimagining the businesses for the future—can potentially break out ahead of the pack.

The 15 tech trends

This report lays out considerations for all 15 technology trends. For easier consideration of related trends, we grouped them into five broader categories: the AI revolution, building the digital future, compute and connectivity frontiers, cutting-edge engineering, and a sustainable world. 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) and interest (based on news and web searches). We also sized investments in relevant technologies and rated their level of adoption by organizations (Exhibit 4).

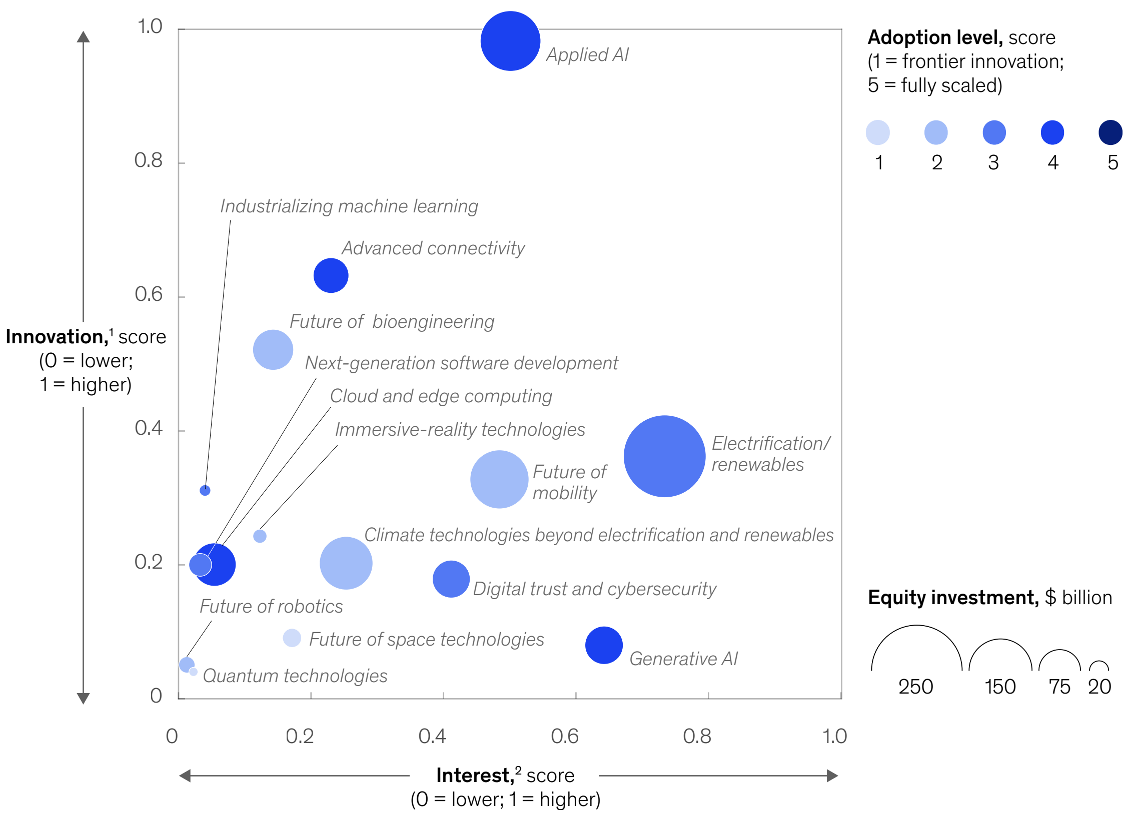
What's new in this year's analysis

This year, we reflected the shifts in the technology landscape with two changes on the list of trends: digital trust and cybersecurity (integrating what we had previously described as Web3 and trust architectures) and the future of robotics. Robotics technologies' synergy with AI is paving the way for groundbreaking innovations and operational shifts across the economic and workforce landscapes. We also deployed a survey to measure adoption levels across trends.

Exhibit 4

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

Innovation, interest, investment, and adoption, by technology trend, 2023



Note: Innovation and interest scores for the 15 trends are relative to one another. All 15 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 technology trend, our team collected data on five tangible measures of activity: search engine queries, news publications, patents, research publications, and investment. For each measure, we used a defined set of data sources to find occurrences of keywords associated with each of the 15 trends, screened those occurrences for valid mentions of activity, and indexed the resulting numbers of mentions on a 0–1 scoring scale that is relative to the trends studied. The innovation score combines the patents and research scores; the interest score combines the news and search scores. (While we recognize that an interest score can be inflated by deliberate efforts to stimulate news and search activity, we believe that each score fairly reflects the extent of discussion and debate about a given trend.) Investment measures the flows of funding from the capital markets into companies linked with the trend.

Data sources for the scores include the following:

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

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

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

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

— *Investment.* Data on private-market and public-market capital raises (venture capital and corporate and strategic M&A, including joint ventures), private equity (including buyouts and private investment in public equity), and public investments (including IPOs) are sourced from PitchBook.

— *Talent demand.* Number of job postings is sourced from McKinsey's proprietary Organizational Data Platform, which stores licensed, de-identified data on 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:

— The future of robotics trend was added since last year's publication.

— Data sources and keywords were updated. For data on the future of space technologies investments, we used research from McKinsey's Aerospace & Defense Practice.

Research methodology
(continued)

Finally, we used survey data to calculate the enterprise-wide adoption scores for each trend:

— *Survey scope.* The survey included approximately 1,000 respondents from 50 countries.

— *Geographical coverage.* Survey representation was balanced across Africa, Asia, Europe, Latin America, the Middle East, and North America.

— *Company size.* Size categories, based on annual revenue, included small companies ($10 million to $50 million), medium-size companies ($50 million to $1 billion), and large companies (greater than $1 billion).

— *Respondent profile.* The survey was targeted to senior-level professionals knowledgeable in technology, who reported their perception of the extent to which their organizations were using the technologies.

— *Survey method.* The survey was conducted online to enhance reach and accessibility.

— *Question types.* The survey employed multiple-choice and open-ended questions for comprehensive insights.

— *Definition of enterprise-wide adoption scores:*

- *1: Frontier innovation.* This technology is still nascent, with few organizations investing in or applying it. It is largely untested and unproven in a business context.
- *2: Experimentation.* Organizations are testing the functionality and viability of the technology with a small-scale prototype, typically done without a strong focus on a near-term ROI. Few companies are scaling or have fully scaled the technology.
- *3: Piloting.* Organizations are implementing the technology for the first few business use cases. It may be used in pilot projects or limited deployments to test its feasibility and effectiveness.
- *4: Scaling*. Organizations are in the process of scaling the deployment and adoption of the technology across the enterprise. The technology is being scaled by a significant number of companies.
- *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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The AI revolution

Generative AI

The trend—and why it matters

Generative AI (gen AI) has been making significant strides, pushing the boundaries of machine capabilities. Gen AI models are trained on vast, diverse data sets. They take unstructured data, such as text, as inputs and produce unique outputs—also in the form of unstructured data—ranging from text and code to images, music, and 3D models.

Over the past year, we've seen remarkable advancements in this field, with text generation models such as OpenAI's GPT-4, Anthropic's Claude, and Google's Gemini producing content that mimics human-generated responses, as well as with image-generation tools such as DALL-E 3 and Midjourney creating photorealistic images from text descriptions. OpenAI's recent launch of Sora, a text-to-video generator, further showcases the technology's potential. Even music composition is being revolutionized, with models such as Suno creating original pieces in various styles.

Gen AI has sparked widespread interest, with individuals and organizations across different regions and industries exploring its potential. According to the latest McKinsey Global Survey on the state of AI, 65 percent of respondents say their organizations are regularly using gen AI in at least one business function, up from one-third last year,[1] and gen AI use cases have the potential to generate an annual value of $2.6 trillion to $4.4 trillion.[2]

However, it's important to recognize the risks that accompany the use of this powerful technology, including bias, misinformation, and deepfakes. As we progress through 2024 and beyond, we anticipate organizations investing in the risk mitigation, operating model, talent, and technological capabilities required to scale gen AI.

1 "The state of AI in early 2024: Gen AI adoption spikes and starts to generate value," McKinsey, May 30, 2024.
2 *The economic potential of generative AI: The next productivity frontier*, McKinsey, June 14, 2023.

THE AI REVOLUTION

Generative AI

Scoring the trend

Gen AI saw a surge in 2023, driven by ChatGPT's late-2022 launch, alongside earlier models such as DALL-E 2 and Stable Diffusion. Gen AI saw significant growth from 2022 to 2023 across each quantitative dimension, such as a sevenfold increase in the number of searches and investments, reflecting a strong sense of excitement about the trend.

Adoption score, 2023

Frontier innovation → Fully scaled

1 2 3 **4** 5

Equity investment, 2023, $ billion

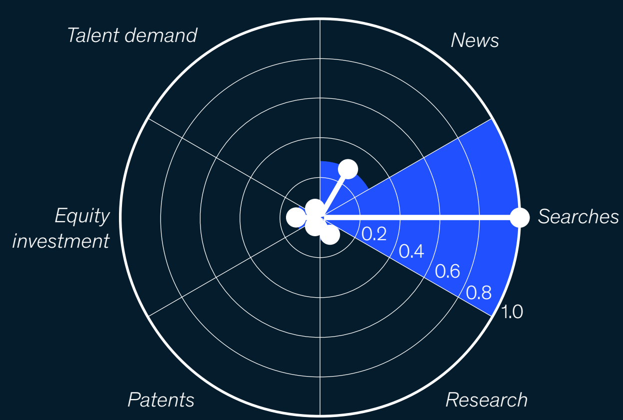
$36

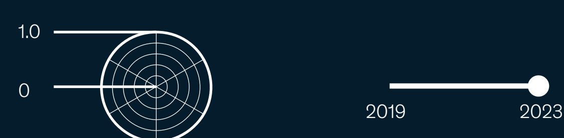
Job postings, 2022–23, % difference

+111%

Industries affected: *Aerospace and defense; Agriculture; Automotive and assembly; Aviation, travel, and logistics; Business, legal, and professional services; Chemicals; Construction and building materials; Consumer packaged goods; Education; Electric power, natural gas, and utilities; Financial services; Healthcare systems and services; Information technology and electronics; Media and entertainment; Metals and mining; Oil and gas; Pharmaceuticals and medical products; Public and social sectors; Real estate; Retail; Semiconductors; Telecommunications*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Gen AI is a fast-growing and constantly innovating trend, with recent developments including the following:

— *Multimodal generative models are on the rise.* As gen AI continues to evolve and gain more attention in various industries, it's becoming increasingly clear that multimodality will play a pivotal role. By combining text, images, sounds, and videos, AI models can generate outputs applicable across a wide range of industries and business functions. This pursuit of multimodality is intensifying across leading players such as OpenAI and Google (with its Lumiere AI web app). For example, Google's Gemini showcases a powerful multimodal system capable of processing information in various formats, including text, code, tables, images, and even audio.

— *Powerful open-source models are challenging their closed-source counterparts in performance and developer adoption.* While significant investments are encouraging the development of proprietary large language models (LLMs), such as GPT-4 with vision (GPT-4V), the AI community is also witnessing a surge in open-source models, such as Llama 3. This momentum is fueled by the enthusiasm of developers and users who welcome the unprecedented access to build innovative tools and study complex systems. The accessibility of open-source models is attracting a growing developer base.

— *The context window in natural-language processing (NLP) is expanding.* This expansion allows for longer and smarter prompts. For instance, in early 2024, Google released the largest context window in the market with Gemini 1.5 Pro, which has a standard context window of 128,000 tokens, with the potential to reach two million tokens.[3] This larger context window enables the model to generate more coherent and contextually relevant responses by considering a larger amount of text. However, expanding prompt size can paradoxically lead to models getting "lost in the middle," as they tend to focus on specific parts of the text while avoiding the rest.

— *LLMs are increasingly being embedded into various enterprise tools.* We are witnessing a significant uptick in the integration of LLMs into various enterprise tools. This surge is fueled by the growing demand for automation, efficiency, personalized user experiences, and the capacity to decipher complex patterns that can lead to actionable insights. Consequently, a rising number of vendors are choosing to integrate LLMs into their applications and tools. This trend is especially prominent in the marketing and customer care domains, with Salesforce Einstein and ServiceNow serving as prime examples.

— *The multiagent approach has gained significant traction with the rapid development of LLMs and continued innovation.* Companies now recognize the benefits of employing multiple language models that work in harmony rather than relying on a single model. This approach offers a fresh perspective on tackling complex challenges by leveraging the capabilities of multiple AI agents, each specializing in different domains, to solve a single problem collaboratively. By working together, these agents can not only accelerate problem-solving but also leverage varied perspectives and expertise to deliver more effective and efficient solutions. Some of the tools using this approach tend to be unstable, but as models improve, their throughput should significantly increase, making them increasingly relevant for the future.

[3] *The Keyword* [Google's official blog], "Gemini breaks new ground with a faster model, longer context, AI agents and more," blog entry by Demis Hassabis, May 14, 2024.

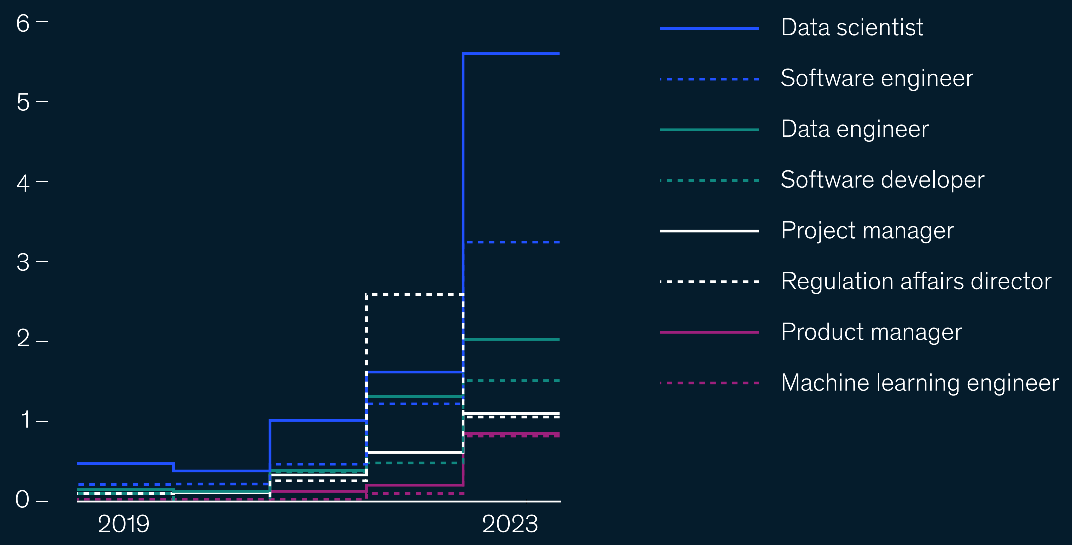
Talent and labor markets

Generative AI

Demand

Roles related to gen AI have experienced significant and rapid growth in talent demand since 2019, with a 111 percent increase in job postings compared with 2023. This growth is driven by increased interest and investment in the field. Almost all roles in gen AI, except for regulation affairs directors, have seen a notable rise in demand, particularly for individual contributor roles. Organizations are now focusing on scaling and expanding their internal capabilities to harness the potential of gen AI, leading to a sharp increase in demand for data scientists, software engineers, and data engineers.

Job postings by title, 2019–23, thousands

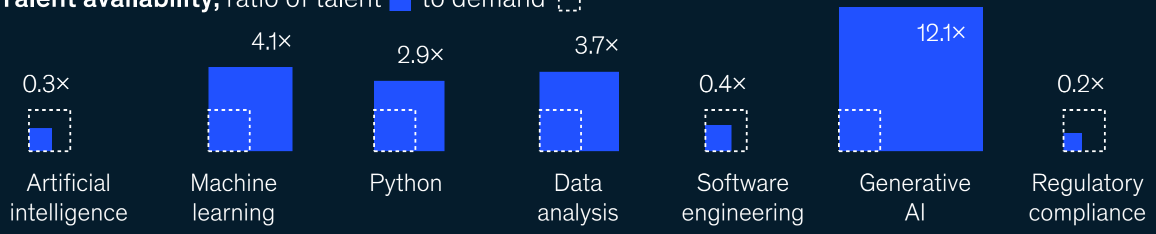


Skills availability

Proficiency in gen AI necessitates expertise in AI, machine learning, and programming languages such as Python. The availability of high-level gen AI skills is notable, with individuals citing proficiency in this area as necessary to capture employers' attention. There are significant skills overlaps with the "applied AI" and "industrializing machine learning" trends (please refer to those trends for more details).

Talent availability, % share of postings requiring skill

Talent availability, ratio of talent to demand



Adoption developments across the globe

Gen AI emerges as a front-runner in the trends landscape, sharing the top spot with electrification and renewables for the highest percentage of respondents scaling its implementation. This underscores its significance as a pivotal, high-growth trend to closely monitor throughout the year.

Many companies have made progress throughout the year on adopting gen AI and are currently working on scaling it across their businesses. While gen AI adoption has surged across various sectors, the technology, media, and telecommunications sector has notably emerged as a leader in the deployment of the technology.

The lack of availability of local language support poses challenges to adoption globally. Some countries, including India, Japan, and countries in the Middle East, have pushed to develop their own LLMs. In Africa, the prioritization of data locality and proximity hampers the building of LLMs.

Significant progress has been made recently with the emergence of multilingual models. Multilingual capabilities could become essential for any LLM, with the primary focus shifting to the degree of localization, including the use of slang, technical terms, and other nuances.

Adoption dimensions

The adoption trajectory of advanced technologies varies for each technology and each use case within that technology. Advancements along the following dimensions could enable reaching the next level of adoption for gen AI:

— a clearly defined ROI for widespread horizontal and vertical use cases by sector, along with a demonstrated ability to control risks and ensure safety with the development and deployment of new AI solutions

— decreased computational costs, alongside improvement in overall AI efficiencies (for example, improving latency)

‘Since gen AI captured public attention at the end of 2022, a significant amount of focus has been placed on delivering value through foundation models. Many are already demonstrating cross-industry value, such as coding acceleration or sales and marketing use cases, as well as domain-specific models, such as protein engineering or chemistry discovery foundation models. The field continues to improve quickly with new tools—for example, multimodal, agent-based models. Companies should concentrate on building capabilities in this domain and prioritize areas of focus to ensure they capture early value and aren’t left behind.’

– Matej Macak, partner, London

In real life

Real-world examples involving the use of gen AI include the following:

— ING, a global financial institution, leveraged gen AI to enhance customer service in the Netherlands, one of its key markets.[4] While the current classic chatbot usually resolves 40 to 45 percent of those chats, that leaves another 16,500 customers a week who need to speak with a live agent for help. Recognizing gen AI's potential, ING developed a bespoke customer-facing chatbot to provide immediate, tailored assistance. This resulted in helping 20 percent more customers avoid long wait times and offering instant gratification in the first seven weeks of use compared with the previous solution. The chatbot is expected to reach 37 million customers as it expands across ten markets.

— Recursion, a biotech company, has developed a new gen AI platform and trained an LLM to accelerate drug discovery. This platform enables scientists to simultaneously access multiple machine learning models that can process large amounts of proprietary biological and chemical data sets to save time during drug development.

— Itaú Unibanco, Latin America's largest private sector bank, created ad campaigns dedicated to women football athletes using AI.[5] The campaign highlighted a 1941 Brazilian law that banned women from playing football. It used AI-generated images from conversations with real players and historians, among others, to create the "Brazilian teams that have never existed" campaign, paving the way for a new generation of AI-based media advertising.

— Nubank is piloting a gen AI virtual assistant to boost customer service.[6] The virtual assistant focuses on delivering personalized credit-related options within the Nubank ecosystem. It helps customers understand their credit card usage, explore collateralized credit opportunities, and use its online payment service NuPay without affecting their credit limits. Additionally, it may offer personal loans based on the customer's profile and eligibility. For the initial phase, this innovative solution will be available exclusively to members of NuCommunity, Nubank's customer engagement platform. The assistant, developed using GPT-4 and Nubank's proprietary tools, was designed to evolve and improve through continuous customer interactions, ensuring a dynamic, customer-focused service.

Underlying technologies

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

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

— *Integration/tooling layer.* Sitting between the application layer and 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 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.

— *Digital infrastructure.* This involves using the digital abstraction of physical infrastructure to support data storage, processing, and computation. Digital abstraction includes databases (for example, SQL and NoSQL) and core tech services (for example, compute, storage, and networking).

— *Physical infrastructure.* This encompasses hardware that enables computational, data storage, and networking needs, including data centers, AI accelerator chips, and data center mechanical, electrical, and plumbing technologies.

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[4] "Banking on innovation: How ING uses generative AI to put people first," McKinsey, accessed May 2024.
[5] "Brazilian teams that have never existed," Ads of the World, Clio Awards, accessed May 2024.
[6] "Nubank begins testing with generative artificial intelligence to enhance customers' experience with credit," Nubank press release, October 18, 2023.

Key uncertainties

The major uncertainties affecting gen AI include the following:

- *Cybersecurity and privacy concerns* are prevalent, notably regarding data leakage risks and vulnerabilities (including customer and protected data).
- *Ethical considerations* surround the responsible use of gen AI, including data governance, justice and fairness, accountability, and explainability.
- *Regulation and compliance* might affect research into gen AI and its potential applications.
- *Copyright ownership and protection* of content generated by open-source models remains an unanswered question.
- *Environmental impact* may increase as training models expend exponentially more computational resources.
- *Inaccuracies* are the most recognized and experienced risk for gen AI uses,[7] and they can affect use cases across the gen AI value chain.

Big questions about the future

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

- How will the cost of model creation evolve, and how will it affect competitive dynamics?
- Will enterprise adoption experience the same level of exponential growth and monetization as seen in consumer adoption?
- How will the market develop in terms of open-source solutions versus closed-source?
- How should companies approach gen-AI-related risks, including data privacy and security, equity, fairness, compliance, and copyright protections?
- What strategies should policy makers adopt to address the risk of social engineering from third-party LLM solutions?
- When will error rates and avoidance of hallucinations get to an acceptable level for large-scale implementations of gen AI in everyday use cases?
- Which workers will see their roles shift due to gen AI, and to what extent will they be affected?
- As technological advancements such as gen AI models, accelerators, and throughput continue to evolve, what are the primary use cases that companies should prioritize, and how should they position themselves for future relevance in terms of their degree of involvement, whether as shapers, takers, or makers?

‘Gen AI is currently at the exciting nexus of demonstrated proof of value, rapid innovation, significant public and private investment, and widespread consumer interest. The year 2023 was the year of pilots, and, moving forward, we can expect to see two important areas of focus to accelerate adoption and value creation: one is a rapid expansion of modular and secure enterprise platforms that will serve as the foundation for developing gen AI applications, and two, a focus on the reskilling and rewiring of processes required in a business domain to drive user adoption and capture value.’

– Delphine Nain Zurkiya, senior partner, Boston

[7] “The state of AI in early 2024,” May 30, 2024.

Applied AI

The trend—and why it matters

As we navigate through 2024, the impact of analytical AI technologies, including applications of machine learning (ML), computer vision, and natural-language processing (NLP), continues to grow across all sectors. Companies are using data to derive insights to automate processes, transform businesses, and make better decisions. McKinsey research estimates that AI applications can potentially unlock an economic value of $11 trillion to $18 trillion annually.[1] The excitement around generative AI (gen AI) has led to increasing awareness of the potential value of applied AI. In our recent global survey on the state of AI in 2024, 67 percent of respondents say they expect their organizations to invest more in AI over the next three years.[2] The survey highlights that organizations continue to see returns from AI efforts across business domains. Regulators and policy makers alike are also taking note of AI's increasing impact, with the European Parliament, for example, passing the unified EU Artificial Intelligence Act.[3]

However, the journey to AI adoption is filled with challenges and learning opportunities, such as transforming organizational culture to foster collaboration, trust, and adaptation to new ways of working; acquiring, leveraging, and organizing valuable sources of large data sets; and interpreting model outputs to build end-user trust in them. Leaders should anticipate challenges such as governance conflicts across the entire business—given the cross-domain nature of AI—and the rapid evolution of the regulatory and ethical landscape. Despite these challenges, establishing protocols and guardrails, along with effective change management, can help mitigate risks and ensure the successful incorporation of AI into business operations.

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1 *The economic potential of generative AI: The next productivity frontier*, McKinsey, June 14, 2023.
2 "The state of AI in early 2024: Gen AI adoption spikes and starts to generate value," McKinsey, May 30, 2024.
3 Melissa Heikkilä, "The AI Act is done. Here's what will (and won't) change," *MIT Technology Review*, March 19, 2024.

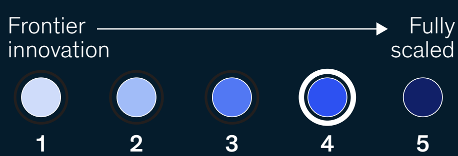
THE AI REVOLUTION

Applied AI

Scoring the trend

High innovation and investment scores for applied AI are commensurate with its large potential impact. Each year from 2019 to 2023, applied AI has had the highest innovation scores of all the trends we studied, and its investment score also ranks in the top five. While demand for applied AI talent declined 29 percent from 2022 to 2023, perhaps unsurprisingly, in 2023, demand for talent in applied AI remained among the highest of all the trends we studied.

Adoption score, 2023



Equity investment, 2023,
$ billion

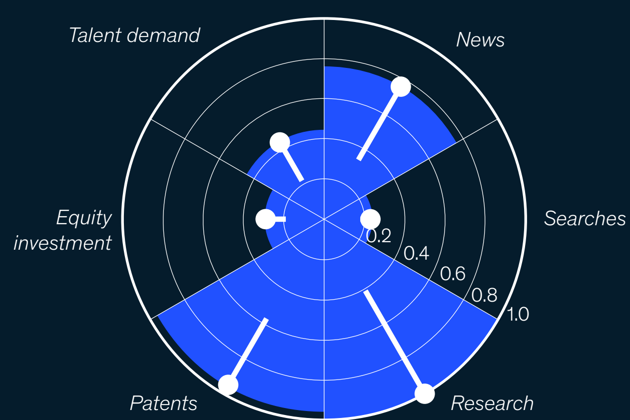
$86

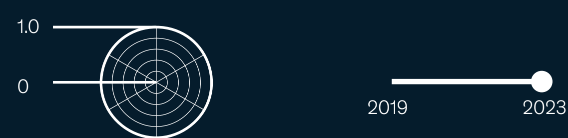
Job postings, 2022–23,
% difference

–29%

Industries affected: *Aerospace and defense; Agriculture; Automotive and assembly; Aviation, travel, and logistics; Business, legal, and professional services; Chemicals; Construction and building materials; Consumer packaged goods; Education; Electric power, natural gas, and utilities; Financial services; Healthcare systems and services; Information technology and electronics; Media and entertainment; Metals and mining; Oil and gas; Pharmaceuticals and medical products; Public and social sectors; Real estate; Retail; Semiconductors; Telecommunications*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Recent developments involving applied AI include the following:

— *The emphasis on data-centric AI is growing.* Rich, high-quality data sets are essential assets for capturing value from AI. The shift toward data-centric AI represents a significant evolution in the field, as capabilities such as picking the right model or hyperparameter tuning become more automated and easier to use. Data-centric AI use cases are diverse and widespread, but specific examples include financial institutions using it to detect and prevent fraudulent activities, healthcare providers promoting transparency in AI-driven diagnoses, or manufacturers identifying potential biases in quality control systems. A company's unique data can be used to train AI models to automate and optimize core processes and unlock new business potential. Having access to unique data sets can provide a distinct competitive advantage, which explains why companies such as OpenAI are actively seeking new data and purchasing exclusive rights.

As companies build their own private AI environments, the scope of data governance will expand beyond privacy to address interconnected threats such as data poisoning (for example, tampering with the training data) and model hijacking (for instance, taking control of an existing model and manipulating it to perform unauthorized tasks). This transition requires robust data practices, including maintaining data quality, tracing data lineage, and employing explainable AI to foster trust and reduce bias.

— *Hardware acceleration has gained significant momentum in applied AI.* The continuous increase in the scale and complexity of deep learning models has surpassed the abilities of conventional central processing units, accelerating hardware development. To train these large models and operate them in real time, organizations are shifting toward specialized hardware such as graphics processing units (GPUs), field-programmable gate arrays (FPGAs), application-specific integrated circuits (ASICs), and high-bandwidth memory (HBM) chips. Originally designed for graphics, GPUs now provide the parallel processing power needed for AI tasks. FPGAs offer adaptability for custom solutions at the edge, while ASICs offer top-tier performance and efficiency for specific tasks. As the complexity of AI increases, the search for faster, more efficient hardware persists. By leveraging the capabilities of specialized hardware, organizations can spearhead the forthcoming wave of AI innovation.

— *Generative AI (gen AI) opens the door to more applied AI.* Gen AI adoption is not only increasing among curious individuals but also catalyzing increased adoption of applied AI. We see organizations getting the most impact from gen AI when they intertwine it with applied AI use cases. For instance, a digital-marketing company is using gen AI to create a variety of unique and engaging content for its customers. However, the real magic happens when its applied AI systems analyze the performance of the generated content, identifying patterns and trends in user engagement. This data is then used to inform the gen AI system, generating insights to produce more effective content in the future. In this way, gen AI is being informed by real-world data and feedback. The synergy between gen AI and applied AI is what truly unlocks the potential of both technologies.

'The prominence of generative AI has opened the aperture for business leaders to explore applied AI, which could have as much or greater business impact.'

– Michael Chui, partner, Bay Area

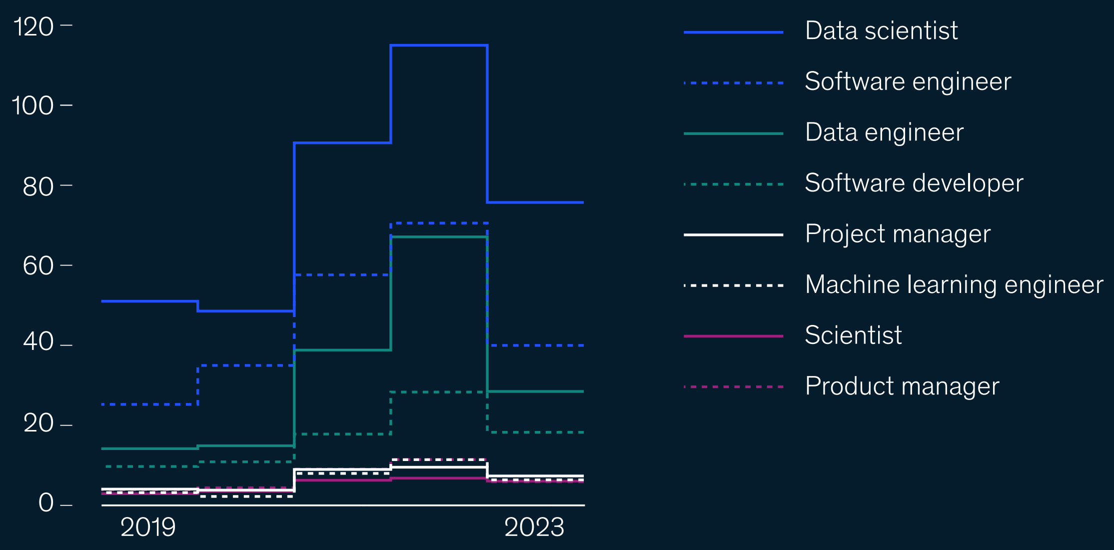
Talent and labor markets

Applied AI

Demand

Between 2019 and 2022, applied AI saw rapid growth in demand for talent, with job postings more than tripling. Then, in line with the overall job market, applied AI saw a 29 percent reduction in total job postings across the most common positions in 2023 compared with 2022. However, applied AI continues to have among the most job postings per trend, with more than 500,000 job postings in 2023. And with high investment activity, one could expect the demand for applied AI talent to remain steady.

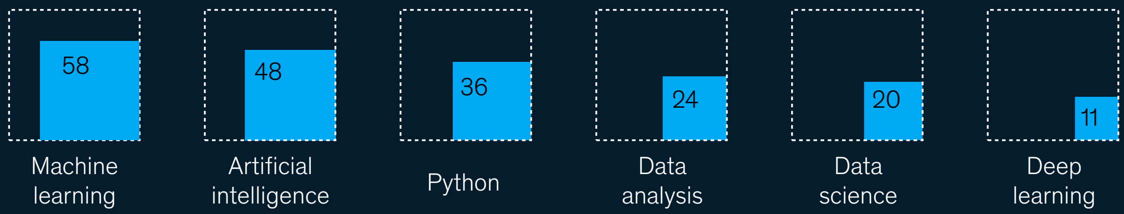
Job postings by title, 2019–23, thousands



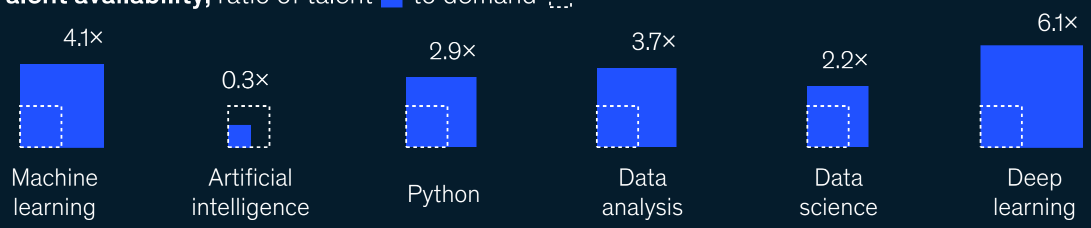
Skills availability

There is a significant demand for specialized AI-related skill sets, and more people are striving to acquire these skills, leading to larger numbers of people listing these skills on their profiles. As the level of competency achieved can vary, companies will need to assess the skills proficiency of potential job applicants.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Applied AI tools are widely adopted across industries and regions, driven by advancements in AI capabilities and an increase in use cases. Most companies adopt applied AI technologies to increase revenue—for example, through integration with existing offerings or completely new product and revenue streams.

The technology, media, and telecommunications and financial-services sectors have emerged as leaders in the adoption of applied AI tools. Some of these companies are also the makers and innovators of the technology itself. Across industries, including financial and professional services, energy and materials, and consumer goods, companies also have made significant investments in applied AI tools.

Adoption dimensions

The adoption trajectory for advanced technologies will look different for each technology and each use case within that technology. Advancements along the following dimensions could enable the next level of adoption for applied AI:

- improved availability of plug-and-play solutions to allow seamless integration into existing IT and cloud infrastructure, combining standardized and interoperable industrialized ML with gen AI capabilities for a broader range of industry use cases and clear ROI
- effective change management to foster continuous learning and knowledge sharing through training, best-practice dissemination, and role modeling to drive effective organizational adoption of AI technologies
- robust implementation of ML-operations (MLOps) and large-language-model-operations (LLMOps) practices to ensure optimal performance of AI models in production environments (for more, see the "Industrializing machine learning" trend), enabling seamless scalability and sustained performance from minimum-viable products to enterprise-wide deployment
- improved data organization, availability, and governance across organizations to enable AI use cases

In real life

Real-world examples involving the use of applied AI include the following:

- Saudi Aramco has built an AI hub to efficiently analyze more than five billion data points per day from wellheads in the oil and gas fields, enhancing the understanding of petro-physical properties and expediting decision making in exploration and drilling. The solutions provide real-time alerts to prevent business disruption, improve reservoir performance, and save millions of dollars by optimizing field development plans and well trajectories. AI technology is also used to predict and prevent drilling challenges, such as stuck pipes, and to monitor the health of essential equipment, such as steam traps, using infrared images.[4]

'Applied AI has been transforming the way we work for some time now. Gen AI takes this to a new level, allowing organizations to tackle end-to-end workflows that were previously too complex to go after. This is possible with gen AI's powerful off-the-shelf models that are complemented by data-centric approaches. As we apply these technologies, organizations need to emphasize the integral human part of these workflows, ensuring that these solutions are built for end users, by end users.'

– Stephen Xu, director of product management, QuantumBlack, AI by McKinsey, Toronto

[4] Victoria Sayce, "The AI Hub at Aramco: The home of our next-generation of digital innovation," Aramco, October 23, 2022.

— DigitalOwl's AI-powered platform facilitates the efficient processing and analysis of extensive medical records, encompassing both traditional and electronic health records. Tailored for life insurance underwriters, this solution simplifies the navigation of complex and voluminous medical documents by extracting and organizing critical information.[5]

— Vistra Corp, the largest competitive power producer in the United States, committed to a 60 percent emissions reduction by 2030 and net-zero emissions by 2050.[6] Among several emissions reduction initiatives, Vistra wanted to understand how AI might help it run its power plants more efficiently. The company used a multilayered neural network model, trained on two years of plant data, to determine optimal plant operations—for example, set points in the control room to achieve maximum heat-rate efficiency for any combination of external factors, such as temperature and humidity. Once power engineering experts validated the models, they began to provide recommendations to operators every 30 minutes to enhance the plant's heat-rate efficiency, helping operators meet energy targets and improve plant reliability. This led to a 30 percent decrease in duct burner usage, annual fuel savings of about $175,000, and reduced carbon emissions, ensuring more efficient, more reliable power. The insights were incorporated into a solution named the Heat Rate Optimizer (HRO), which was implemented across the company's entire fleet, yielding $23 million in savings. Vistra has since extended the HRO to 67 additional power generation units across 26 plants.[7]

Underlying technologies

AI comprises several technologies that perform cognitive-like tasks. For further information on underlying technology for gen AI, please refer to the gen AI section of the report. The technologies underlying applied AI include the following:

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

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

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

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

— *Additional hardware tools and technologies.* These are other tools and technologies—such as cloud computing and domain-specific architectures, including GPUs—that improve access to high-capacity compute for AI and ML workflows.

Key uncertainties

The major uncertainties affecting applied AI include the following:

— *Cybersecurity and privacy concerns,* notably on data risks and vulnerabilities, are prevalent: 51 percent of survey respondents cited cybersecurity as a leading risk in 2024.[8]

— *Regulation and compliance* might affect AI research and applications.

— *Ethical considerations*—including data governance, equity, fairness, and explainability—surround the responsible and trustworthy use of AI.

— *Operational risks* may arise from AI failure modes, as well as potential risks associated with data quality and integrity, model drift, adversarial attacks, and the need for ongoing training and education.

Big questions about the future

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

— How might companies identify the most beneficial AI applications and strategically use generative and applied AI together?

— What are the talent and tech stack implications of adopting applied AI?

— How can companies get ahead of their competitors and capture the value at scale associated with applied AI (regarding either revenue or cost benefits)?

— How will companies balance AI's potential cost savings while integrating features to make AI trustworthy and responsible?

— What checks should companies implement to guard against AI-related risks associated with data privacy and security, equity, fairness, and compliance?

[5] "DigitalOwl revolutionizes medical record analysis and review with the latest release of version 4.0 of their Digital Medical Abstract (DMA)," Business Wire, January 17, 2023; "Nationwide is streamlining life underwriting process with DigitalOwl's advanced AI technology," *LIFE&Health Advisor*, June 3, 2024.
[6] "An AI power play: Fueling the next wave of innovation in the energy sector," McKinsey, May 12, 2022.
[7] Ibid.
[8] "The state of AI in early 2024," McKinsey, May 30, 2024.

Industrializing machine learning

The trend—and why it matters

Industrializing machine learning (ML), also known as machine learning operations (MLOps), is the process of scaling and maintaining ML applications within enterprises. As we progress through 2024, MLOps tools are rapidly evolving, improving in both functionality and interoperability. These tools are facilitating the transition from pilot projects to robust business processes, enabling the scaling of analytics solutions, and enhancing team productivity. Successful industrialization of ML can help sustain solutions, reduce the production timeline for ML applications by eight to ten times, and decrease development resources by up to 40 percent.[1] Initially introduced by a few pioneering companies, MLOps is becoming more widely adopted as more companies use AI for a broader spectrum of applications. The rise of generative AI (gen AI) has reshaped the AI landscape, demanding a corresponding upgrade in MLOps capabilities to service its unique demands. This is the newest field for novel developments in the industrializing ML trend. MLOps and foundation model operations (FMOps) are essential for industrializing and scaling gen AI safely and efficiently.

[1] Based on observations from MLOps deployment in a series of large-scale analytics transformations supported by McKinsey.

THE AI REVOLUTION

Industrializing machine learning

Scoring the trend

Scores across news, searches, publications, and patents have more than doubled between 2019 and 2023, while demand for talent has more than tripled in the same time frame. These increases suggest that the use of methods for industrializing ML could expand in the years ahead. Equity investment activity in MLOps has dropped in two consecutive years.

Adoption score, 2023

Frontier innovation → Fully scaled

1 2 **3** 4 5

Equity investment, 2023, $ billion

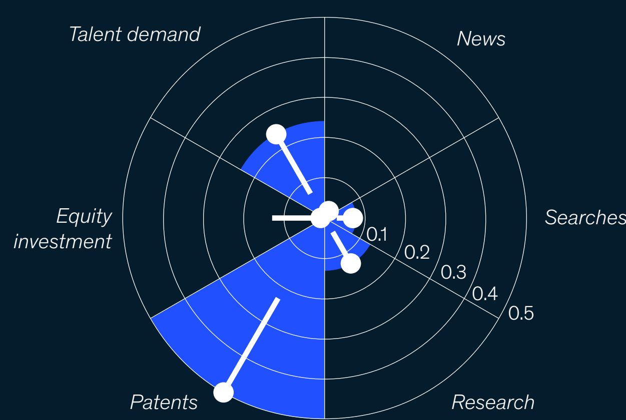
$3

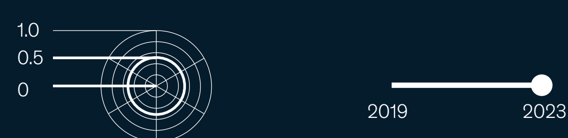
Job postings, 2022–23, % difference

–36%

Industries affected: *Aerospace and defense; Agriculture; Automotive and assembly; Aviation, travel, and logistics; Business, legal, and professional services; Chemicals; Consumer packaged goods; Education; Electric power, natural gas, and utilities; Financial services; Healthcare systems and services; Information technology and electronics; Media and entertainment; Metals and mining; Oil and gas; Pharmaceuticals and medical products; Public and social sectors; Real estate; Retail; Semiconductors; Telecommunications*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Recent developments involving industrializing ML include the following:

— *Monitoring and orchestration are becoming crucial components of MLOps.* This is particularly evident in the complex task of upgrading enterprise technology architecture to integrate and manage models and orchestrate interaction between ML models and other applications and data sources. Several integration patterns are emerging, including those that allow models to call APIs in response to user queries. Recent advancements in integration and orchestration frameworks, such as LangChain and LlamaIndex, have greatly facilitated these developments. To effectively integrate these models, it's essential for MLOps pipelines to incorporate specific performance measurement tools. For instance, they need to assess a model's ability to retrieve the correct information. Companies such as Fiddler and Databricks are actively investing in this field. They offer performance tracking, validation, and orchestration, enabling companies to monitor their live operations effectively. This ensures the smooth facilitation of their ML applications, further emphasizing the importance of monitoring and orchestration in the successful implementation of MLOps.

— *The use of prebuilt solutions and APIs is on the rise.* In recent years, there has been a significant surge in the availability of machine learning APIs and preconfigured solutions, partly due to the explosive growth of gen AI. Accessed predominantly through APIs, gen AI technologies—encompassing advanced tools such as computer vision libraries and pretrained image recognition models—have profoundly reshaped the ML development landscape. As these APIs gain popularity and continue to evolve, they are progressively assuming responsibilities that were once the purview of ML engineers, such as data preprocessing and model training on predefined data sets. As gen AI continues to evolve, its impact on the field is expected to expand, making it a pivotal driver of industrializing ML technologies.

— *MLOps is important to gen AI from the get-go.* It is increasingly recognized that gen AI, including large language models, should not be viewed as separate from the ML ecosystem. Instead, there is a call to broaden the scope of MLOps to incorporate gen AI. MLOps is crucial in developing, deploying, and maintaining gen AI solutions, allowing ML algorithms to be dispatched quickly and effectively. By standardizing processes, enabling version control and tracking, and integrating shared metrics and monitoring, MLOps breaks down organizational silos and fosters close collaboration between data scientists, ML engineers, and operations teams and thus is pivotal in the end-to-end life cycle of gen AI.

'The past several years have yielded huge advances in the mathematics of machine learning, but the tasks of making that math really useful have lagged. MLOps—the way that the math gets made useful—is finally catching up. The tools and processes are beginning to mature, but we still need additional talent and skills to reap the benefits of machine learning.'

– Douglas Merrill, partner, Southern California

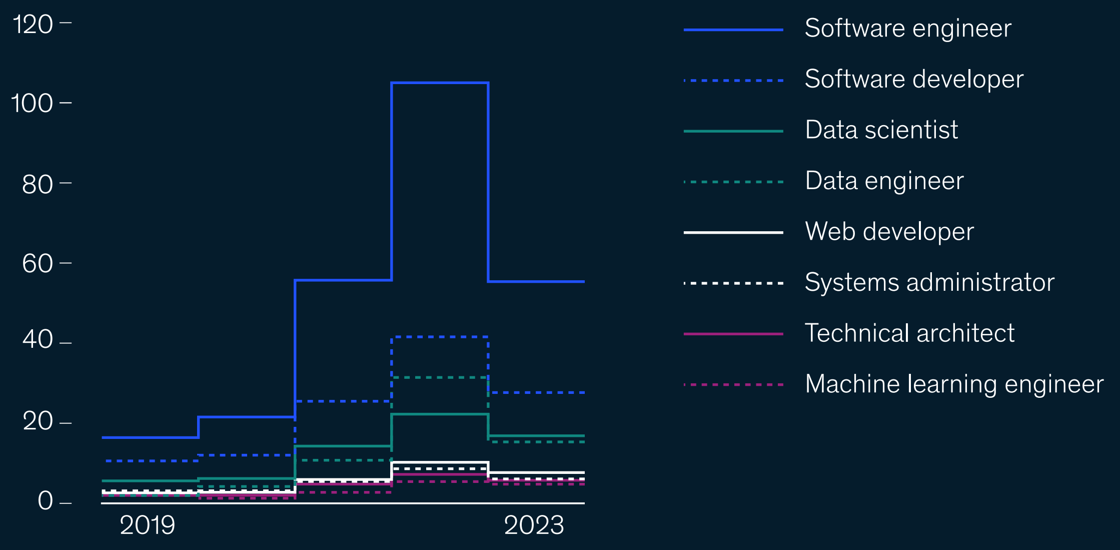
Talent and labor markets

Industrializing machine learning

Demand

Job postings for roles related to industrializing ML decreased by 36 percent compared with 2022 levels, significantly greater than the 26 percent average decrease across all technology trends. As software evolves, many tasks will be automated, and many MLOps tasks are expected to become the responsibility of frontline ML developers. Companies investing in industrializing ML are shifting their focus from rapid application development to effective scaling and implementation. Monitoring is becoming a crucial component, encompassing performance tracking, validation, and orchestration. MLOps offerings are also growing to streamline industrialization (for example, Databricks).

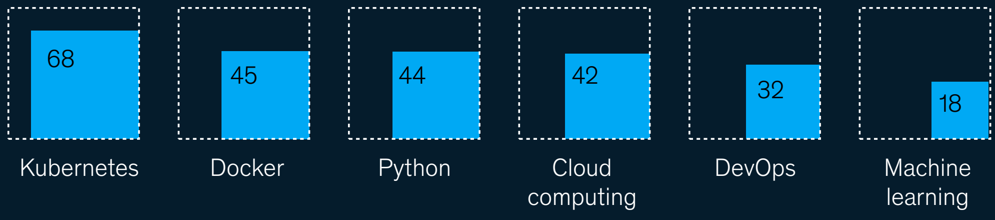
Job postings by title, 2019–23, thousands



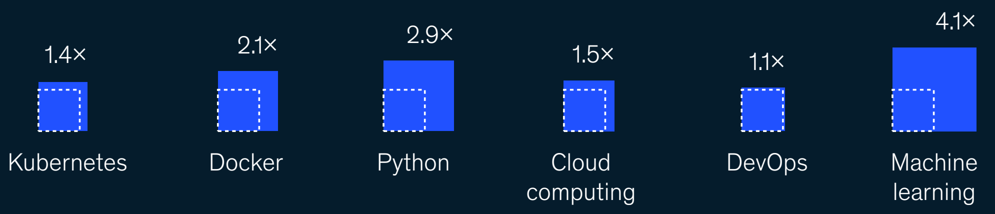
Skills availability

Companies that are industrializing their ML initiatives require advanced technological skills, and there is talent available to meet this demand. These skills include expertise in containerization with Docker, orchestration with Kubernetes, and proficiency in programming languages such as Python.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Adoption levels of industrialized ML fall in the middle relative to other trends, as other advancements have generated more buzz in recent years. Some of the leading sectors in adopting industrialized-ML practices include energy and materials and technology, media, and telecommunications. Additionally, financial-services companies made significant investments in ML tools, driven by a focus on enhancing customer satisfaction and improving decision making.

Adoption dimensions

The adoption trajectory for advanced technologies will look different for each technology and each use case within that technology. Advancements along the following dimensions could enable the next level of adoption for industrializing ML:

— greater availability of simplified tools for data management and an increase in data source availability and robustness in terms of data quality and volume of data points, potentially through improved data services

— continued standardization and improvements in underlying technologies across the ML/AI software development life cycle (for example, model development, deployment, and monitoring)

— organizational adoption and awareness to improve—making the technology more broadly accessible and understood by nontechnical employees

In real life

Real-world examples involving industrializing ML include the following:

— Meta uses HawkEye internally to gain a comprehensive understanding of its ML workflows.[2] HawkEye functions as a real-time monitor, anomaly detector, and analyst for potential issues, from data quality to model performance. It also ensures end-to-end observability through tracing of ML pipelines, integration with explainable AI, and the provision of debugging tools.

— MLflow, an open-source platform aimed at streamlining ML development, is adding generative AI–centered capabilities. For example, its prompt engineering user interface provides an opportunity to try out multiple large language models (LLMs), parameter configurations, and prompts.[3]

‘Solving for gaps in automated monitoring and life cycle management of deployed AI solutions will ensure the lasting and scalable impact of AI. That includes continued focus on gen AI: industrializing bespoke gen AI solutions will require robust gen AI operational ecosystems, and we see more options emerging for processing unstructured data, engineering and operating LLM flows, and automating the gen AI solutions life cycle. Continued progress on enablement of regulatory and ethical alignment and explainability will help unlock new areas of AI impact.’

– Alex Arutyunyants, senior principal data engineer, QuantumBlack, AI by McKinsey, Boston

[2] Partha Kanuparthy, Animesh Dalakoti, and Srikanth Kamath, “AI debugging at Meta with HawkEye,” Engineering at Meta, December 19, 2023.
[3] *MLflow Blog*, “2023 Year in Review,” blog entry by Carly Akerly, January 26, 2024.

Underlying technologies

Software solutions enable the various stages of the ML workflow, which are as follows:

- *Data management.* Automated data management software improves data quality, availability, and control in feeding the ML system.
- *Model development.* Tooling is used to build and optimize ML models, engineer features, and standardize processes.
- *Model deployment.* Provision tooling helps to test and validate ML models, brings them into production, and standardizes processes.
- *Live-model operations.* With this process, software maintains or improves the performance of models in production.
- *Model observability.* These tools go beyond basic monitoring and delve deeper into understanding a model's behavior. They provide insights into model performance, identify potential biases, explain model decisions, and help diagnose issues such as data drift or concept drift.

Key uncertainties

The major uncertainties affecting industrializing ML include the following:

- *Up-front investment and resources* will be required to establish industrialized ML in organizations.
- *Processes and accountability* will be crucial for maintaining ML solutions at an industrial scale.
- *A fast-evolving market* will require organizations to balance the efficiency of using their existing vendors' offerings with realizing value from newer offerings provided by players outside their existing vendor ecosystem.
- *The potential for misaligned capabilities* will need to be avoided by ensuring that organizations are investing in the right solutions and at the right levels for their specific use case needs.
- *Continuous monitoring and evaluation* will be crucial for identifying and addressing unwanted bias throughout the ML life cycle, from initial data selection to ongoing model performance assessments.
- *Technology and talent evolution* will be essential, due to increasing automation of certain roles and the need for workers who are skilled in building and maintaining productionized ML systems at scale.

Big questions about the future

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

- With the emergence and acceleration of gen AI, how will MLOps practices and the technology ecosystem evolve?
- With the proliferation of new technologies in ML, how should organizations prioritize those along the ML workflow that are most relevant to their needs?
- How will industrialized ML change organizations, their operating models, and their engineering roles?
- As industrialized ML proliferates, how can organizations define accountability roles to ensure the trustworthy and responsible use of AI/ML?
- How can organizations best integrate their MLOps efforts across machine learning, deep learning, and gen AI models?

Building the digital future

Next-generation software development

The trend—and why it matters

The landscape of software development is currently experiencing a transformative shift, driven by an influx of cutting-edge technologies such as generative AI (gen AI) and cloud-native architectures. The year 2023 saw a significant rise in AI-powered tools, building on previous years' advancements in software development and DevOps automation (for example, continuous integration, continuous delivery, infrastructure as code, and improved integrated development environments). These innovations are revolutionizing how engineers operate throughout the entire software development life cycle (SDLC), from planning and testing to deployment and maintenance. These technological breakthroughs are not only enhancing the capabilities of engineers but also opening doors for less technical professionals to participate in application development as complex tasks are simplified and accelerated.

While the path to wide-scale adoption may take more time—because of obstacles such as integration challenges, lack of clear measurement metrics for developer productivity, and need for large-scale retraining of developers and test engineers—an increase in the adoption of AI-powered software development tools is promising. Early adopters are already experiencing productivity boosts, laying the groundwork for more widespread adoption in the near future. This year promises even more groundbreaking possibilities as maturing technologies like user-friendly low-code platforms, AI assistants throughout the SDLC, integration with gen-AI-enabled product management tools, and scalable cloud architectures converge, leading to democratized development, hyperefficiency, and exceptional adaptability.

BUILDING THE DIGITAL FUTURE

Next-generation software development

Scoring the trend

A large uptick in searches, publications, patents, and talent demand between 2019 and 2023 clearly signals that both institutions and enterprises are seeing long-term potential in the evolution of next-generation software development tools. The investment climate for this technology has seen peaks and valleys over the past five years (the peaks reflecting a few mega deals in some years).

Adoption score, 2023

Equity investment, 2023,
$ billion

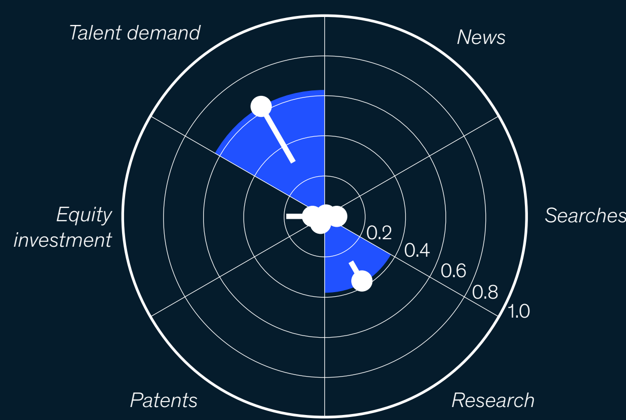
$17

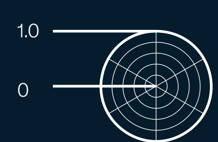
Job postings, 2022–23,
% difference

–37%

Industries affected: *Advanced industries; Business, legal, and professional services; Consumer packaged goods; Financial services; Healthcare systems and services; Information technology and electronics; Manufacturing; Media and entertainment; Telecommunications*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Recent developments involving next-generation software development include the following:

— *New versions of AI-powered development tools are transitioning from proof of concept to wide-scale application.* The software development industry has witnessed a significant turning point in the past year with the release of new versions of advanced AI-powered tools that are transforming the landscape. Unlike their static and off-the-shelf predecessors, these new versions have moved beyond the proof-of-concept phase and now offer a higher degree of adaptability and customization, catering to the specific needs of individual projects. This shift is resulting in a wider application of these tools. For instance, Tabnine, an AI-powered auto-completion tool, has improved its ability to understand the context of developers' code, leading to more accurate and relevant code completions. Developers can now create and share custom code templates within Tabnine, allowing them to automate repetitive tasks specific to their projects or coding style, thereby increasing the tool's applicability on a larger scale.[1]

— *There is a growing trend toward more integrated development platforms.* Companies are moving away from a multitude of disparate tools and, instead, adopting a smaller number of robust or better-integrated solutions that offer a wide range of functionalities throughout the development life cycle. This shift provides several advantages, including streamlined workflows that lead to improved collaboration, reduced context switching, and enhanced data visibility. However, catering to diverse use cases within the organization requires a careful selection of tools with robust capabilities and flexibility.

— *The talent landscape will undergo changes*. The availability of advanced underlying technologies, such as gen AI, is enabling software engineers to reallocate their time from tasks such as pure code generation to tasks such as architecture design and problem solving. This change is not only causing a strong mindset shift among engineers but also influencing how companies approach talent selection, upskilling, and onboarding. The focus is no longer solely on the coding skills of potential candidates. Instead, companies are investing in defining a differentiated upskilling strategy to retain and develop talent and are now also assessing how effectively candidates can utilize and adapt to these advanced tools in their day-to-day tasks.

— *The focus on compliance and trust is increasing.* The software development industry is experiencing a significant shift toward compliance and trust in response to growing concerns about legal and security risks associated with software tools. This past year has seen growing attention to compliance-focused tools like SonarQube, which provide features like code tagging, labeling, and detection to improve transparency and accountability. Developers are also choosing tools with guaranteed indemnity to mitigate potential legal risks associated with code generated or analyzed by the tool. By prioritizing compliance and safety, the industry can improve the quality and reliability of their software while also reducing the risk of legal and security issues.

'These new-generation tools are now guaranteeing indemnity for use, with the ability to detect, tag, and label code. This metadata will make generated code easier to track and manage. The future of tooling is likely to see consolidation over time, with companies opting for several comprehensive tools or tool chains instead of numerous specialized ones.'

– Martin Harrysson, senior partner, Bay Area

[1] "Tabnine + Pieces for Developers is a win-win for your workflow," Pieces for Developers, May 3, 2023.

Talent and labor markets

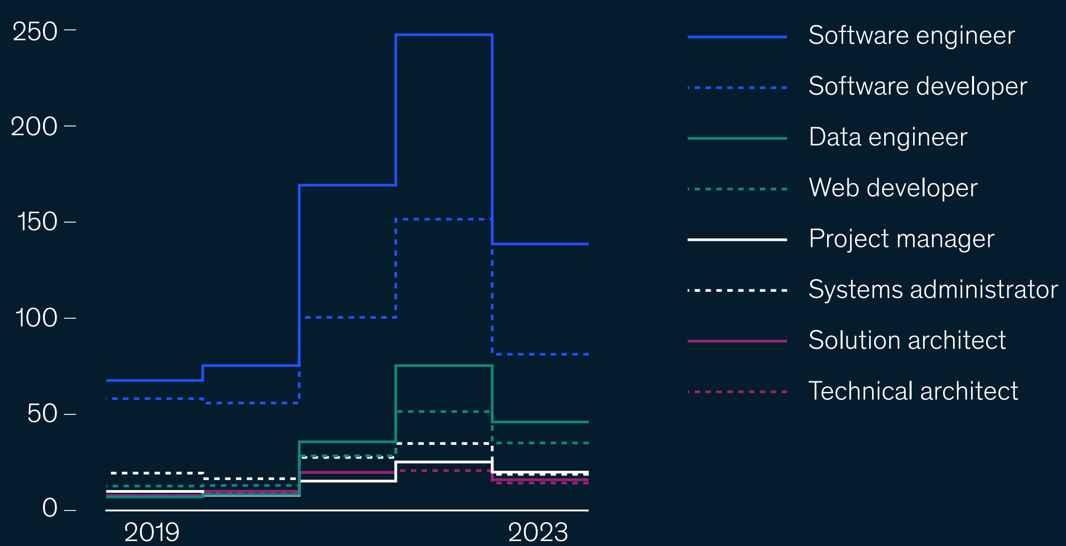
Next-generation software development

Demand

The number of job postings for next-generation software development peaked in 2022 and showed the most job demand of all the technology trends in that year. Unsurprisingly, 2023 saw a decline, but even with a 37 percent decrease in job postings, next-generation software development still scores the highest in job demand among the tech trends, with over 800,000 job postings.

Postings across the board have declined compared with 2022, which is in line with the layoffs seen predominantly in the technology industry. In the near future, it will be interesting to see what the impact of gen AI will be on both the types of roles and demand for roles in next-generation software development.

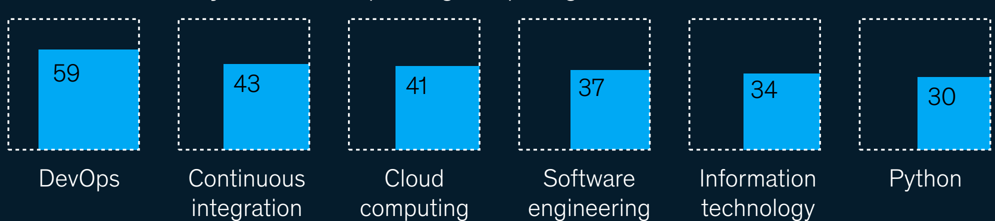
Job postings by title, 2019–23, thousands



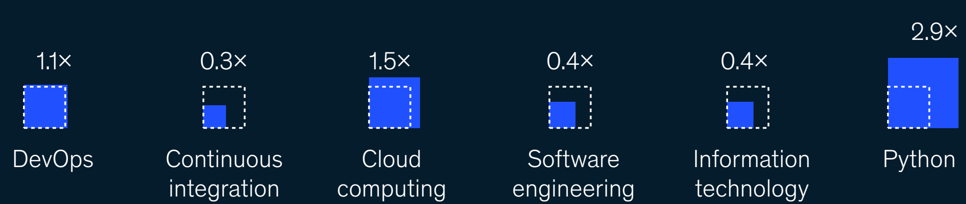
Skills availability

Key talent areas for next-generation software development are focused on DevOps, continuous integration, and cloud computing. Some skills are more plentiful (for example, DevOps and cloud computing), while others are harder to find (for example, continuous integration).

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

The financial-services and technology, media, and telecommunications sectors have emerged as leaders in the adoption of next-generation software development. Investments are driven by the changing compliance landscape and the availability of more customizable tools.

Adoption dimensions

From nascent to mainstream, the adoption trajectory will look different for each technology and even each use case within that technology. As AI-generated code—the most recent innovation within next-generation software development—becomes a standard way of working in the software development cycle, it provides an interesting example of how the adoption trajectory could develop.

Advancements along the following dimensions could enable the next level of adoption:

— clear and measurable ROI of AI-generated code tools (for example, an increase of more than 25 percent in developer productivity for high-complexity tasks)[2]

— a legal framework for liability of AI-generated code outcomes to create transparency on who bears the risk in case of malfunctions

— an increase in the applicability of AI-generated tools that can provide sufficient performance for most common software development use cases

— implementation of AI-generated code as part of the core curriculum and upskilling programs for software developers

In real life

Real-world examples involving the use of next-generation software development include the following:

— Citi leverages the Harness Continuous Delivery platform to provide an integrated experience across all stages of software delivery, with a user base of over 20,000 engineers. The platform brings together all the tools and services involved in software delivery with the aim of improving performance, consistency, and maintenance across the enterprise while operating in the unique regulatory and risk management environment that comes with financial services. The platform helps streamline software delivery, automating deployment, testing, and change management after code approval. It facilitates faster rollbacks and integrates with observability tools for proactive issue detection and auto-rollback if needed. This translates into increased developer and operations control, reduced manual effort, and enhanced security.[3]

— Goldman Sachs is exploring the use of gen AI tools to assist its software developers in writing and testing code. The tools can automatically generate lines of code, freeing developers from repetitive tasks and allowing them to focus on core functionalities and client needs.

‘Next-generation software development tools are fundamentally changing the role of developers, freeing up capacity for improved experiences and architectures, and ultimately, greater value creation.’

– Santiago Comella-Dorda, partner, Boston

2 “Unleashing developer productivity with generative AI,” McKinsey, June 27, 2023.
3 “Citi improves software delivery performance, reduces toil with Harness CD,” Harness, accessed on April 22, 2024.

Underlying technologies

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

— *AI-generated code.* AI applications can go beyond code suggestions and recommendations and also enable users to generate entire functions, optimize existing code, create boilerplate code, and adapt to different programming languages.

— *Low- and no-code platforms.* Software development systems, such as Microsoft Power Apps and Google AppSheet, make it easier for nondevelopers to build applications more quickly.

— *Infrastructure as code.* This is the process of configuring infrastructure, such as a data center, with machine-readable code, which enables rapid reconfiguration and version control. The cloud, for example, is based on the concept of infrastructure that is fully abstracted as code.

— *Microservices and APIs.* These are self-contained, independently deployable pieces of code that can be coupled to form larger applications.

— *AI-based testing.* Next-generation software can use AI to automate unit and performance testing to reduce the amount of time developers spend on this task.

— *Automated code review.* These applications use AI or predefined rules that enable users to check source code.

Key uncertainties

The major uncertainties affecting next-generation software development include the following:

— *Relying on automated testing and reviews* without having humans check the work can lead to increased errors in software and erosion of user trust.

— *The growth in the use of low- and no-code tools by nondevelopers* could be limited because experienced developers are needed to monitor and debug applications.

— *Comprehensive monitoring and version control* could become more difficult due to uncoordinated changes and upgrades from multiple vendors.

— *Quality and security remain concerns with code generated by AI pair programmers,* particularly if they are not regularly updated with the latest standards or are not trained on clean, fast code.

— *Addressing intellectual property, legal liability, and potential regulations* surrounding gen-AI-generated code is essential for responsible development and deployment.

— *APIs add an extra layer of potential security vulnerabilities* that can be exploited, and their customization can be a challenging task requiring substantial time and effort.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with next-generation software development:

— To what extent will the development of AI-generated code affect the day-to-day tasks and responsibilities, as well as number, of software engineers?

— To what extent might no-code tech used by amateur developers reduce the demand for fully trained software development professionals?

— From a cultural standpoint, will teams—both developers and nondevelopers—embrace or resist changes in ways of working?

— What intellectual property issues might affect AI-generated code?

— To what extent will business units take responsibility for the health of applications, or will accountability continue to rest with a shared IT function?

— Will organizations invest in the retraining needed to enable their software teams to adapt to the fast-changing domain?

— How do organizations upskill engineers to know what good outputs from AI-enabled tools look like?

Digital trust and cybersecurity

The trend—and why it matters

Digital trust and cybersecurity enable organizations to manage technology and data risks, accelerate innovation, and protect assets. Moreover, building trust in data and technology governance can enhance organizational performance and improve customer relationships. In this trend, we include technologies that enhance trust (for instance, digital identity and privacy-enhancing technologies), cybersecurity capabilities (such as identity and access management), and Web3 (such as blockchain).

The importance of digital trust and cybersecurity is increasing as organizations adopt emerging and maturing technologies within their enterprises (for example, cloud and edge computing, applied AI, and next-generation software development).[1] While the adoption of these emerging technologies comes with exciting new benefits, it also exposes organizations to cybersecurity and other risks, increasing the need for digital-trust technologies. The adoption of digital trust and cybersecurity, however, has been affected by a range of factors, including integration challenges, organizational silos, talent shortages, and its limited consideration as a critical component of value propositions. Capturing the full benefit of digital trust and cybersecurity will require top-down leadership and deliberate changes to multiple spheres of activity, from strategy and technology to enterprise capabilities.

[1] "The cyber clock is ticking: Derisking emerging technologies in financial services," McKinsey, March 11, 2024.

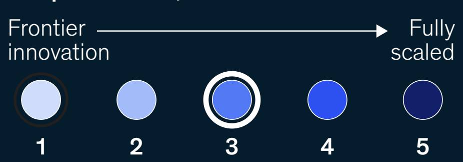
BUILDING THE DIGITAL FUTURE

Digital trust and cybersecurity

Scoring the trend

The digital trust and cybersecurity market has experienced high growth over the recent years: the cybersecurity market growth rate in 2021 was 12.4 percent.[1] But, as with other trends affected by the macroeconomic slowdown, the digital trust and cybersecurity trend took a hit in 2023, compared with 2022, across dimensions such as investment and talent demand. That said, the five-year view (2019–23) shows robust growth across all dimensions, and as the digitization of enterprises continues, this trend is likely to keep gaining traction.

Adoption score, 2023



Equity investment, 2023, $ billion

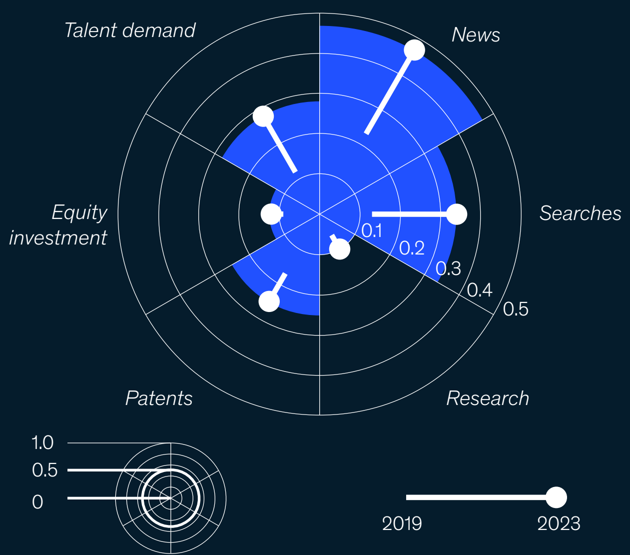
$34

Job postings, 2022–23, % difference

–34%

Industries affected: *Aerospace and defense; Aviation, travel, and logistics; Consumer packaged goods; Education; Electric power, natural gas, and utilities; Financial services; Healthcare systems and services; Information technology and electronics; Media and entertainment; Pharmaceutical and medical products; Public and social sectors; Retail; Telecommunications*

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



Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

[1]Bharath Aiyer, Jeffrey Caso, Peter Russell, and Marc Sorel, "New survey reveals $2 trillion market opportunity for cybersecurity technology and service providers," McKinsey, October 27, 2022.

Latest developments

Recent developments involving digital trust and cybersecurity include the following:

- *Managing generative AI risk and readiness has become a key focus.* The rise of generative AI (gen AI) has sparked innovation across industries while also heightening the focus on managing its associated risks. Key concerns include fairness and bias, as gen AI can perpetuate existing biases embedded in training data. To counter these concerns, companies like IBM are creating fairness tool kits to identify and remove bias within AI models during the development process. Privacy issues arise as a result of gen AI's ability to create deepfakes, prompting research into watermarking AI-generated content. The potential misuse of gen AI for cyberattacks underscores the importance of robust AI security frameworks. Intellectual property (IP) rights over gen AI's creative output remain unclear, and challenges around the explainability of gen AI's outputs hinder trust. President Biden's executive order on gen AI, calling for research into these risks and the development of trustworthy AI standards, and the recently adopted EU AI Act create pressure for responsible deployment and will likely lead to the adoption of new tools, such as those coming from emerging players like Credo AI and Holistic AI.
- *Cybercriminals and threats are evolving at a rapid rate.* Threat actors, including cybercriminals and state-sponsored groups, are becoming more sophisticated. Their attacks exploit new vulnerabilities (for example, intricate ransomware that is debilitating power grids) and aim for maximum disruption (for example, targeting industrial control systems). Unfortunately, current security systems and company readiness are often not at the level needed to deal with this increased cybersecurity risk.
- *New buyers are emerging outside of the CISO role.* Responsibility for cybersecurity is expanding beyond the office of the chief information security officer (CISO), with cyber spend now increasingly coming from nonsecurity business functions such as product and engineering.[2] Consequently, cybersecurity providers must adapt their strategies to use cases with a wide range of stakeholders, including and stretching beyond the CISO office. Improving cybersecurity maturity, increasing efficiency, and possibly increasing the use of AI-enabled automation remain key growth drivers.
- *The ongoing debate between cybersecurity platforms and best-of-breed solutions is evolving.* Cybersecurity platforms offer a unified environment, simplifying management but potentially compromising on functionality. Conversely, best-of-breed solutions offer specialized tools but can struggle with data integration and user experience. We see a shift as the lines between platforms and best-of-breed solutions are blurring, with platforms becoming more modular and integrating best-in-class security tools. The market is at an inflection point in the "best of breed" versus "best of suite" debate: customers have not reached a consensus on a preference in any segment. Smaller companies might favor the simplicity of platforms, while larger ones may value the customization offered by best-of-breed solutions. The best path lies in balancing comprehensive security with manageable complexity while considering the company's security maturity, IT staff skills, and growth prospects.
- *Bitcoin and Ethereum ETFs are sparking mainstream interest.* After a period marked by regulatory challenges for crypto exchanges, multiple Bitcoin exchange-traded funds (ETFs) have been approved. This has effectively lowered the entry barrier, opening up the world of cryptocurrencies to a wider audience. In addition to Bitcoin, Ethereum ETFs are also gaining traction. Several Ethereum ETFs are currently awaiting approval, indicating a growing interest in diversifying cryptocurrency investments. While these developments have significantly influenced the digital-asset market, it remains volatile.
- *Blockchain companies are moving from piloting to at-scale deployment of tokenized financial assets.* Tokenization, the process of creating a unique digital representation of an asset on a blockchain network, has started to scale after many years of promise and experimentation. The benefits—including programmability, composability, and enhanced transparency—can empower financial institutions to capture operational efficiencies, increase liquidity, and create new revenue opportunities through innovative use cases. However, as infrastructure players pivot away from proofs of concept to robust at-scale solutions, many opportunities and challenges remain to reimagine the future of financial services.

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[2] A recent McKinsey survey on cyber market customers (n = 200) asked respondents, "In your best estimation, how much of your cybersecurity spend comes from outside of your CISO organization? Where does that non-CISO cyber spend come from?"

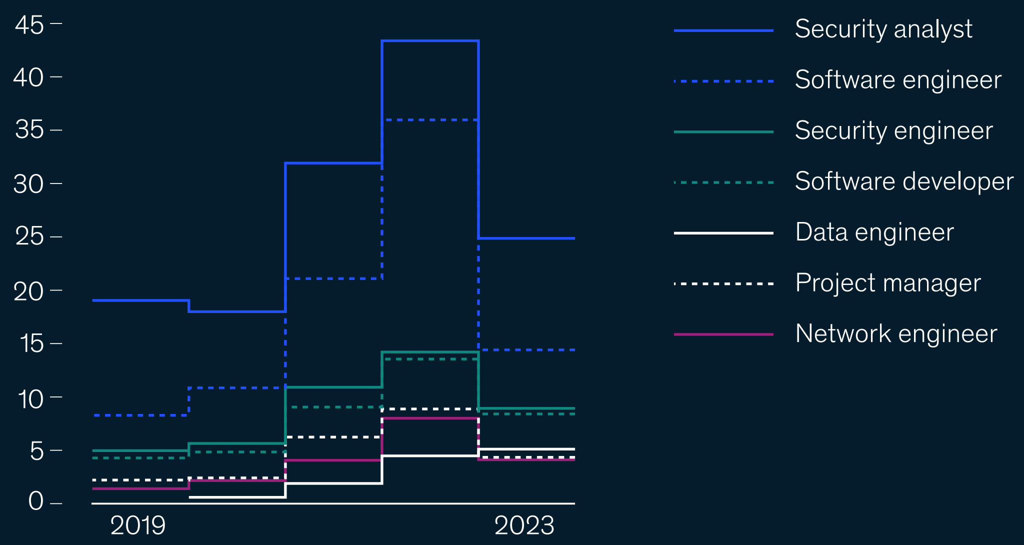
Talent and labor markets

Digital trust and cybersecurity

Demand

Job postings for digital trust and cybersecurity decreased by 34 percent between 2022 and 2023. But in the longer-term view, we saw an increase of 123 percent between 2019 and 2023. Security analyst remains the highest-demand job for digital trust and cybersecurity, followed by software and security engineers.

Job postings by title, 2019–23, thousands

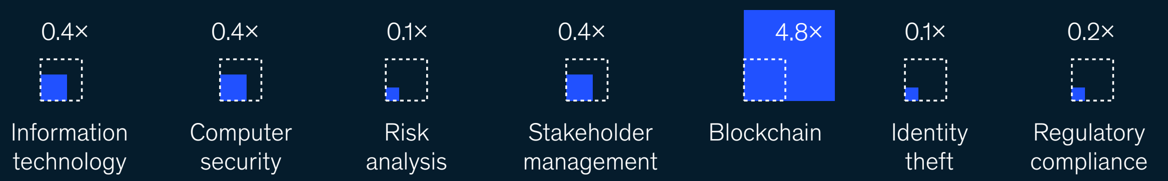


Skills availability

Companies expanding their digital trust and cybersecurity initiatives have a strong demand for skills associated with security, compliance, and risk analysis. Despite the short-term decrease, the demand for relevant skills still generally outpaces supply (except for blockchain), and the talent gap is significant.

Talent availability, % share of postings requiring skill

Talent availability, ratio of talent to demand



Adoption developments across the globe

The digital trust and cybersecurity trend has seen high adoption levels among our trends, with some subcomponents achieving widespread use, while others remain at the forefront of innovation, such as emerging Web3 applications. About 30 percent of survey respondents reported that they had either fully scaled or were scaling digital trust and cybersecurity, and more than 60 percent mentioned they had invested in it. Financial-services companies, in particular, have adopted this trend, driven by a need to combat an increasing range of threats and meet regulatory requirements.

Telecommunications, media, and technology companies are also at the forefront of adopting digital trust and cybersecurity. This is likely because they are leading the way in enhancing security measures, particularly in the realm of AI, and developing effective tools to address the constantly evolving threat landscape.

Companies of any size need to consider how to optimize their defenses as cyberthreats and regulatory and customer pressures increase.

Adoption dimensions

The adoption trajectory for advanced technologies varies for each technology and each use case within that technology. Advancements along the following dimensions could enable the next level of adoption for digital-trust and cybersecurity technologies:

— new digital identity systems integrated and scaled into existing personal-identification processes

— enhanced integration of advanced technologies into existing cybersecurity frameworks, including upgrading midmarket companies' defenses

— strong protection mechanisms to ensure user privacy and control of personal data

— improved government and public perception of the benefits and risks of digital identities

— security capabilities to meet varying regulatory requirements, ensuring compliance and fostering trust

— innovative applications with tangible real-world implications for Web3 to continue expansion beyond decentralized finance as practical applications emerge across various sectors—for example, the decentralized physical infrastructure network (DePIN), still in its early stages, which aims to enable cell phones to function on a decentralized network

In real life

Real-world examples involving the use of digital trust and cybersecurity include the following:

— Salesforce built its Einstein Trust Layer specifically to address security concerns about using large language models (LLMs) within the Salesforce platform. This innovative system acts as a secure intermediary for Salesforce users interacting with LLMs. The Einstein Trust Layer ensures data confidentiality and privacy by masking personally identifiable information (PII) before it is used as input for the LLM and by adhering to a zero-retention architecture, meaning none of the Salesforce data is stored outside the platform or used to train the LLM itself. Additionally, the Trust Layer monitors outputs for inappropriate content and streamlines communication between the user and the LLM.

— Cisco created a customer-facing trust portal called the Cisco Trust Portal. This self-service tool provides customers with on-demand access to a wide range of documents related to security, trust, data protection, and privacy compliance. The purpose of the Trust Portal is to assist customers in gaining a deeper understanding of Cisco's security measures and evaluating the security of its offerings.

'Digital-trust technologies are the cornerstone of value creation in the age of gen AI. By embedding robust security, privacy, and ethical frameworks into AI systems, organizations not only protect their assets but also build a foundation of trust that drives innovation, enhances customer loyalty, and unlocks new opportunities for sustainable growth.'

– Liz Grennan, partner, Stamford

- Skyflow offers a platform called the Skyflow Data Privacy Vault, designed to help companies manage, protect, and utilize sensitive data while ensuring compliance and privacy.[3] It acts as a secure central hub for sensitive data, isolating it from other systems and encrypting it with advanced techniques. Despite strong security, Skyflow's secure APIs still allow users to utilize this data for workflows, sharing, or analysis—all without ever decrypting the original information.
- Franklin Templeton launched the Franklin OnChain U.S. Government Money Fund (FOBXX), the first US-registered mutual fund to use a public blockchain to process transactions and record share ownership. Toward the end of March 2024, it had exceeded $330 million in assets under management. The fund is primarily issued on the Stellar public blockchain and Polygon. Franklin Templeton has also announced plans to issue tokens on other blockchains, including Avalanche and Aptos.[4]
- French banking giant Société Générale completed its first tokenized green-bond issuance on the Ethereum network, reflecting the growing interest in real-world-asset tokenization among traditional financial institutions. The bank's digital-asset-focused division, SG-FORGE, registered the issuance of digital green-bond tokens valued at €10 million ($10.8 million). These security tokens were purchased by two major institutional investors, AXA Investment Managers and Generali Investments, through a private placement.
- Citibank has developed a token service using blockchain technology to offer digital-asset solutions for its institutional clients.[5] The new service, called Citi Token Services, converts clients' deposits into digital tokens, facilitating immediate cross-border payments, liquidity, and automated trade finance solutions around the clock at virtually no cost. As an integral part of the bank's Treasury & Trade Solutions, Citi Token Services aims to integrate these tokenized deposits into Citi's global network, thereby strengthening its core cash management and trade finance functions.

Underlying technologies

Digital-trust and cybersecurity technologies include the following:

- *Zero-trust architecture.* This IT security design concept assumes an organization's network is compromised by default and, therefore, enforces access decisions for every interaction with every entity.
- *Digital identity.* An identity consists of all the digital information that characterizes and distinguishes an individual or an entity. With self-sovereign identity, users control which identifying information to share and with whom. Passwordless identity allows users to verify and authenticate themselves not with traditional alphanumeric passwords but with alternatives such as biometrics, devices and applications, and documents. 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 by design. It focuses on the strategic reduction of privacy risks, enabling purposeful decision making about resource allocation and effective implementation of privacy controls in information systems.
- *Explainable AI.* This AI model covers methods and approaches that increase the transparency and interpretability of the inputs, weightings, and reasoning of machine learning algorithms, thus enhancing trust and confidence in them.
- *Technology resilience.* Technology resilience is the sum of practices and technical foundations necessary to architect, deploy, and operate technology safely across an enterprise environment. It includes components such as immutable backup and self-healing networks. Such capabilities help organizations identify and overcome challenges such as latency, outages, or compromise and have the dual goal of reducing the likelihood of technology risk events and enabling faster recovery if a technology risk event does occur.

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3 Manish Ahluwalia, "What is a data privacy vault?," Skyflow, June 23, 2022.
4 "What is Web3?," McKinsey, October 10, 2023.
5 "Citi develops new digital asset capabilities for institutional clients," Citibank press release, September 18, 2023.

‘In a world where information is digital, connected, and widely accessible, cybersecurity forms the very bedrock of trust through which competitive advantage can be accelerated. But it must be designed, built, and implemented in the right way to realize the benefits.’

– Justin Greis, partner, Chicago

- *Blockchain.* This is a digitally distributed, decentralized ledger that exists across a computer network and facilitates the 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.
- *Digital assets and tokens.* These digitally native intangible items include native cryptocurrencies, governance tokens, stablecoins, nonfungible tokens (NFTs), and tokenized real-world and financial assets, including cash.
- *Decentralized applications.* These applications operate on peer-to-peer networks, removing dependence on centralized servers. They leverage blockchain technology for data storage and security, often utilizing cryptocurrencies for transactions and user engagement.

Key uncertainties

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

- *Implementation complexity* is significant, given resource requirements, talent scarcity, inadequate funding, lack of shared taxonomies and aligned risk frameworks, coordination challenges across multiple parties, and required shifts in organizational norms and practices needed to achieve effective deployments.
- *Compatibility challenges* will be encountered when updating or migrating technologies and integrating them with legacy systems or with an abundance of fragmented point solutions.
- *Lack of standardization and widely accepted best practices* for how or when to use trust architecture techniques across industries will continue to be a challenge. Additionally, differences in national cybersecurity regulations necessitate changes to local company policies.
- *Tensions between privacy and fairness* or privacy and safety can arise. An example might be tension between the avoidance of an excessive collection of demographic data and the need for that data to assess and mitigate bias or spot harms against minors.
- *Geopolitical tensions* may lead to increased cyber risk. Organizations should adopt comprehensive and adaptive cybersecurity strategies to mitigate these risks and ensure resilience when navigating geopolitical uncertainty.
- *Regulatory landscapes for blockchain and tokenization remain fragmented* and under development across various jurisdictions, posing significant challenges for compliance. While some regions have begun to establish comprehensive frameworks, such as the EU’s Markets in Crypto-Assets (MiCA) regulations, the United States and other countries are still navigating through legislative processes with bills like the Blockchain Regulatory Certainty Act. Therefore, it is wise to continuously monitor these evolving regulations to adapt and ensure compliance.[6]
- *The path to explainability is unclear.* There is no one-size-fits-all approach to open up the black box of large AI models to provide meaningful explanation for outputs. These need to be tailored to context and data. However, more efficient tooling and new approaches to explainability create hope for future improvement.
- *Businesses have doubts* about data usage. Many companies are worried about their confidential data being used to train LLMs, leading to data and IP leakage. This can cause them to default to more expensive solutions requiring in-house training. Meanwhile, to alleviate these fears, vendors are offering stronger commitments to data protection, and some are offering various forms of indemnity against IP claims.

[6] “Tokenization: A digital-asset déjà vu,” McKinsey, August 15, 2023.

- *Many executive leaders are beginning to recognize the importance of integrating digital-trust measures* (such as security, resiliency, explainability, and privacy) as core product functionality that should be considered from the start of a product life cycle. This lack of prioritization at the inception of AI-powered products can be driven by the perception of ROI on these measures, with doubts raised by concern that measures could lower value creation (or increase the erosion of value). On the other hand, some leaders are finding that investment in trust accelerates adoption and value capture and, thus, increases ROI.
- *The value proposition and user experience* of Web3 compared with incumbent systems (which are also continuing to evolve) are often not fully understood. Even as platforms such as Reddit and Discord are beginning to experiment with Web3 solutions, the benefits remain unclear to many consumers and enterprises.[7]
- *Consumer protection* is increasingly becoming a focal point for regulators, especially amid recent failures of several nascent Web3 projects and fraud at major cryptocurrency exchanges.

Big questions about the future

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

- How do organizations manage higher customer, employee, and community expectations for security, experience (for example, frictionless log-in), and privacy by design?
- How will regulators reconcile past standards governing data privacy, data permanency, and other issues with the capabilities and requirements of new trust technologies? How can regulators be increasingly proactive in a rapidly evolving threat and technology landscape filled with complexity?
- How can companies manage the costs of reporting with regulators increasing the expectations for proactive cybersecurity risk management?
- What are the most critical systems and data types, and where are organizations typically exposed to risk? How can organizations be comfortable that they are sufficiently protected in line with the organization's risk appetite, especially as the attack surface is expanding, data is flowing out to many cloud surfaces, and the use of contract workers is becoming more prevalent?
- How can organizations embed leading concepts such as "zero trust" into all developments in their digital-portfolio architecture to future-proof security?
- Which Web3 business models and value chains will emerge as technically reliable, scalable, and commercially viable? What will unlock mainstream adoption?
- How will Web3 ecosystems coexist and interconnect with today's enterprise system architectures and hyperscaled Web2 platforms?

'Tokenization enhances transparency, composability, and programmability, enabling financial institutions to improve operational efficiencies, increase market liquidity, and create new revenue opportunities. Tokenized financial assets issued on blockchain are advancing from pilots to live, at-scale deployments, emphasizing the need for companies to advance their capabilities to stay ahead. Rising user awareness and investor demand will further accelerate this trend.'

– Matt Higginson, partner, Boston

[7] "What is Web3?," McKinsey, October 10, 2023.

Compute and connectivity frontiers

Advanced connectivity

The trend—and why it matters

Advanced-connectivity technologies can potentially revolutionize the experiences of consumers and industries such as mobility, manufacturing, and agriculture. Organizations have been widely adopting proven technologies to enhance their connectivity infrastructure, but they have been more hesitant to invest in some of the latest connectivity technologies because of unclear ROI.

However, with cutting-edge technology—such as the latest generation of satellite connectivity, private 5G networks, and eventually 6G—progressing rapidly, telcos and other enterprises must prepare to reap the full benefits of these innovations. An increasingly connected world will require businesses to think through their strategies, investments, and business models to identify and unlock new growth opportunities.

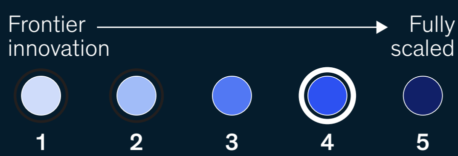
COMPUTE AND CONNECTIVITY FRONTIERS

Advanced connectivity

Scoring the trend

Momentum for advanced connectivity highlights the significant innovation and growth in the sector, driven by the substantial investment made during the early 2020s. Although investments declined this year, underlying drivers, including steady growth in interest and innovation, highlight the continued excitement about advanced connectivity's potential.

Adoption score, 2023



Equity investment, 2023,
$ billion

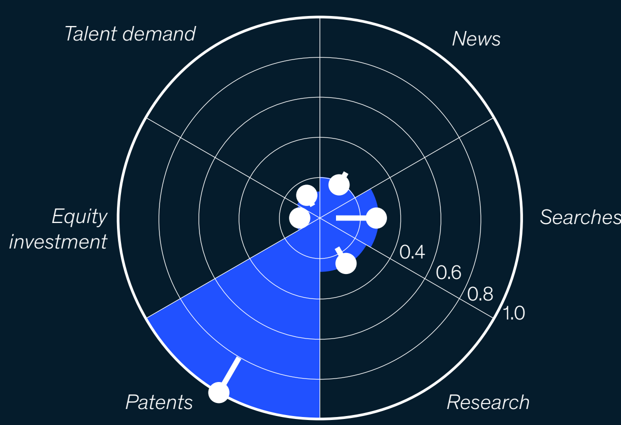
$29

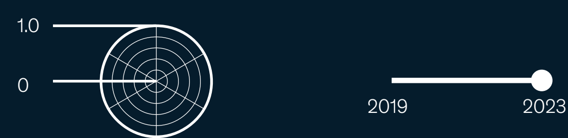
Job postings, 2022–23,
% difference

–24%

Industries affected: *Aerospace and defense; Agriculture; Automotive and assembly; Aviation, travel, and logistics; Construction and building materials; Electric power, natural gas, and utilities; Financial services; Healthcare systems and services; Information technology and electronics; Media and entertainment; Manufacturing; Metals and mining; Oil and gas; Retail; Telecommunications*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Recent developments involving advanced connectivity include the following:

— *Telecommunications industry struggles continue.* The telecom industry faces ongoing pressure to invest in 5G despite seeing limited gains in incremental revenues from the technology.[1] These players continue to forge partnerships with next-generation technology companies, such as satellite connectivity providers, in hopes of driving innovation within their industry and overcoming their financial challenges.

— *Adoption of private networks progresses.* Private-network adoption, specifically with 5G, has increased, with industries such as manufacturing, oil and gas, and mining seeking out the potential latency and security benefits. While the pace of adoption is modest, enterprises are beginning to pilot and subsequently implement this technology, with telecom players, OEMs, and cloud providers also building out the supporting infrastructure.

— *6G continues to develop, but some questions remain.* Progress is being made through research with public–private partnerships, regulatory preparation, and standardization, but there are outstanding questions about the road to monetization and adoption. It is still unclear whether the value added by 6G to certain applications will outweigh the associated costs and whether telecom companies will be able to successfully monetize this new innovation. In any case, securing external investments, critical infrastructure, and the right talent mix will be essential to navigating toward a 6G future. Another source of uncertainty is that adoption speed will largely depend on spectrum cost and sharing regulation.

— *Adoption of xRAN in mobile networks is emerging.* In 2023, large partnerships formed to build out radio-access-networks (xRAN) infrastructure. The technology makes use of the development of xRAN—that is, open interfaces (oRAN), virtualization of network functions (vRAN), and centralization of control (cRAN)—to enhance the flexibility and interoperability in the design and operation of wireless networks.[3] Both vRAN and oRAN enable a potential shift away from tightly integrated hardware and software components from single vendors to open interfaces and standardization of components, increasing flexibility to select services from a wider range of vendors.

— *Deployment of LEO satellite constellations is advancing.* Low-Earth orbit (LEO) is the orbit range for satellites that is closest to Earth. LEO satellite constellations offer wide-area coverage with significantly reduced latency compared with existing satellite offerings. They can be used to provide coverage in remote areas, as well as to provide connectivity for mission-critical applications. SpaceX-owned Starlink currently has more than 6,000 satellites and aims to expand their fleet to tens of thousands of satellites.[4]

‘Transforming the technology architecture of networks to unlock cloud-like scalability, enable [generative] AI and its business impact, and drive platform capabilities will be crucial for connectivity players. On that journey, new ways to monetize will emerge—for example, through 5G stand-alone and network APIs—which will be important to pave the way for the next generation of RAN and broadband.’

– Martin Wrulich, senior partner, Vienna

1 Shamik Bandyopadhyay, Pallav Jain, Jeremy Leing, and Stefan Prisacaru, “Navigating the three horizons of 5G business building,” McKinsey, February 22, 2023.
2 Zina Cole, Tomás Lajous, Fabian Queder, and Martin Wrulich, “Shaping the future of 6G,” McKinsey, February 28, 2024.
3 Gerardo de Geest, Gustav Grundin, Ole Jørgen Vetvik, and Nemanja Vucevic, “Telecom networks: Tracking the coming xRAN revolution,” McKinsey, February 24, 2023.
4 Elizabeth Howell and Tereza Pultarova, “Starlink satellites: Facts, tracking and impact on astronomy,” Space.com, May 30, 2024.

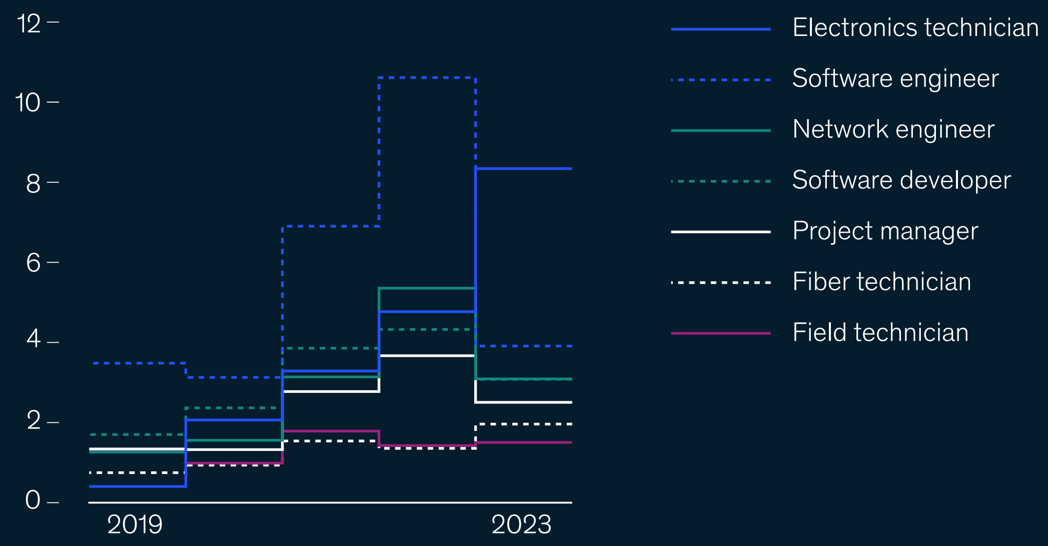
Talent and labor markets

Advanced connectivity

Demand

To leverage advanced connectivity at scale, companies require technical talent, including specialized engineers. In the context of advanced-connectivity-related job postings, the rising demand for technicians and declining job postings for roles like software and network engineers highlight the industry's focus on maintaining existing infrastructure and thoughtfully expanding their digital capabilities.

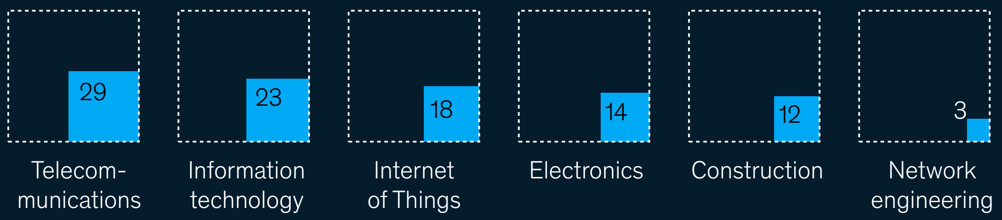
Job postings by title, 2019–23, thousands



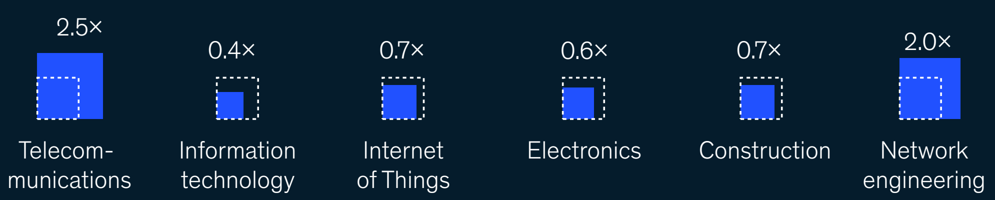
Skills availability

Advancements in connectivity require skills such as network engineers for both wireline and wireless technology. Skills such as telecommunications and network engineering currently have sufficient supply relative to demand. This could potentially result from the expansion of networks into the greater technology ecosystem, allowing telecom players to tap into a larger talent pool for network engineers shared with other traditional tech companies.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Advanced connectivity is one of the top five most adopted trends and is driven by the growth of technologies such as the Internet of Things (IoT), which rely on advanced-connectivity capabilities.

Outside of the technology, media, and telecommunications sector, financial-services and energy and materials companies have emerged as leaders in the adoption of advanced-connectivity tools, with many companies in these industries reporting that they are scaling or fully implementing the technology.

Adoption dimensions

The adoption trajectory of advanced technologies, such as 5G private networks, varies for each technology and each use case within that technology. Advancements along the following dimensions could enable reaching the next level of adoption:

— additional software applications to promote interoperability with existing enterprise infrastructure (for example, digital twins leveraging 5G capabilities)

— clarification of spectrum licensing regulation to advance adoption for bands reserved for private networks in high-traffic areas

— reduction in installation costs and proliferation of 5G end points to allow small and medium-size enterprises to implement the technology feasibly

— enterprise-level holistic vision of all the use cases that require 5G over other connectivity technologies (such as Wi-Fi), along with investment in scaling the use cases with demonstrated proof of concept

In real life

Real-world examples involving advanced connectivity include the following:

— In January 2024, AT&T, Google, and Vodafone were involved in a strategic $155 million investment in AST SpaceMobile. The investment is intended to fund a "direct-to-smartphone connectivity constellation" that will allow wireless users to stay connected outside of cell tower coverage.[5]

— Verizon partnered with Allegiant Stadium, host of 2024's Super Bowl, to provide private 5G networks for coach-to-coach communications and 5G nodes for spectators. The company estimated that about half of the approximately 61,000 spectators were Verizon customers. They used 52 terabytes of data, up 10 percent from the prior year.[6]

— AT&T announced that it will begin deploying oRAN in collaboration with Ericsson, aiming at a commercial-scale deployment of the technology to increase the interoperability of its infrastructure. AT&T plans to spend approximately $14 billion over the five-year contract with Ericsson, with 70 percent of its wireless network traffic to pass over open platforms by 2026.[7]

Underlying technologies

The noteworthy technologies in advanced connectivity include the following:

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

— *Low-power wide area networks.* These wireless networks (for example, narrowband IoT, LoRa, and Sigfox) can cover large areas more efficiently while being energy efficient at the end points, focused particularly on providing connectivity for Internet of Things.

— *Wi-Fi 6 and 7.* Next-generation Wi-Fi offers higher throughput, more controllable quality of service, and a cellular-like level of security.

— *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 massive amount of connected end points, as well as low-power connectivity suitable for IoT.

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

— *Direct-to-handset satellite connectivity.* Partnerships between telecom companies and satellite players allow direct access from phone to satellite, expanding network coverage beyond the reach of traditional cellular towers.[8]

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5 Jason Rainbow, "Google and AT&T join $155 million AST SpaceMobile investment," *SpaceNews*, January 19, 2024.
6 "Verizon customers used 52.34 TB of data in and around Allegiant Stadium for Super Bowl LVIII," Verizon press release, February 12, 2024.
7 "AT&T to accelerate open and interoperable radio access networks (RAN) in the United States through new collaboration with Ericsson," AT&T press release, December 4, 2023.
8 Ivan Suarez and Calil Queiroz, "The coming era of satellite direct-to-handset connectivity," *Via Satellite*, November 28, 2022.

‘Advanced connectivity enabled an array of industrial use cases and transformed the day-to-day lives of people across the globe. Creating value for investors is something the telecom industry was struggling with quite a bit, as a large share of extra profits is going to the tech players sitting on top of the advanced telecom networks.’

– Zina Cole, partner, New York

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

— *Low-Earth-orbit satellites.* A constellation of satellites in orbits at relatively low altitudes above Earth’s surface can enable connecting remote or inaccessible locations with high-speed internet, in addition to other use cases, such as satellite imaging.

Key uncertainties

Key uncertainties of advanced-connectivity adoption vary by technology:

— *Telco profitability* is being strained as a result of competitive pricing, the commoditization of connectivity, challenges in monetizing better network quality, and the increasing traffic and deployment costs, all of which have led to challenging ROI. While advanced connectivity undoubtedly creates value, the connectivity layer does not currently capture enough to sustain investment.

— *The availability* of mature use cases, such as 5G-enabled robotics and gaming on the go, caters to both industrial verticals and consumers requiring higher-service-level agreements, such as high throughput or low latency.

— *Ecosystem maturity* plays a critical role in the adoption of IoT, whose uptake has been slower than expected as a result of a highly fragmented market, security concerns, interoperability, complex deployments involving a vast assortment of players, and a lack of standardization. For 5G and 6G, telecom operators’ monetization struggles might affect their ability to build the necessary infrastructure for at-scale rollouts globally.

— *Government involvement* is still unfolding and will play a role in regulations and funding for 5G and next-generation digital infrastructure. Currently, many governments are involved in the supply factors, while developing demand-side use cases remains the exception.

Big questions about the future

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

— What fundamental shifts does the telecom industry need to make to improve profitability?

— How will changes in the fiber market (for example, financing and delayering) affect network options for customers? Will 5G be sufficiently monetized?

— What are the expectations from various stakeholders for next-generation wireless technologies?

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

— Will private-network adoption take off? What do industrial verticals need to know about it to avoid missing out on its benefits?

— Will there be an oversupply of satellites as providers ramp up LEO launches and benefit from technological advancements?[9]

[9] Chris Daehnick, John Gang, and Ilan Rozenkopf, “Space launch: Are we heading for oversupply or a shortfall?,” McKinsey, April 17, 2023.

Immersive-reality technologies

The trend—and why it matters

Immersive-reality technologies allow users to experience an augmented form of our world or virtual worlds while uncovering a series of new use cases for consumers and enterprises alike. These technologies simulate the addition of objects to real-world settings and enable interactions in virtual worlds by using spatial computing to render the physical space around users. Industry players have taken different approaches that range the spectrum from augmented reality (AR) to mixed reality (MR) to virtual reality (VR). The year 2023 saw tenuous investment and consumer demand, with start-up funding decreasing by roughly 50 percent[1] and sales of VR headsets down by 40 percent from 2022.[2] Some notable highlights, such as the launch of Apple's Vision Pro headset and continued interest from enterprises in digital-twin technology,[3] demonstrate resilience despite financial and market hurdles.

1 Joanna Glasner, "Startup investors have fled the metaverse," Crunchbase, January 16, 2024.
2 Jonathan Vanian, "VR market keeps shrinking even as Meta pours billions of dollars a quarter into metaverse," CNBC, December 19, 2023.
3 Digital twins can be used in non-AR or non-VR contexts, but the use cases for digital twins in this publication relate to AR and VR. For additional reading, see Roberto Argolini, Federico Bonalumi, Johannes Deichmann, and Stefania Pellegrinelli, "Digital twins: The key to smart product development," McKinsey, July 31, 2023.

COMPUTE AND CONNECTIVITY FRONTIERS

Immersive-reality technologies

Scoring the trend

Scores across news, searches, publications, and patents saw increases between 2019 and 2023. These increases suggest that companies perceive long-term potential in the development of immersive-reality technologies. Continued increases in innovation and interest indicate technological progress and exploration of a broader set of use cases for the technology, such as for consumer engagement and digital twins.

Adoption score, 2023

Frontier innovation → Fully scaled

Equity investment, 2023,
$ billion

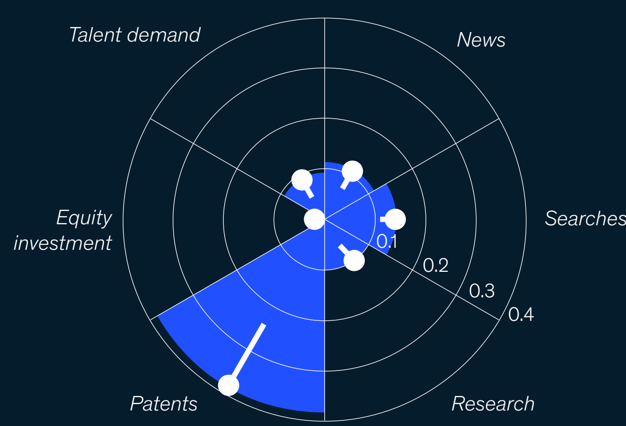
$6

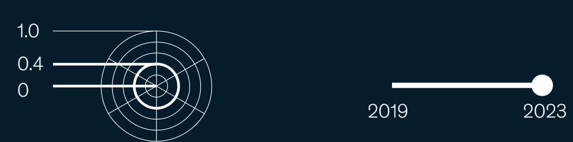
Job postings, 2022–23,
% difference

–36%

Industries affected: *Aerospace and defense; Automotive and assembly; Aviation, travel, and logistics; Construction and building materials; Consumer packaged goods; Education; Electric power, natural gas, and utilities; Financial services; Healthcare systems and services; Information technology and electronics; Media and entertainment; Real estate; Retail*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Recent developments involving immersive-reality technologies include the following:

— *The headset market is experiencing selective growth.* Over the past year, we have seen standout headset launches from Apple and Meta,[4] with the Vision Pro and Quest 3, respectively. While a significant number of units of the Vision Pro were sold at launch, several other companies are postponing the release of their headsets and deferring investments in hardware development. However, despite some delays, hardware development is expected to continue. The demand seems to indicate the proportion of consumers that are willing to accept the size and comfort of today's headsets for immersive-reality experiences at current price points.

— *Virtual worlds are expanding beyond their gaming roots.* Virtual worlds such as Roblox[5] and Fortnite[6] are increasingly offering digital events, such as concerts, that allow users to engage with the programs more as digital experiences than games. This has led many third parties to form partnerships or acquire stakes in these platforms, such as LEGO's partnership with Fortnite, which gives consumers a new way to engage with LEGO products and increases their brand recognition.[7]

— *Enterprise adoption persists, but scaling is taking longer than expected.* VR use cases persist in enterprise adoption, though at-scale adoption is taking longer than expected. For AR, additional advances are required to see significant enterprise and consumer adoption. One area that has seen increased implementation is digital twins (a digital representation of a physical object, person, or process, contextualized in a digital version of its environment to simulate real situations and their outcomes). Digital twins have a projected CAGR of approximately 30 percent over the next four years and have been used in combination with AR for use cases including manufacturing and training.[8]

'Virtual-reality and augmented-reality experiences are poised to reshape our lives in the coming decade, with innovation driving advancements across both enterprise and consumer use cases. Recently, we have seen growth in B2B applications of immersive-reality technologies such as spatial computing—specifically digital twins gaining traction for training, testing, and design in industrial sectors such as aerospace and defense. On the consumer side, virtual- and augmented-reality experiences are reshaping consumer engagement by offering immersive brand interactions.'

– Eric Hazan, senior partner, Paris

4 "Meta Quest 3 coming this fall + lower prices for Quest 2," Meta, June 1, 2023.
5 "How Roblox is setting the stage for more and more concerts," *Forbes India*, July 9, 2021.
6 Gene Park, "The future of events is uncertain. 'Fortnite' is forging ahead anyway," *Washington Post*, September 11, 2020.
7 "Build, play, survive: The LEGO Group and Epic Games unveil LEGO Fortnite," LEGO, December 2, 2023.
8 Mohammad Hasan, "Digital twin market: Analyzing growth and emerging trends," IoT Analytics, November 15, 2023.

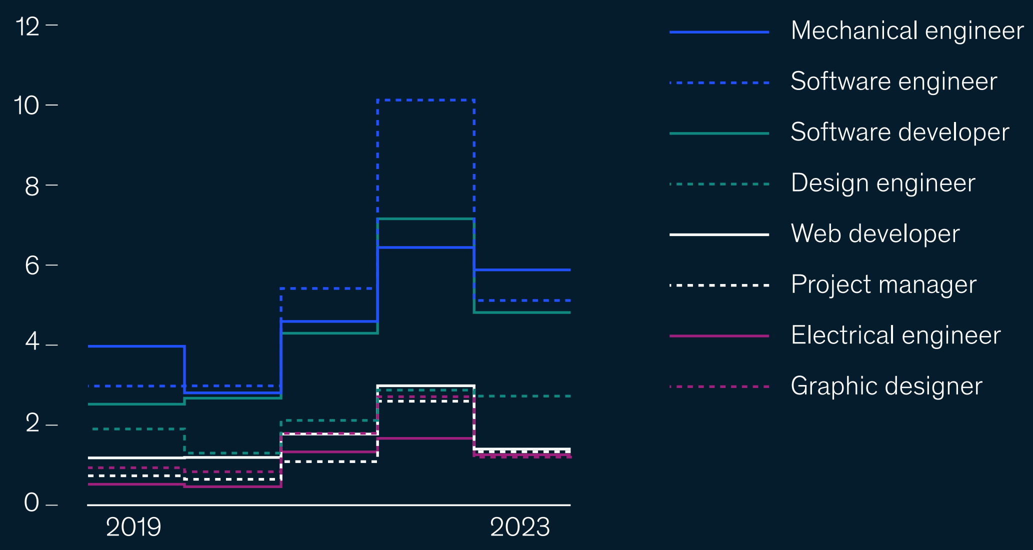
Talent and labor markets

Immersive-reality technologies

Demand

Immersive-reality job postings have doubled since 2020, but a decline in talent demand in 2023 indicates that the job market is recalibrating itself as the use cases and support structure for this area evolve.
The field represents the nexus of technology, art, and business management, with high job demand for graphic designers, project managers, and mechanical, software, and design engineers.

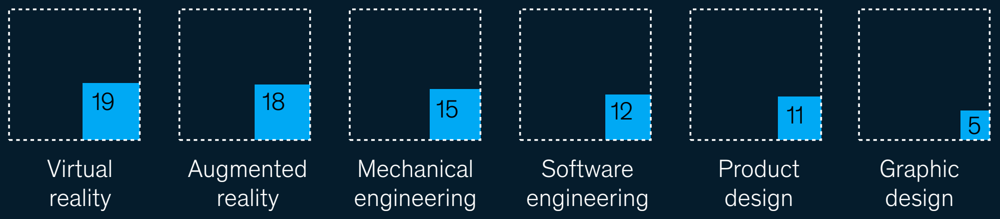
Job postings by title, 2019–23, thousands



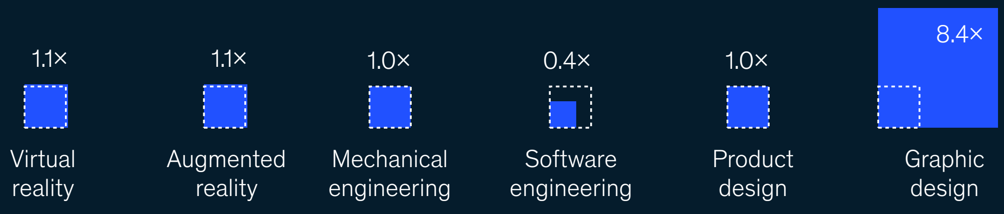
Skills availability

For the most part, talent with the skills required is available, with the exception of software engineering talent, which is less plentiful for immersive reality.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Immersive reality falls in the middle for adoption level relative to other trends. Most companies that are adopting immersive-reality technologies are using them to increase the value of existing offerings through integration with the technologies.

The technology, media, and telecommunications sector has emerged as a leader in adopting immersive-reality technologies, with the highest percentage of companies in the industry scaling or fully scaling the technology. Capital investment has slowed, in line with the macro environment and partially as a result of companies narrowing the technologies they highly fund.

Adoption dimensions

The adoption trajectory for advanced technologies varies for each technology and each use case within that technology. For example, consider the potential adoption trajectory for AR headsets. Advancements along the following dimensions could enable the next level of adoption:

— decreases in battery size (that is, battery density of more than approximately 400 watt-hours per kilogram to construct a small enough battery), headset weight, and heat management

— a larger optical field of view (that is, more than 90 degrees) to enhance immersive experiences

— increased computing power to enable seamless rendering and complex workloads either on the AR device or through external sources

— increased immersive display brightness (that is, more than 3,000 nits[9]) to allow for outdoor usage

— customer ecosystems to develop a library of use cases for integrating the technology into consumer lifestyle or business operations

In real life

Real-world examples involving immersive-reality technologies include the following:

— Disney acquired a $1.5 billion stake in Epic Games and announced a collaboration between the two companies to build a new virtual entertainment universe. Consumers in the virtual world will be able to engage with characters and stories in the Disney universe not only through games but also through shopping and media experiences.[10]

— Porsche announced a partnership with Meta to use its Quest 3 MR headsets to facilitate event presentations and vehicle walk-throughs. This will allow multiple people to move around and interact in a shared VR environment during product showcases.[11]

— In September 2023, Mercedes-Benz became one of the first automakers to implement digital-twin technology on Nvidia's Omniverse platform. Digital twins of its factories and assembly lines in more than 30 locations will allow factory planners to optimize and streamline production line layouts.[12]

— Following Apple's launch of its new AR headset, Apple Vision Pro, in February 2024, several companies have begun leveraging the technology to give consumers a more immersive product experience. Lowe's recently launched Lowe's Studio Style, an app that allows customers to design kitchen renovations inside 3D AR kitchen models, while the PGA launched PGA Tour Vision, which lets golf fans follow play and virtually walk the course on some of the tour's most iconic events.[13]

Underlying technologies

Immersive-reality technologies 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.* MR 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.

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

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[9] A nit is the unit for the amount of light that passes through the area of a solid angle.
[10] "Disney and Epic Games to create expansive and open games and entertainment universe connected to Fortnite," Disney, February 7, 2024.
[11] "Porsche partners with Meta to demonstrate metaverse potential," *XR Today*, January 22, 2024.
[12] *NVIDIA Blog*, " Virtually incredible: Mercedes-Benz prepares its digital production system for next-gen platform with NVIDIA Omniverse, MB.OS and generative AI," blog entry by Mike Geyer, September 20, 2023.
[13] Cathy Hackl, "How early-adopter companies are thinking about Apple Vision Pro," *Harvard Business Review*, February 9, 2024.

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

— *Location-mapping software.* This software integrates real-time user physical location and surroundings into AR to provide an overlay of the surrounding physical environment in the virtual environment.

Key uncertainties

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

— *Hardware and software improvements, particularly for AR devices, are needed* to enable miniaturization and weight reduction, make devices more durable, improve sensor precision, increase user comfort, enhance heat management, and extend battery life.

— *The pace and level of cost reductions remain uncertain* but will be needed to make applications more consumer-friendly and scalable.

— *Growth in the breadth of user needs is still in question.* While a version of immersive reality exists today, a true tipping point where demand grows from targeted niche needs to broader mass-market customer usage is likely a few years away. Certain business-focused considerations, including how end-consumer price points evolve, will also affect the pace of adoption.

— *Mitigating security and privacy concerns* related to tracking user behavior will be critical to building trust.

— *Safety concerns need to be addressed* when considering the usage of vision-limiting AR and VR platforms outside of highly controlled environments.

— *Proliferation of form factors.* End-user devices take multiple forms depending on intended usage, from independent AR and VR platforms to peripheral AR accessories for mobile phones. The proliferation of multiple form factors is creating uncertainty in terms of what specific use cases each one is most appropriate for.

Big questions about the future

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

— What is the potential impact of use cases in various settings (for example, home, workplace, commuting)?

— How and how quickly will device hardware evolve?

— How will immersive reality shift the new wave of remote and hybrid work and the human–machine interface?

— How will enterprises effectively manage the tech infrastructure required for new and evolving use cases?

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

'As widely expected, the near frenzy around immersive-reality technologies has mostly settled. While many global start-ups may feel the funding crunch, the committed investors and builders that remain will continue on their concrete product development and commercialization road maps over a more measured five-to-ten-year horizon.'

– Hamza Khan, partner, London

Cloud and edge computing

The trend—and why it matters

Enterprises are in the process of transitioning away from traditional on-site storage and management toward distribution across multiple infrastructure points that range from remote hyperscale data centers to on-site servers at the edge of the business. The public cloud allows enterprises to host workloads remotely and scale the consumption of computing and storage resources on demand, resulting in better economies at scale, flexibility, and speed of deployment of applications. With edge computing, organizations can process data much closer to where the data originate, providing lower latency, lower data-transfer costs, and increased data privacy compared with the cloud (while adhering to data residency laws as well). Cloud and edge computing has amplified AI capabilities for both training and inferencing on foundational models and will continue to be a major driver for the adoption of these technologies. Balancing workloads across cloud and edge (and the locations in between) will allow enterprises to optimize resourcing, latency, data privacy, and security at scale and, in turn, unlock business value.

COMPUTE AND CONNECTIVITY FRONTIERS

Cloud and edge computing

Scoring the trend

Investment scores have increased since 2019, with significant funding during the peak years of 2020–22. Overall innovation scores (patents and publications) have trended upward since 2019. For interest scores, the data reveal that searches are growing while news searches stayed steady. These factors speak to a trend of leveraging early 2020s investments to rapidly deploy new innovations.

Adoption score, 2023

Frontier innovation → Fully scaled

1 2 3 **4** 5

Equity investment, 2023,
$ billion

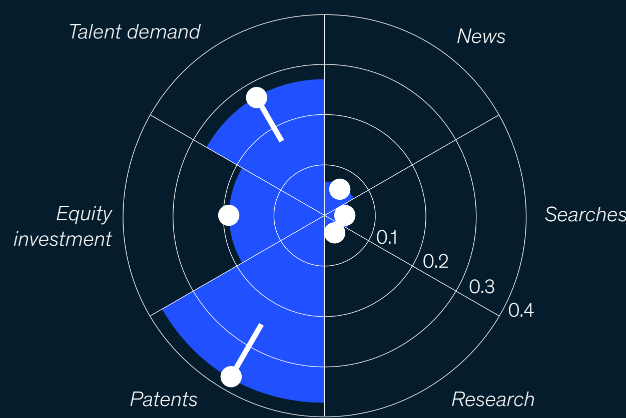
$54

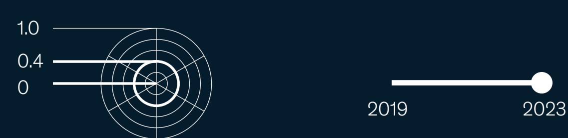
Job postings, 2022–23,
% difference

–38%

Industries affected: *Aerospace and defense; Automotive and assembly; Aviation, travel, and logistics; Business, legal, and professional services; Chemicals; Electric power, natural gas, and utilities; Financial services; Healthcare systems and services; Information technology and electronics; Manufacturing; Media and entertainment; Pharmaceuticals and medical products; Retail; Semiconductors; Telecommunications*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Recent developments involving cloud and edge computing include the following:

— *The use of cloud and edge computing has grown substantially due to additional AI demand.* The rise of AI in 2023 resulted in a massive increase in cloud and edge usage, with a CAGR of approximately 30.9 percent expected in the cloud AI market between 2023 and 2030 and an estimated increase in cloud spend of about 20.0 percent,[1] as companies train and fine-tune models and perform inferences. The need for extremely large amounts of compute for AI model training has forced businesses that have not yet transitioned to the cloud to commit to it for AI endeavors, since most on-premises data centers cannot meet the compute requirements of AI workloads. Start-ups such as Lambda Labs[2] and CoreWeave[3] also took advantage of the AI boom to compete with hyperscalers on providing graphics-processing-unit (GPU) services ("GPU as a service") for enterprises that do not have access to GPU compute on their own.

— *Priority shifts to on-premises edge solutions.* Some organizations are shifting focus from operating at the network and operator edge (computing locations situated at sites that are owned by a telecommunications operator, such as a central data office in a mobile network) to on-premises edge solutions that are closer to the end user (such as an on-site data center) to minimize latency and data transmit times, while demand for private network connectivity has driven customer adoption of edge-enabled use cases. A variety of enterprise locations are poised to take advantage of on-premises edge; they include manufacturing plants, restaurants, retail stores, and hospitals.

— *For some use cases, the shift from cloud to edge computing marks the next evolution of AI models.* While 2023 was mostly focused on training foundation models for AI, companies are expected to begin performing inference at scale on their models in 2024. With low latency taking priority when performing inference for some use cases, some workloads will likely shift to the edge as companies begin to put their models into commercial use.

— *Companies diversify their GPU supply base.* Nvidia's well-documented success in the GPU market throughout 2023 has improved GPU access for customers, from hyperscalers to start-ups such as CoreWeave. Companies of all sizes are considering additional options for sourcing or building GPUs. For example, hyperscalers are exploring and actively working on a collection of sources for their compute needs and have started designing in-house hardware and chips. Other alternatives to Nvidia chips include chips from Advanced Micro Devices (AMD) and Intel.[4] However, the ability to interchange GPU chips is also affected by the software that facilitates their utilization. For instance, Nvidia's CUDA platform presents more challenges in chip swapping than other, more standardized software solutions.

'With the increasing growth of data volumes, particularly with the widespread deployment of AI and generative AI use cases, edge and cloud will continue to work in tandem. Edge infrastructure will play a crucial role in enabling real-time inference much closer to the source of data generation. Edge will help enterprises maintain their edge.'

– Bhargs Srivathsan, partner, Bay Area

1 "Gartner forecasts worldwide public cloud end-user spending to reach nearly $600 billion in 2023," Gartner press release, April 19, 2023; *Cloud AI market*, Fortune Business Insights, May 6, 2024.
2 Matt Kimball, "Analyzing the Lambda Labs partnership with VAST Data," *Forbes*, November 1, 2023.
3 Chris Mellor, "CoreWeave GPU-as-a-service cloud farm using VAST storage," Blocks & Files, September 26, 2023.
4 Leo Sun, "Could AMD become the next Nvidia?," Motley Fool, March 16, 2024.

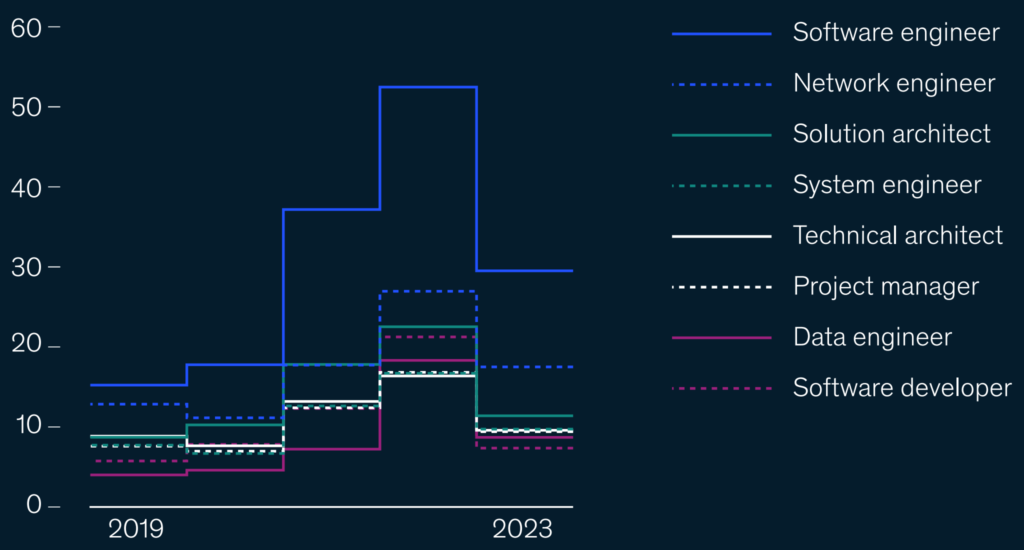
Talent and labor markets

Cloud and edge computing

Demand

Cloud and edge job postings saw reductions across the board but remained high for software engineers. Data engineers and software developers saw a larger relative decrease in job postings than other technical roles. Since the growth of AI heavily influences the growth of cloud and edge computing, we also noted postings for roles such as machine learning (ML) engineers (for more on this, please see the "Industrializing machine learning" trend in this report).

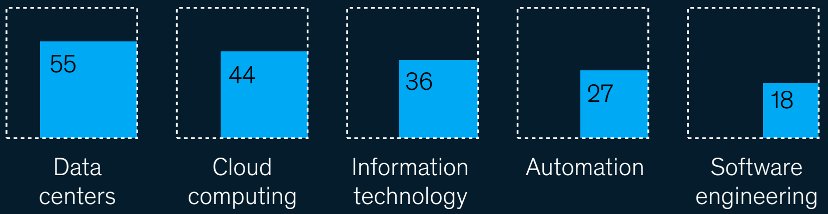
Job postings by title, 2019–23, thousands



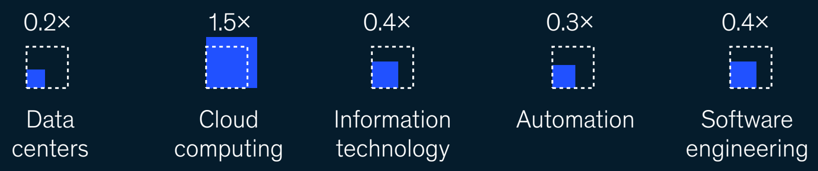
Skills availability

There is a shortage in the supply of people with experience working in data centers. This shortfall indicates a need for the field to continue developing more specialized professionals in cloud-computing roles.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



'In 2023, we saw an acceleration of large cloud partnerships with CSPs [cloud service providers] in the context of scaling generative AI adoption. It will be very interesting to see how these will unfold in 2024 and 2025 as line of sight for real profit-and-loss impact at scale is still emerging.'

– Andrea Del Miglio, senior partner, Milan

Adoption developments across the globe

Cloud and edge computing is the most widely adopted trend across industries and regions, boosted by the growth of AI. Most companies adopt cloud and edge computing technologies to increase the value of existing offerings, lower costs, better serve their customers, and optimize the use of computer and storage resources. Companies in regions like Africa show a strong interest in adopting cloud but struggle with a lack of local data centers from hyperscalers, legacy infrastructure, and connectivity issues.[5] Cloud adoption in the Middle East is growing fast, with significant investment in regional data centers.[6]

Some of the leading industries in adopting cloud and edge computing include technology, media, and telecommunications; energy and materials; and financial services.

Adoption dimensions

Enterprises are likely to seek improvements in latency, cost, and security, spurring the next level of adoption of edge computing technologies. Advancements along the following dimensions could enable the next level of adoption:

— Scaled adoption of low-latency use cases (such as self-driving cars and virtual reality headsets) or an increase in AI inferencing needs could lead to a shift from cloud to edge computing to improve latency for consumer and enterprise use cases and to process data much closer to where the data originate.

— Enterprises could move computation from the cloud to the edge, potentially as a result, for example, of increased data security requirements.

— A reduction in the cost of edge connectivity makes it more feasible for small and medium-size enterprises to migrate relevant, expensive cloud workstreams to the edge.

In real life

Real-world examples involving cloud and edge computing include the following:

— McDonald's and Google Cloud announced a multiyear global partnership to use edge computing for the restaurant's mobile app, self-service kiosks, and other machinery. They will use a combination of Google's cloud and edge capabilities and McDonald's own software to draw insights on equipment performance and reduce complexity for staff.[7]

— In early 2024, the *International Space Station* (*ISS*) installed a Kioxia (previously Toshiba Memory) solid-state drive (SSD) for edge computing and AI tasks. This upgrades the HPE Spaceborne Computer, the first commercial edge-computing and AI-enabled system on the *ISS*, originally installed to reduce dependency on mission control for data processing.[8]

— Amazon, Google, and Microsoft all released proprietary in-house AI chips.[9]

[5] Sven Blumberg, Jean-Claude Gelle, and Isabelle Tamburro, "Africa's leap ahead into cloud: Opportunities and barriers," McKinsey, January 18, 2024.
[6] "The Middle East public cloud: A multibillion-dollar prize waiting to be captured," McKinsey, January 30, 2024.
[7] "McDonald's and Google Cloud announce strategic partnership to connect latest cloud technology and apply generative AI solutions across its restaurants worldwide," McDonald's press release, December 6, 2023.
[8] Roshan Ashraf Shaikh, "International Space Station gets Kioxia SSD upgrade for edge computing and AI workloads – HPE Spaceborne Computer-2 now packs 310TB," Tom's Hardware, February 5, 2024.
[9] Cade Metz, Karen Weise, and Mike Isaac, "Nvidia's Big Tech rivals put their own AI chips on the table," *New York Times*, January 29, 2024.

Underlying technologies

We see edge being deployed in various formats, depending on proximity to the user or data generated and the scale of resources involved.

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

— *On-premise or "close to the action" edge.* These are computing and storage resources deployed within the premises or a remote or mobile location where data are being 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, typically one network hop away from enterprise premises.

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

Key uncertainties

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

— *Scaling hurdles could arise* as the number of edge nodes and devices grows, because edge computing does not benefit from the same economies of scale as traditional cloud computing.

— *There is limited availability of talent and management buy-in.* Companies scaling cloud computing often face a shortage of in-house talent to implement cloud solutions effectively. This shortage poses challenges in identifying new use cases tailored to the local context, such as those specific to a retail store. Additionally, it hinders the scaling of cloud infrastructure. This challenge is further exacerbated if there is a lack of local management buy-in.

— *Technical challenges make it difficult to maintain and scale cloud computing.* The complexity of ML/AI models and the absence of readily deployable solutions pose significant challenges for companies seeking to build cloud-computing capabilities. Additionally, maintaining and managing edge hardware at scale can be tedious. Furthermore, current 5G MEC coverage is not yet extensive enough to support the scaling of use cases.

— *Other challenges include limited ROI visibility,* an overall longer path to returns for edge development, a lack of customer understanding of value-add use cases, large investment requirements for scaling from pilot to at-scale implementations, a complicated technical stack requirement (especially due to integration with the existing tech landscape at most companies), and a lack of ready-to-deploy solutions.

— *Privacy in the cloud is still a concern* for many enterprises. Some organizations are subject to strict data privacy laws and are generally hesitant to make a full migration to the cloud in the event of a breach or cyberattack.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with cloud and edge computing:

— Will flexibility and positioning in a business and regulatory sweet spot make edge more disruptive than cloud? Or will inhibitors such as lack of interoperability and commonality of standards in networking prevent edge from reaching its full potential?

— Will hyperscale cloud providers be leaders in edge computing? And how will telecommunications companies with 5G-enabled MEC contend or partner with hyperscalers?

— How will rapidly evolving AI technology and, importantly, accompanying regulatory changes alter cloud and edge provider business models?

— How will specialized chips deployed both in data centers and at the edge, such as AI inference or always-on sensors, modify the competitive cloud and edge landscape?

— Will the increase in the number of storage and processing units lead to security vulnerabilities?

— How will the transition to green infrastructure facilitate the continued evolution of cloud and edge technology?

— As sensor costs drop and their performance increases, how will edge and cloud resources cope with growing demand for data movement and AI-enabled analytics?

— Will reduced connectivity costs drive more edge adoption?

Quantum technologies

The trend—and why it matters

Quantum technologies encompass three pillars: quantum computing, which not only will provide a speedup over current computing systems for certain problems but also could enable applications that are impossible to implement on classical computers; quantum communication, which will be critical for secure communication in the era of quantum computers; and quantum sensing, which provides higher sensitivity in more modalities than conventional sensors for specific applications. The estimated full potential economic impact of these technologies could be upward of roughly $0.9 trillion. While the actual quantum advantage for useful applications is still outstanding, we see promising research and experimentation within pioneering enterprises across industries, including chemicals, pharmaceuticals, finance, automotive, and aerospace. In 2023, we saw steady progress on both the hardware and software fronts while organizations took more practical steps to ensure that their infrastructure and security are ready for the technology. Quantum technology must overcome a series of technical hurdles to unlock its proposed benefits, which requires both private and public sector efforts. It's strategically wise for companies to invest intelligently now to capitalize on future advancements.

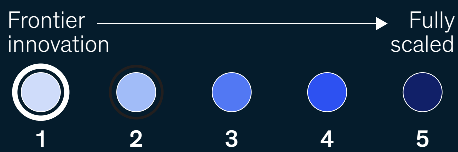
COMPUTE AND CONNECTIVITY FRONTIERS

Quantum technologies

Scoring the trend

Despite continued interest and innovation in the past few years, quantum technologies saw a slowdown in private investments. The 2022–23 period marked a shift in investment toward more established companies, with 62 percent of funding directed to companies founded more than five years ago, reflecting a focus on scaling promising ventures. However, public sector investment in this field increased in 2023, underscoring a sustained commitment to advancing quantum technologies. While there is a long road ahead before companies can achieve large-scale fault-tolerant quantum computing, the groundbreaking potential for quantum technology to be leveraged in appropriate use cases could allow early innovators to extract significant value once key performance milestones are met.

Adoption score, 2023



Equity investment, 2023, $ billion

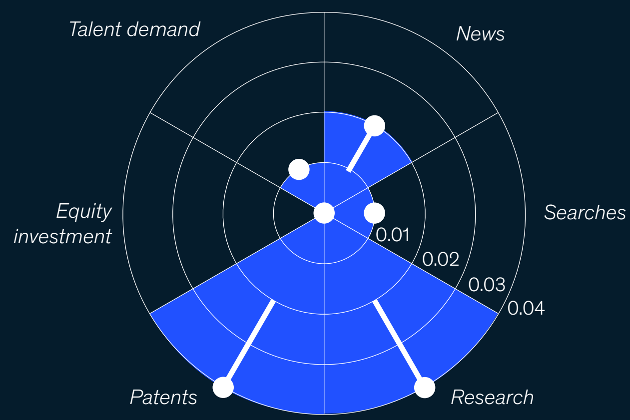
$1

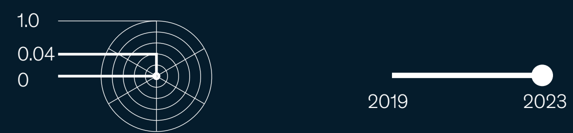
Job postings, 2022–23, % difference

–17%

Industries affected: *Aerospace and defense; Automotive and assembly; Aviation, travel, and logistics; Chemicals; Financial services; Information technology and electronics; Pharmaceuticals and medical products; Telecommunications*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Recent developments involving quantum technologies include the following:

- *Major steps forward in error correction have occurred.* In collaboration with QuEra, MIT, and the National Institute of Standards and Technology (NIST), Harvard researchers demonstrated large-scale algorithms on 48 logical units, with an error rate below 0.5 percent. This breakthrough was followed recently by a collaboration between Microsoft and Quantinuum that produced four reliable qubits with an error rate below 0.01 percent.[1] Teams at IBM[2] and Google's Quantum AI[3] also made advances throughout the year to push the boundaries of logical qubit storage, error rate per cycle, and error frequency. These developments could serve as a promising stepping stone to necessary advancements on the long road from focusing on record qubit numbers to achieving higher-quality, scalable qubits capable of delivering meaningful results. Open hardware questions about the efficacy of several qubit technologies are currently being explored, as each has its own benefits, challenges, and optimal use cases.

- *Additional emphasis is being placed on building out the full stack, including software and the integration of quantum into classical computing infrastructure.* Quantum computers will be useful only for a small but impactful set of problems; therefore, it will be important to think about which parts are calculated on a quantum-processing unit (QPU) versus other computer architectures (for example, central processing units and graphics processing units). Moreover, while there are many technological hurdles to overcome, there has been additional emphasis on building out the rest of the stack, from software development kits (such as IBM's Qiskit) to testing and simulation of quantum algorithms (such as NVIDIA's Quantum Cloud that was built on its open-source CUDA platform in March 2024).

- *Strides have been made in information security because of the progress in quantum computing.* Major tech players are ramping up their information security measures to reduce the risk of newer threats emerging from advancements in quantum computing. These are termed "harvest now, decrypt later" attacks, where data expected to have a long shelf life are captured and stored so they can be decrypted once quantum computers are powerful enough to crack today's classical public key encryption such as RSA or elliptic-curve cryptography. For instance, various organizations are enhancing these classical public key encryptions with postquantum-cryptography algorithms this year. This allows these organizations to proactively mitigate the risks of harvest now, decrypt later attacks with currently available classical tools ahead of potential additional quantum-level protection—such as quantum key distribution (QKD)—maturing and becoming available. In December 2022, the Biden administration signed into law the Quantum Computing Cybersecurity Preparedness Act, asking government agencies to "adopt technology that will protect against quantum computing attacks."[4] Various intergovernmental organizations have also published policies and strategies to develop quantum technologies and prepare for potential quantum cyberattacks.

- *Start-up partnerships with conventional enterprises continue.* Quantum computing start-ups and conventional enterprises announced more partnerships in 2023. These continue to occur as start-ups attempt to get closer to the proposed use cases of their computers and conventional enterprises try to gain a future competitive edge. For example, Rolls-Royce partnered with quantum start-up Riverlane to develop algorithms and computational tools to accelerate complex material discovery for jet engines and other components in hostile environments.[5]

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1 Stephen Nellis, "Microsoft, Quantinuum claim breakthrough in quantum computing," Reuters, April 3, 2024.
2 Sergey Bravyi et al., "High-threshold and low-overhead fault-tolerant quantum memory," *Nature*, 2024, Volume 627.
3 "Suppressing quantum errors by scaling a surface code logical qubit," *Nature*, 2023, Volume 614.
4 John Hewitt Jones, "Biden signs quantum computing cybersecurity bill into law," *FedScoop*, December 21, 2022.
5 Matt Swayne, "NQCC, Rolls-Royce and Riverlane partner to accelerate materials discovery," Quantum Insider, December 18, 2023.

Talent and labor markets

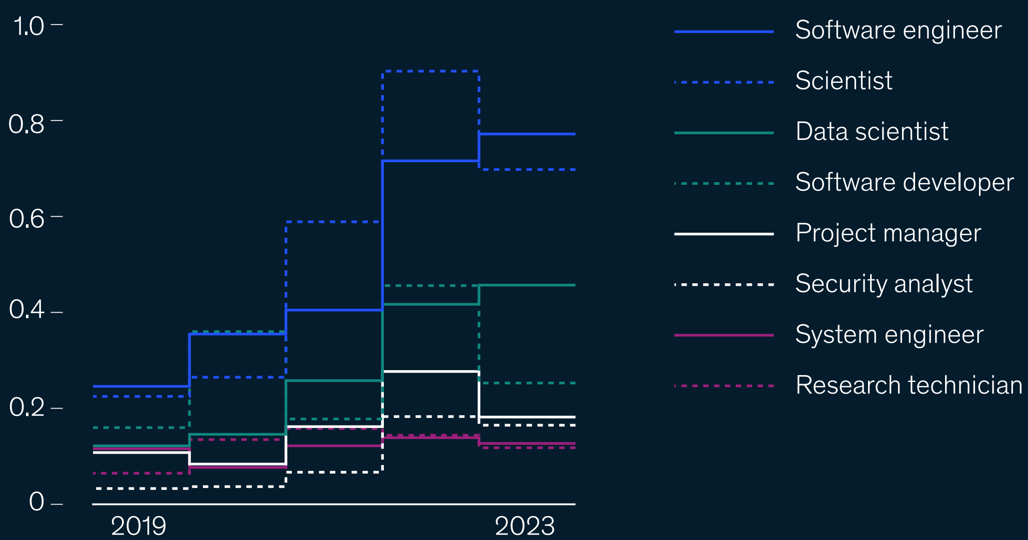
Quantum technologies

Demand

While quantum technology has a small labor market, talent demand has more than doubled since 2019. Given the nascency of the technology, the number of graduates from quantum-specific programs is low. As a result, talent is sourced from the broader fields of physics, mathematics, electrical engineering, chemistry, biochemistry, and chemical engineering. All told, approximately 367,000 people graduated in 2023 with degrees relevant to quantum technology, with the number of universities offering programs and master's degrees in quantum technology increasing by 8.3 percent and 10.0 percent, respectively, over the past year.[1]

While quantum-technology talent demand saw a slight decrease in 2023, in line with the broader talent market, the hiring mix of applied roles, such as data scientists, and more specialized roles, such as software engineers, lines up with the path followed by more mature technologies, such as AI. As quantum technology continues to develop, this shift toward more specialized hiring will likely strengthen.

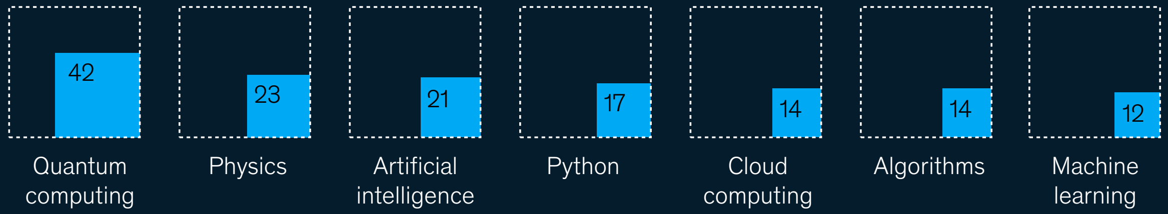
Job postings by title, 2019–23, thousands



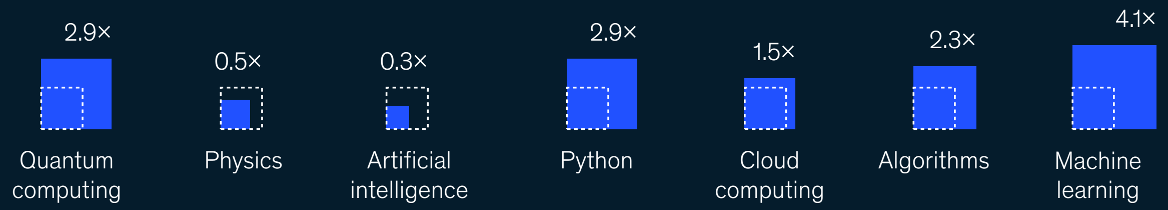
Skills availability

Although the total demand for jobs in quantum technologies remains low, growth in the supply of skilled talent—especially for skills such as quantum and cloud computing, machine learning, risk management, and Python programming—indicates a strong dynamic for further industry acceleration.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



[1] "Steady progress in approaching the quantum advantage," McKinsey, April 24, 2024.

Adoption developments across the globe

Given quantum technology's nascency, it is unsurprising that it is one of the least widely adopted technologies across our set of analyzed trends. However, the potential for future quantum applications to be disruptive in select sectors and use cases has inspired several companies to engage in experimentation and pilots of different quantum technologies. These companies most commonly see the ultimate goal of adopting quantum technologies as increasing the value of existing offerings through better outcomes or products (for example, optimized portfolios and routing).

The finance, pharmaceuticals, technology, energy and materials (including chemicals), and telecommunications sectors have emerged as leaders in the adoption of quantum technologies, with more than roughly 40 percent of companies in these industries reporting that they are conducting experiments and pilots. These industries cover both shapers of quantum technologies (primarily telecommunications and technology) and eventual end users, with significant use cases across chemicals, finance, and pharmaceuticals. Investments in quantum communications are driven by improvements in quantum-resistant cryptography and QKD to protect against future decryption attacks by quantum computers, indicating a forward-looking approach to managing risk.

Adoption dimensions

The adoption trajectory of advanced technologies varies for each technology and each use case within that technology. If or when certain technical challenges are overcome, the dawn of quantum computers that are powerful enough to jeopardize current encryption provides a potentially disruptive use case for quantum technologies.

The next level of adoption likely will involve companies leveraging quantum computers to significantly speed up the solution to a set of valuable computational problems. Additionally, companies will be motivated to enhance their encryption methods to include postquantum cryptography, ensuring the protection of mission-critical and long-lived digital data.

Advancements along the following dimensions could enable the next level of adoption for quantum technologies:

- to achieve further milestones suitable for large-scale fault-tolerant computing, an increased number of physical qubits (that is, greater than 1,000) with lower error rates (that is, 10^{-6} or less) across several qubit platforms (for example, superconducting and spin), along with a road map to scalably interconnect qubits and possibly chips of qubits
- to increase reliability, an increased number of logical, error-corrected qubits (more than 50 to 100)
- to secure data that retains its value over several years, implementation of quantum-resistant cryptographic algorithms (such as the four algorithms selected in 2022 by NIST: CRYSTALS-Kyber for key establishment and CRYSTALS-Dilithium, Falcon, and SPHINCS for digital signatures)

'While the technology still faces challenges, significant advancements have been made this year, especially in the field of error correction. In addition, major enterprises are actively working to improve encryption by incorporating postquantum-cryptographic algorithms. This highlights the importance of taking proactive measures now to minimize the impact of potential "harvest now, decrypt later" attacks.'

– Mena Issler, associate partner, Bay Area

In real life

Real-world examples involving the use of quantum technologies include the following:

- Banks are partnering with quantum businesses to build their capabilities. HSBC, for example, announced a partnership with quantum computing start-up Quantinuum. The companies will work together to explore the benefits of quantum machine learning and quantum natural-language processing to analyze customer data more accurately and prevent fraud.[6]

- Apple upgraded its iMessage encryption with a new protocol known as PQ3 that utilizes postquantum cryptography to protect messages against future encryption breaches from quantum computers.[7] The company joins messaging app Signal in using the NIST-selected Kyber algorithm.[8]

- The Biden administration, through the US Department of Commerce's Economic Development Administration (EDA), designated 31 tech hubs across the United States, including the Bloch Tech Hub (Bloch), a consortium led by the Chicago Quantum Exchange,[9] and Elevate Quantum Colorado (led by Elevate Quantum). Bloch will make use of Chicago's universities, national labs, private quantum companies, investors, accelerators, and other partners to increase access to quantum facilities and meet industry demand. Elevate Quantum Colorado encompasses the Denver–Aurora region of Colorado and has proposed initiatives focused on infrastructure, entrepreneurship, workforce development, and stakeholder engagement throughout the quantum value chain.[10]

- Several successful quantum-communications milestones occurred throughout 2023. New York University and Qunnect performed a successful test of a ten-mile quantum network between Brooklyn and Manhattan, with 99 percent uptime.[11] Amazon Web Services (AWS) researchers conducted a successful test of point-to-point QKD between two devices three miles apart in Singapore.[12] A team of scientists from Russia and China established an encrypted quantum-communication link using secure keys over 3,800 kilometers, leveraging China's quantum satellite, *Mozi*.[13]

Underlying technologies

Noteworthy quantum technologies include the following:

- *Quantum computing.* Quantum processors use the principles of quantum mechanics to perform simulations and process information. They can provide exponential performance improvements over classical computers for some applications.

- *Quantum communication.* This is the secure transfer of quantum information across space. It could ensure security of communications, enabled by quantum cryptography, even in the face of unlimited (quantum) computing power.

- *Quantum key distribution.* QKD is the use of quantum technology to secure communications against possible attacks by quantum computers.

- *Quantum sensing.* Quantum sensors could provide measurements of various physical quantities at a sensitivity that exceeds those of classical sensors by orders of magnitude.

6 "HSBC and Quantinuum explore real world use cases of quantum computing in financial services," Quantinuum, May 30, 2023.
7 *Apple Security Research Blog*, "iMessage with PQ3: The new state of the art in quantum-secure messaging at scale," Apple, February 21, 2024.
8 *Signal*, "Quantum resistance and the Signal Protocol," blog entry by Ehren Kret, September 19, 2023.
9 "Biden–Harris administration designates tech hub in Illinois to drive innovation in quantum computing and communications," US Economic Development Administration press release, October 2023.
10 "Biden–Harris administration designates tech hub in Denver–Aurora to drive innovation in quantum information technology," US Economic Development Administration press release, October 2023.
11 "NYU takes quantum step in establishing cutting-edge tech hub in Lower Manhattan," New York University press release, September 13, 2023.
12 John Russell, "AWS partners report successful quantum key distribution trial in Singapore," *HPCwire*, March 6, 2023.
13 Matt Swayne, "China and Russia test quantum communication link," Quantum Insider, January 2, 2024.

'Recent advancements in quantum computing show that we are moving away from research toward real application. It's interesting to see that these advancements happen currently across different technologies. So the race for the best technology or combination of technologies—and how best to use them—is still on.'

– Henning Soller, partner, Frankfurt

Key uncertainties

The major uncertainties affecting quantum technologies include the following:

— *Technical challenges* include the ability to manage a sufficient quantity and quality of qubits over enough time to derive meaningful computational results while navigating potential barriers to adoption (for example, regulatory, technological, and financial) that are not yet apparent.

— *Cost-effectiveness* may take time. Traditional supercomputers can perform most calculations that businesses require reasonably well and at a much lower cost; this is expected to change once quantum advantage is achieved and general-purpose quantum computers take center stage.

— *Ecosystems* are nascent. Limited awareness and adoption of quantum technologies (such as differing levels of technology maturity and applicability for different industries), the need for increased interdisciplinary coordination required to bring technologies to market (for example, between academia and industry), and quantum companies' continued work to access talent (talent includes theory, hardware, and software development) hinder development and innovation outside quantum hubs.

Big questions about the future

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

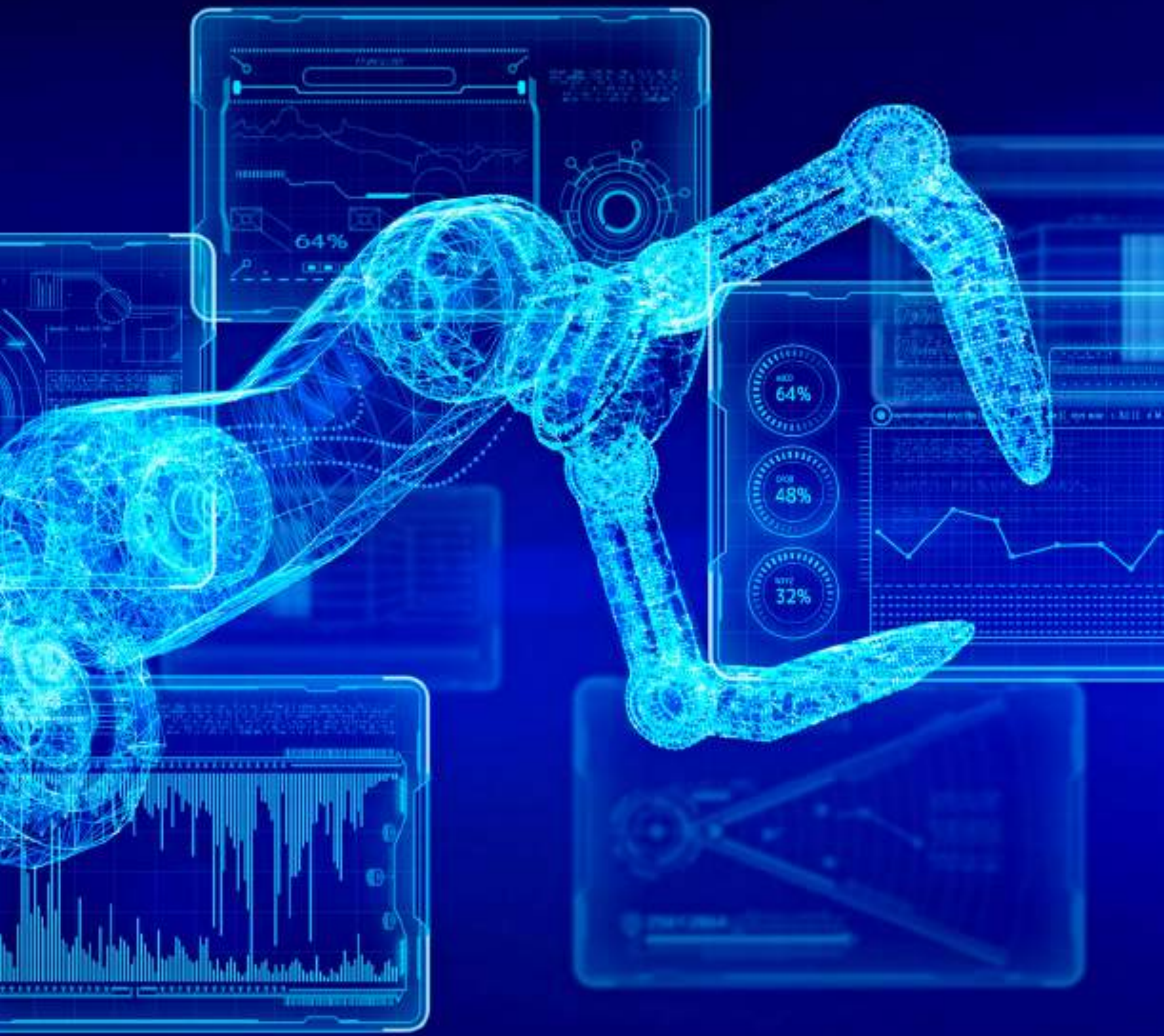
— On what timeline over the next decade will quantum technology advance and reach major milestones (for example, full error correction, quantum advantage, and vulnerability of current RSA encryption)?

— What benefits could arise from the combination of quantum and AI?

— How and when should companies start to prepare for quantum technology, particularly the security threats posed by quantum computers?

— Will talent supply catch up to demand? What levers are available, and how can organizations help fill the talent gap?

Cutting-edge engineering



Future of robotics

The trend—and why it matters

Advanced robotic systems are characterized by their high sophistication in automating a variety of physical tasks. The range of use cases—from consumer-level services to enterprise-level assembly—has proliferated in recent years because of both macroeconomic conditions and technological advances. In terms of macroeconomics, the world has seen rising labor costs, aging populations, and additional complexity regarding offshoring labor, leading to tight labor markets in many countries.[1] From a technological perspective, AI has led to many innovations that have increased the capabilities and accelerated the training of physical robots. While there are technological and social hurdles to overcome, widescale adoption can be key to unlocking productivity, shifting the economy to incorporate new ways of working that are fundamentally different from current human-centric jobs.

[1] "Help wanted: Charting the challenge of tight labor markets in advanced economies," McKinsey Global Institute, June 26, 2024.

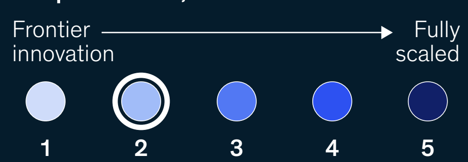
CUTTING-EDGE ENGINEERING

Future of robotics

Scoring the trend

We see an uptick in research, patents, and investment in 2023 for these technologies.

Adoption score, 2023



Equity investment, 2023, $ billion

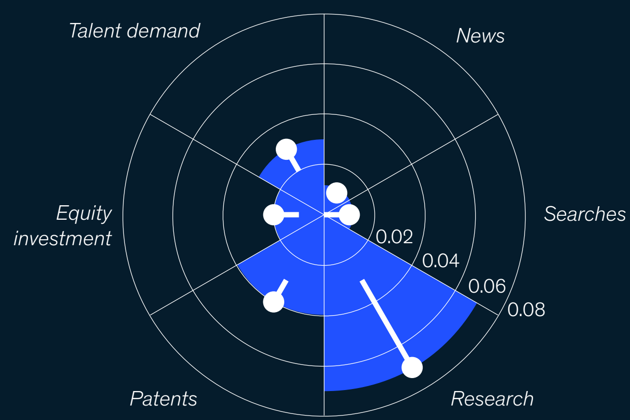
$6

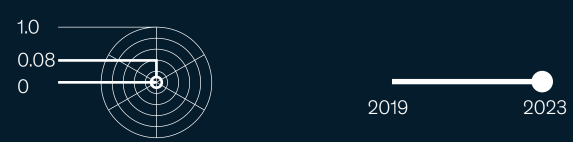
Job postings, 2022–23, % difference

–20%

Industries affected: *Agriculture; Automotive and assembly; Chemicals; Consumer packaged goods; Information technology and electronics; Manufacturing; Metals and mining; Oil and gas; Pharmaceutical and medical products; Retail; Semiconductors; Telecommunications*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

'We stand on the brink of revolutionary advances in robotics, with more autonomous, more dexterous, and more mobile machines emerging [at scale]. These advances promise a future where robots enhance our capabilities and expand the operational domains of automation, from intricate tasks on manufacturing floors to dynamic service environments. Thoughtful adoption of these technologies could unlock productivity while elevating the nature of labor.'

– Ani Kelkar, partner, Boston

Latest developments

Recent developments involving the future of robotics include the following:

— *A proliferation of sectors are adopting robots.* With increasing capabilities and decreasing costs, robots are branching out from assembly and manufacturing to new sectors such as life sciences and agriculture. In life sciences, for example, we have seen a surge in interest in automated liquid handling—robots that assist with pipetting, handling, and transferring liquid chemicals for drug development—with a range of off-the-shelf and custom robot options for buyers and an estimated market value of approximately $3 billion in 2023.[2] In agriculture, restaurant chain Chipotle announced at the end of 2023 that it was investing in GreenField, a company that builds autonomous, lightweight robots that can cut weeds without damaging crops.[3]

— *The types of robots are expanding.* Robot types are expanding beyond the typical industrial robots. Companies in the electronics industry are using newer, small-scale collaborative robots (cobots) that can be placed on desktops to aid in material handling and assembly. Service robots have also seen steady growth, with a forecasted CAGR of approximately 18 percent over the next five years[4] and expansion to mostly commercial-sector operations in the form of cleaning and kitchen robots. In 2023, Miso Robotics and Cali Group opened an automated restaurant in Pasadena, California—equipped with sensors, cameras, and algorithms, Miso's smart commercial kitchen robot can cook a variety of food items and is not limited to a single type of cuisine or dish.[5]

— *Humanoid and general-purpose robots have surged in interest.* Although most robots are still used for specific tasks, AI has led to considerable interest in humanoid robots, which have the potential of being deployed in environments that will require minimal retrofitting. While early demonstrations still show limited functionality, humanoid robots are already being tested in commercial settings and garnering investor interest. Humanoid robot start-ups Figure and 1X Technologies closed $675 million and $100 million funding rounds, respectively, with major investors including Microsoft, Nvidia, and OpenAI.

— *AI continues to boost progress toward more autonomous robots.* AI has been crucial to the development of robotics, through both the construction of new algorithms and techniques as well as the refinement of older ones. New generative AI approaches, such as Covariant's robotics foundation models or Toyota Research Institute's Large Behavioral Models (LBMs), train robots to react to unexpected situations and build generalizable skills. Toyota's LBMs, for example, allow robots to learn a series of fundamental skills, such as pouring liquids and using tools, by observing humans. These skills are generalizable to many more tasks, with the company aiming to improve its current skill count from 60 to 1,000 by the end of 2024.[6]

2 "Automated liquid handling industry report 2023-2035: Patent surge reflects thriving innovation," PR Newswire, August 16, 2023.
3 "Chipotle invests in autonomous agricultural robots and climate-smart fertilizer to improve the future of farming," PR Newswire, December 13, 2023.
4 "Service robotics market size, share & COVID-19 impact analysis," Fortune Business Insights, April 22, 2024.
5 Brianna Wessling, "Miso Robotics and Cali Group open automated restaurant," *The Robot Report*, December 11, 2023.
6 "Toyota Research Institute unveils breakthrough in teaching robots new behaviors," Toyota, September 19, 2023.

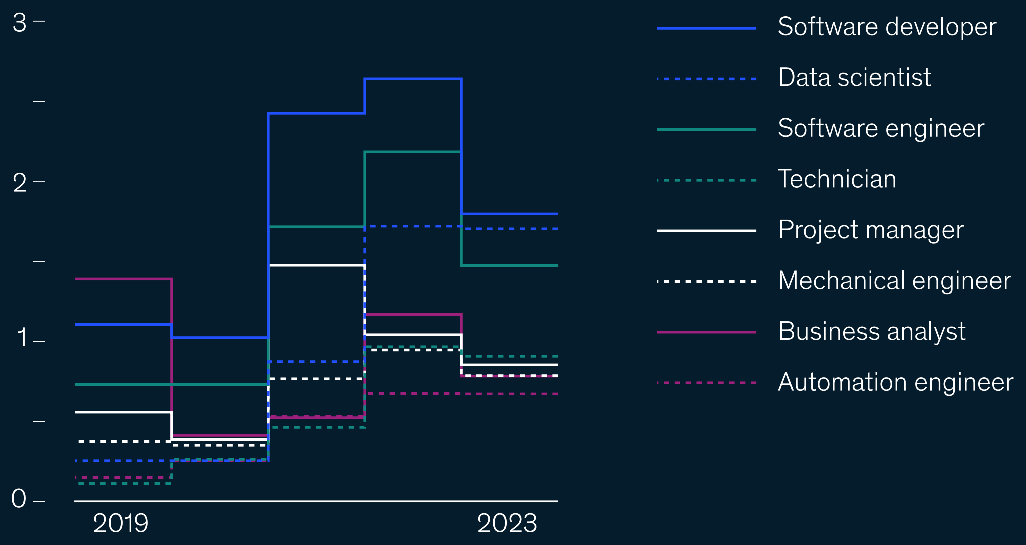
Talent and labor markets

Future of robotics

Demand

Data scientists, technicians, and automation engineers saw smaller decreases in job postings relative to other top jobs, which could point to an increasing focus on using AI models to train robots.

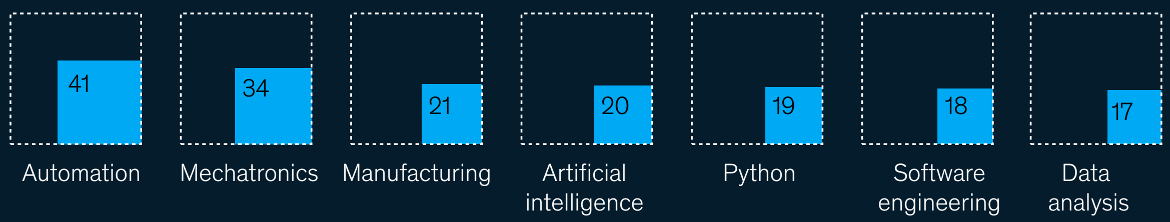
Job postings by title, 2019–23, thousands



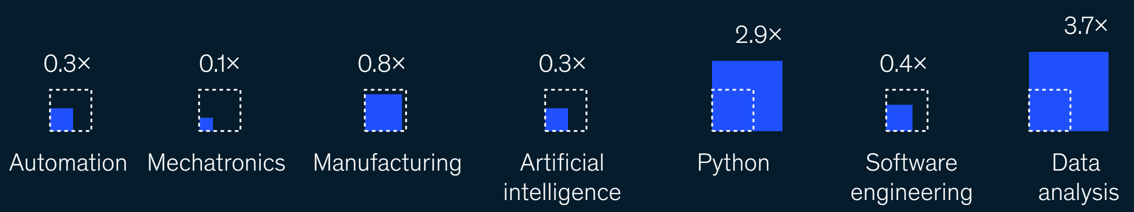
Skills availability

Skills in automation, mechatronics, and manufacturing are all in high demand for the future of robotics. As robots' functionality is improved, more programming and AI skills may be needed.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Robotics technologies saw the highest experimentation rates and have had one of the lowest levels of investment out of all trends, indicating its emergence as a nascent trend with significant advancement opportunities. However, we do see advanced-industries companies making the largest average initial and run-rate investments in gross dollars, highlighting the maturity of robotics use cases in the automotive and manufacturing sectors.

Adoption dimensions

We define the next level of adoption of humanoid or general-purpose robots as their wide-scale deployment in factories and commercial pilots at other enterprises. Advancements along the following dimensions could enable the next level of adoption:

— increased dexterity so that robots can manipulate objects at a similar skill level as that of their human counterparts (for example, for assembly-line tasks)

— improved battery life, allowing robots to operate untethered for most of a standard working day (that is, approximately eight hours)

— sufficient autonomy so that robots can operate in certain edge-case scenarios without requiring human intervention when difficulties are encountered (for example, the ability to troubleshoot and decide on the next action in case of unexpected circumstances)

In real life

Real-world examples involving the future of robotics include the following:

— BMW and robotics start-up Figure signed a partnership that would bring the start-up's humanoid robots to BMW's auto manufacturing facilities. After undergoing training to perform the related functions, the robots will operate in the body shop, warehouse, and sheet metal line in the next one to two years.

— Chevron has been using robotics company Boston Dynamics' four-legged Spot robot in its oil and gas operations. The Spot robots are equipped with many different sensors to help in operations, safety, inspections, and more. Spot has been considered for use in environmental and safety monitoring, as well as in emergency management.

— After acquiring robot kitchen start-up Spyce in 2021, Sweetgreen opened its first restaurant that uses kitchen robots in 2023. The company claims that it can reduce the time needed to make a bowl by 50 percent and that the location employing the robot had 10 percent higher average tickets, faster throughput, and improved order accuracy.[7]

— In preparation for future deep-space infrastructure construction, such as solar-power stations, communications towers, and crew shelters, NASA developed robots that learned how to build a shelter on their own in about 100 hours. The test involved three robots—two builders and one fastener—that were given plans for the shelter and had to use software and digital simulations to determine the best approach for constructing the building.

Underlying technologies

A future of more autonomous and dexterous robots will depend on the following technologies:

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

— *Motion and sensor technology.* This technology involves using actuators, motors, and sensors that can enhance dexterity, movement, and environmental perception and could expand the set of use cases.

— *Connectivity technologies.* Technologies such as 5G/6G, private networks, and the Internet of Things can enable real-time updates and improved security levels.

— *Materials innovation.* Using new materials (for example, carbon fiber and other lightweight materials) and processes (for example, 3D printing) can improve efficiency and sustainability.

— *Electrification technologies.* These solutions allow robots to operate untethered for longer time frames, leading to increased versatility.

[7] Lisa Jennings, "Sweetgreen's robotic makelines show 10% sales lift," *Restaurant Business*, March 1, 2024.

Key uncertainties

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

- *Safety, privacy, and accountability concerns* could arise as robots become further integrated with society and work alongside humans.
- *The impact on the labor market and public perception* might initially be negative. Although adoption of the trend has the potential to automate many work activities, it can also provide the opportunity to redesign the job market for new roles. Integration of robots into the workforce would most likely require training to upskill human workers for different roles or to work effectively with their new counterparts.
- *Access to sufficient resources,* such as batteries and talent, will remain critical to both the technology development and supply of future products.
- *Cross-border competition* can have an outsize effect on global technology trade flows.
- *The potential for regulatory shifts* adds significant uncertainty to the market outlook, as some companies are concerned that regulation could reshape technological development and deployment plans, potentially leading to inconsistent practices and challenges in ensuring accountability and public trust in the development and deployment of these technologies.

Big questions about the future

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

- At what rate will companies adopt robots into their organizations?
- How will integration with robots reshape the workforce of the future?
- When can we expect general-purpose robots?
- What new business use cases may be created by advanced robots?

‘Labor scarcity, the need for manufacturing flexibility, and the productivity imperative are expected to remain key drivers of growth in the robotics industry. Humanoid robots powered by AI are anticipated to offer significant flexibility, enabling them to shift from single-purpose robots to multifunctional machines. This increased flexibility is expected to further propel growth in the robotics industry, as manufacturers seek to optimize their production processes and increase efficiency.’

– Ahsan Saeed, partner, Munich

Future of mobility

The trend—and why it matters

Technical advancements, coupled with rising sustainability concerns, have given rise to a new era of mobility. Autonomous and electric vehicles (AVs and EVs), urban air mobility, and ACES (autonomous driving, connectivity, electrification, and shared/smart mobility) technologies have become the focus of many organizations trying to revolutionize the transport of people and goods while improving accessibility, safety, and sustainability.[1] Although the regulatory environment remains nascent, ACES technology has seen accelerating adoption by both new industry players and incumbents in the automotive and aerospace industries. For example, 2023 saw more major steps on the path to wide-scale adoption of these technologies, with commercial pilot programs of autonomous robo-taxis in major cities and flight testing of urban aircraft. Even with high growth projections and early signs of success for many of these technologies, innovators still wrestle with technological, regulatory, and consumer sentiment issues, which have added volatility to the industry over the past year.

[1] Kersten Heineke, Nicholas Laverty, Timo Möller, and Felix Ziegler, "The future of mobility," *McKinsey Quarterly*, April 19, 2023.

CUTTING-EDGE ENGINEERING

Future of mobility

Scoring the trend

Significant increases in news, research, and patents indicate increasing interest from the public sphere and an acceleration of R&D from enterprises and research institutions. While investment saw a dip, in line with macroeconomic conditions and a general reduction in investment activity, talent demand is increasing as companies extend commercial pilot programs and testing in aviation and autonomy and manufacturers of autos and trucks with electric drivetrains scale up their volumes.

Adoption score, 2023

Frontier innovation → Fully scaled

1 **2** 3 4 5

Equity investment, 2023, $ billion

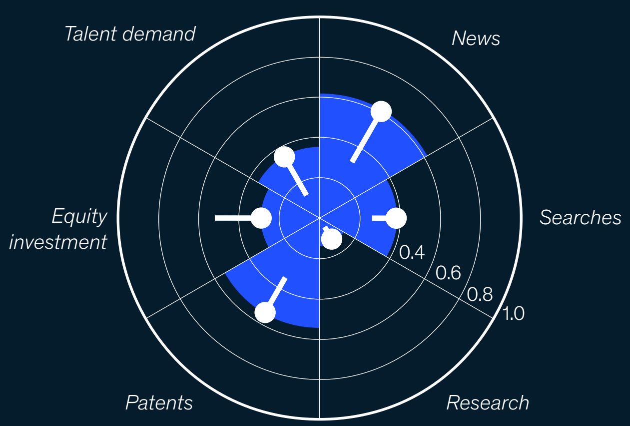
$83

Job postings, 2022–23, % difference

–5%

Industries affected: *Automotive and assembly; Aviation, travel, and logistics; Electric power, natural gas, and utilities; Financial services; Metals and mining; Oil and gas; Public and social sectors; Retail*

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



Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Recent developments involving the future of mobility include the following:

- *EV demand remains high, despite recent slowing growth in major regions.* EVs have been soaring in popularity for several years and remain in high demand, despite the recent slowing growth rate in certain regions.[2] EVs saw record sales in 2023, but manufacturers are seeing slowing consumer demand with lower growth projections for 2024, partially because of high prices and customer range anxiety. This is leaving automakers with high EV inventory and forcing some to cut prices. The industry is now exploring how to make EVs meaningfully cheaper, particularly in the United States and Europe. Even China, the world's largest EV market, saw a slowdown in growth in 2023 that coincided with reduced subsidies, touching off a price war among domestic and foreign manufacturers.[3] The battery industry continues to grow quickly because of heavy public and private investment in EV development. For example, approximately 30 battery factories are currently planned, being constructed, or operational in the United States alone; 13 of them are expected to open by 2025.

- *Robo-taxis navigate hurdles to achieve more widespread commercial use.* In August 2023, California regulators granted Waymo and Cruise permission to operate commercial robo-taxi services in San Francisco. However, following a series of safety incidents, Cruise had its license revoked in October. Waymo continues its commercial operations and has gained initial regulatory approval to expand within California and operate on highways. China issued its first regulation on commercial AVs in December 2023, requiring a robo-taxi to remote-operator ratio of no more than 3:1.

- *Autonomous trucking reaches a pivotal moment as testing begins.* The year 2024 could be a watershed one for autonomous trucking as companies begin larger-scale on-the-road pilots. This is especially the case in the United States, where demand has been demonstrated, given that the trucking industry has been experiencing a shortage of drivers. Start-ups are beginning commercial tests amid a mixed regulatory and investment environment. Aurora Innovation, a company specializing in self-driving technology, began an on-the-road pilot for commercial trucking on public highways between Houston and Dallas, with the goal of achieving fully autonomous trips by the end of 2024. Like the industry for robo-taxis, the autonomous trucking sector faces regulatory challenges related to safety concerns. However, interest remains strong.

- *Micromobility generally demonstrates resilience amid market consolidation.* The micromobility sector has shown signs of steady growth and robust progress. Lime, an e-scooter start-up, reported that for the first time in 2022, it achieved profitability, which continued into the first half of 2023. Users of micromobility are also wide ranging: a National Association of City Transportation Officials (NACTO) report indicates that customer segments of micromobility include commuters, tourists, and recreational users.[4] As the micromobility market progressed in 2023, it saw increased consolidation in a bid to compete for funding and chase profitability while also seeing postpandemic demand levels for e-bikes decline in Europe.

'Batteries require building new supply chains from raw materials to recycling to enable the energy transition in mobility.'

– Andreas Breiter, partner, Bay Area

[2] Kersten Heineke, Philipp Kampshoff, and Timo Möller, "Spotlight on mobility trends," McKinsey, March 12, 2024.
[3] Selina Cheng, "Even the world's biggest electric-vehicle market is slowing," *Wall Street Journal*, February 18, 2024.
[4] Andrew J. Hawkins, "Bird may be bankrupt, but shared micromobility is doing just fine," *Verge*, December 21, 2023.

— *The scale and breadth of drone delivery operations have increased.* In 2023, commercial drone deliveries saw a 14 percent increase from 2022, exceeding one million, and drone delivery was the only future mobility technology to see a significant increase in funding.[5] This growth is partially due to favorable regulatory developments, such as the Federal Aviation Administration (FAA) granting 120 waivers for beyond-visual-line-of-sight (BVLOS) operations in 2023.[6] This includes approvals for drone delivery players such as UPS Flight Forward, Wing Aviation, and Zipline, representing a 65 percent increase in waivers from 2022. BVLOS operations allow drones to fly farther, with less costly oversight from nearby pilots or visual observers, making expanded operations possible and the economics attractive.[7]

— *Funding for eVTOL aircraft experienced a slight decline, but the potential for certification maintains momentum.* Funding for electric vertical takeoff and landing (eVTOL) aircraft experienced a slight decline, with eVTOL companies securing only about 50 percent of the funding they received in 2022. However, there is a positive outlook regarding potential certifications from regulatory bodies, which could reinvigorate the segment. To support this growth, players are developing additional infrastructure and manufacturing capabilities, including charging facilities and landing sites. The approval for commercial flights for eVTOL operators is expected to further accelerate the expansion of this infrastructure.

'While last year saw both advances and setbacks, we've gotten another step closer to autonomous vehicles being a reality at scale. The first mass adoption use cases will be in autonomous trucks, robo-taxis, and robo-shuttles, with further advances in autonomy levels for personal vehicles at the same time. Remote operating is another interesting use case that we expect to grow sizably over the next years.'

– Kersten Heineke, partner, Frankfurt

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5 *Future of Air Mobility Blog*, "Clouds or clear skies? Prospects for future air mobility," blog entry by Axel Esqué, Tore Johnston, and Robin Riedel, McKinsey, January 23, 2024.
6 Other jurisdictions allowed BVLOS operations prior to the FAA waivers.
7 *Future of Air Mobility Blog*, "Clouds or clear skies?," McKinsey, 2024.

Talent and labor markets

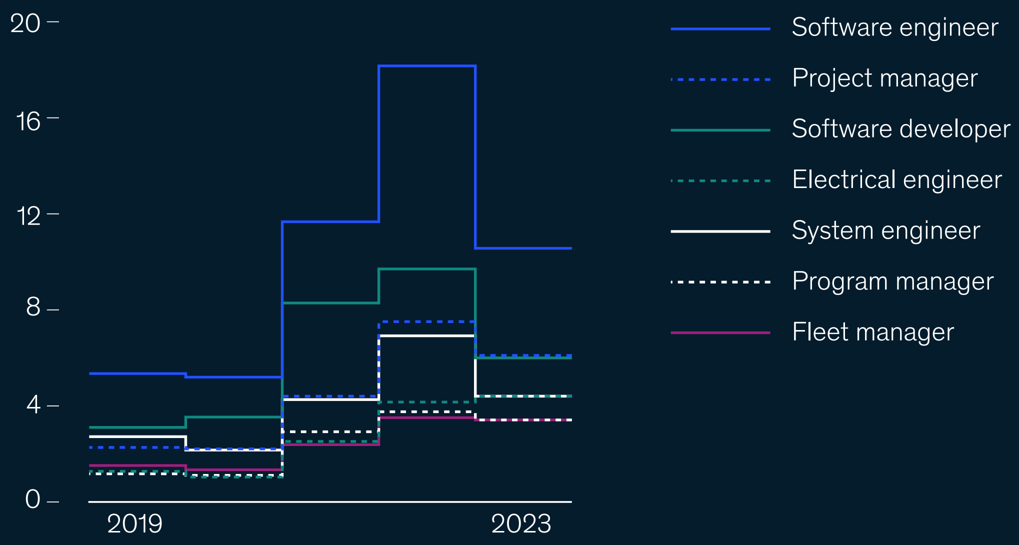
Future of mobility

Demand

Software engineer was once again the job posting with the highest demand for future mobility technologies in 2023, with only a 5 percent decrease in job postings relative to a 26 percent average decrease across all technology trends.

While most technical and managerial roles, such as system engineers and project managers, saw decreases, the demand for jobs such as drivers remained fairly constant or saw slight upticks.

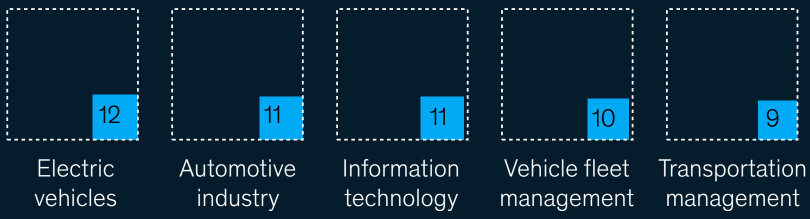
Job postings by title, 2019–23, thousands



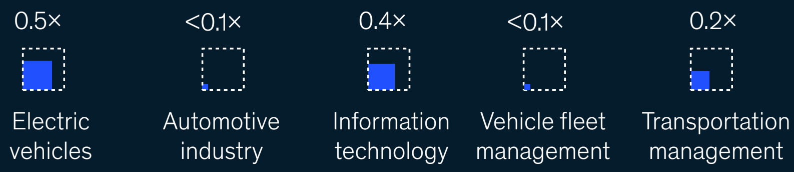
Skills availability

There was a decline in talent demand in 2023 alongside a shortage in talent availability.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Among the trends observed this year, the future of mobility trend ranks in the bottom three for initial investment, adoption, and optimism. These rankings can be seen as indicators of the significant innovation, regulatory, and behavioral hurdles companies will have to overcome to reach next-level adoption of future mobility technologies.

Adoption dimensions

The adoption trajectory varies for technologies and use cases within the future of mobility trend. For example, robo-taxi and robo-shuttle ridesharing illustrate the potential adoption trajectory for consumer use cases of future mobility technology.

As an extension of public transit and an alternative to traditional ridesharing and private vehicles, the next level of adoption for robo-taxis and robo-shuttles could be at-scale deployment of fleets in significant metropolitan areas and across all road types.

Advancements along the following dimensions could enable the next level of adoption:

— safety and technological reliability to be demonstrated for both highway and city operations to fully cover metropolitan areas (currently, human drivers have approximately five incidents per million miles)[8]

— robo-taxis and robo-shuttles to become comparable to traditional ridesharing options in terms of cost

— regulatory changes to lay the groundwork for scalability of robo-taxis in major metropolitan areas (currently, there are around half a dozen cities in the United States and China piloting the technology)[9]

In real life

Real-world examples involving the future of mobility include the following:

— After performing more than 700,000 robo-taxi trips in 2023,[10] Waymo gained approval to expand its commercial robo-taxi services to additional parts of the San Francisco Bay Area, Los Angeles, and Phoenix. This expansion allows the company to operate on highways for the first time in designated areas. Meanwhile, Baidu's Apollo Go gained approval to offer 24/7 services of its robo-taxis and to begin operating on highways to Beijing Daxing International Airport, making Beijing the first capital city to offer airport robo-taxi rides.[11]

— Uber had its first profitable year as a public company in 2023, with a net income of about $4 billion. This was driven by a combination of robust user growth and more efficient cost management practices. This milestone could be a potential inflection point for the company as it shifts from a growth-focused start-up to a more mature profit-oriented company and serves as a positive indicator of the viability of the mobility model.

— Joby Aviation signed a six-year contract with Dubai's Road and Transport Authority to conduct air taxi services in the city by early 2026, with Joby aiming to commence operations as early as 2025. The company's aircraft are built to carry a driver, a pilot, and four passengers at speeds of up to 200 miles per hour. In February 2024, Joby became the first developer of eVTOL aircraft to complete the third of five stages of the FAA type certification process.[12]

— E-scooter start-ups Tier Mobility and Dott merged to form Europe's largest e-scooter company, with an additional $66 million fusion into the newly formed business. This merger will allow for operations spanning 20 countries in cities such as Berlin, London, Paris, and Rome, with a combined annual revenue of about $250 million.

— Many EV automakers—including Ford and General Motors—announced that they would adopt Tesla's North American Charging Standard (NACS) port in an effort to gain access to the company's extensive supercharging network amid consumer concerns about unreliable third-party chargers.

8 *Waypoint: The Official Waymo Blog*, "Waymo significantly outperforms comparable human benchmarks over 7+ million miles of rider-only driving," Waymo, December 20, 2023.
9 *Off the Kuff*, "The state of robotaxis in 2024," blog entry by Charles Kuffner, February 29, 2024.
10 *Waypoint: The official Waymo Blog*, "Dear Waymo community: Reflections from this year together," blog entry by Dmitri Dolgov and Tekedra Mawakana, Waymo, December 21, 2023.
11 "Baidu launches China's first 24/7 robotaxi service," PR Newswire, March 8, 2024.
12 "Joby completes third stage of FAA certification process," Joby Aviation press release, February 21, 2024.

Underlying technologies

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

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

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

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

— *Shared-mobility solutions.* Hardware and advanced digital solutions, as well as new business models and social adoption, enable the use of alternative shared modes of transportation in addition to—or instead of—privately owned vehicles.

— *Materials innovation.* The use of new materials (for example, carbon fiber and other lightweight materials) and processes (such as engine downsizing) can improve efficiency and sustainability.

— *Value chain decarbonization.* In addition to electrification, technical levers (such as green primary materials) can abate emissions from materials' production and increase recycled materials' use.

Key uncertainties

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

— *The global energy supply expansion* that is required to meet EV demand remains uncertain. Demand for lithium-ion batteries is surging as EV production expands, necessitating more and larger battery factories. At the same time, critical upgrades are required to EV-charging infrastructure. Europe, for instance, may need to invest upward of €240 billion to complete extensive utility grid updates, increase renewable-energy production capacity, and provide the estimated 3.4 million public charging points required by 2030 (up from 375,000 in 2021).[13]

— *Safety and accountability concerns* surround uncrewed and autonomous-mobility technologies.

— *Technology uncertainties* about batteries with sufficient range to support more applications (such as air mobility) may hinder greater adoption.

— *Customer perceptions* of noise and visual impact remain in play (for example, noise pollution from delivery drones).

— *Equipment and infrastructure costs* are factors for new modes of transportation (for instance, building EV-charging networks).

— *Regulation shifts* will occur as mainstream certification frameworks are developed (for example, controlling expanded air traffic).

— *Privacy and security concerns* for underlying AI algorithms and workflows that rely on consumer data should be addressed.

— *Access to sufficient resources* (such as raw materials for battery production and software developers for autonomous-driving software) will be required to scale these technologies.

Big questions about the future

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

— How will the future of mobility trends shape cities?

— What regulatory enablers and barriers need to be addressed to enable widespread adoption?

— What share of vehicle sales will autonomous vehicles account for, and what business models will predominate?

— What achievements need to be made to win over consumer trust for autonomous vehicles and urban air mobility?

— What scale will advanced air mobility achieve in the next decade?

— What needs to be in place for advancements in shared mobility to deliver on anticipated financial and environmental impact?

[13] Kersten Heineke and Timo Möller, "Future mobility 2022: Hype transitions into reality," McKinsey, March 10, 2023.

Future of bioengineering

The trend—and why it matters

The combination of biological and computing advancements has led to a range of innovations in products and services for industries such as healthcare, food and agriculture, consumer products, sustainability, and energy and materials. With the possibility of more than $2 trillion of potential economic impact in the next decade,[1] as well as hundreds of use cases, bioengineering technologies such as gene therapy have the potential to improve human health and longevity, and technologies such as alternative-protein production could contribute to sustainability. Although the science underlying many of these use cases has been demonstrated today, the technologies must also achieve commercial viability and overcome social and regulatory challenges.

[1] "What is bioengineering?," McKinsey, June 23, 2023.

CUTTING-EDGE ENGINEERING

Future of bioengineering

Scoring the trend

Although bioengineering ranked second among emerging trends in publications and research in 2023, with a noticeable uptick in both areas, news coverage and searches of the trend have remained constant since 2019. There has also been a decline in investment, which is in line with the overall market in 2023, as well as a slight decline in patents (patent scores are based on patents granted and, therefore, subject to a 12-to-18-month lag). Nonetheless, talent demand has nearly doubled since 2019.

Adoption score, 2023

Frontier innovation → Fully scaled

1 2 3 4 5

Equity investment, 2023, $ billion

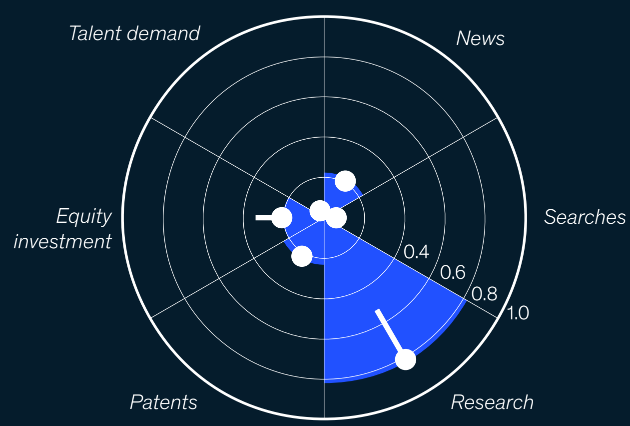
$62

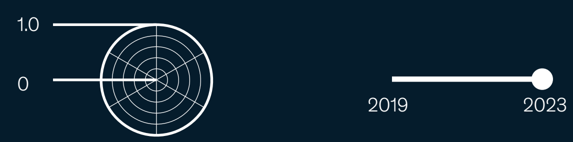
Job postings, 2022–23, % difference

–23%

Industries affected: *Agriculture; Chemicals; Consumer packaged goods; Healthcare systems and services; Pharmaceuticals and medical products*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Recent developments involving the future of bioengineering include the following:

- *CRISPR-based gene therapies are taking a significant step forward.* The FDA and the European Commission granted regulatory approval for Vertex Pharmaceuticals' Casgevy, the first gene therapy that uses the renowned CRISPR-Cas9 technology. The therapy treats rare blood disorders such as sickle cell disease and beta thalassemia, marking a significant moment for the technology.[2]
- *Researchers continue to discover new uses for AI in bioengineering.* Advancements in AI led to additional successes in bioengineering in 2023. Although generative AI has been used in the industry for research and trials, many of the recent advancements in protein engineering and drug repurposing have used other proprietary AI algorithms. For example, researchers at the University of Pennsylvania used an AI ranking algorithm to reveal a previously unknown use for an existing drug to treat a man with idiopathic multicentric Castleman disease (iMCD). While using the drug for this purpose has not yet been tested or approved at scale, its utilization in this case shows promising potential.
- *Advances in alternative-protein production continue despite regulatory constraints.* There has been renewed interest in using technologies such as precision fermentation for producing alternative proteins. Having already shown its viability, the technology, which is more sustainable than other forms of alternative-protein production, was granted safety approval in 2023, with New Culture becoming the first company to achieve a generally-recognized-as-safe (GRAS) grading for its animal-free protein. Cultivated meat, another form of alternative protein, has seen a mixed regulatory environment, however. Italy banned the production of cultivated meat in a bid to protect farmers, while the Netherlands became the first EU government to allow cultivated-meat tastings.

'We may look back at the past year as the point in time when gene editing became 'everyday.' We now have approved cures for a well-known and widespread disease like sickle cell anemia and also have more consumer-oriented products, including purple tomatoes and glow-in-the-dark plants. Genetic modification has been around and commercialized for years but never before in such a tangible way for the average person.'

– Tom Brennan, partner, Philadelphia

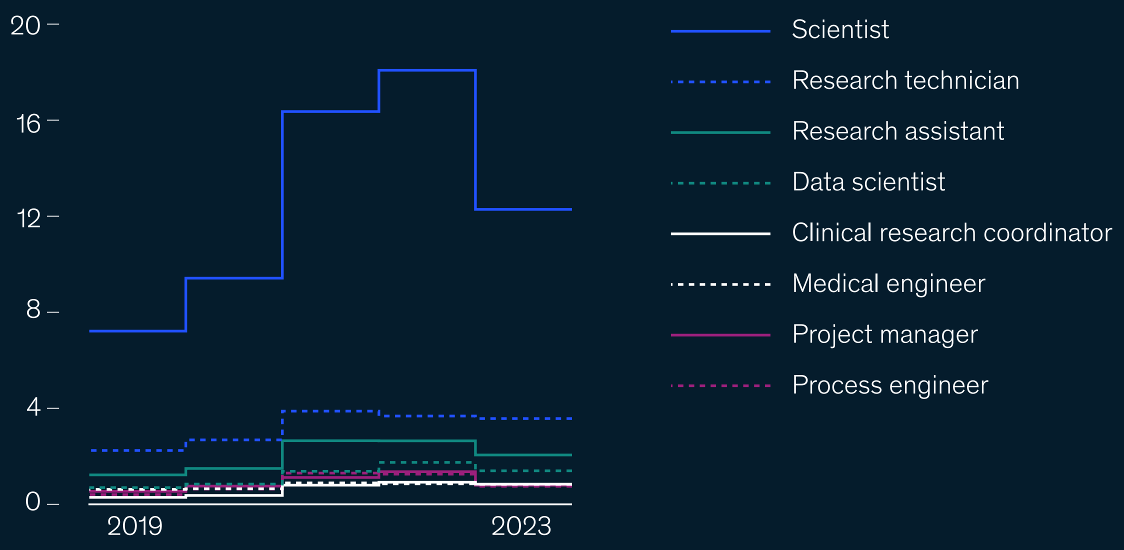
2 Julianna LeMieux, "The first CRISPR drug: Vertex Pharmaceuticals' Casgevy wins U.K. approval for sickle cell disease," *Genetic Engineering & Biotechnology News*, November 16, 2023.

Future of bioengineering

Demand

The future of bioengineering has seen an overall decline in job postings from 2022 to 2023, yet a few roles have seen growth in 2023. Job postings for research technicians, clinical-research coordinators, and medical engineers have remained largely consistent with prior years' postings. However, the scientist role has experienced the most notable decline, possibly due to a surge in demand during the COVID-19 pandemic, along with a slowdown in investment in 2023.

Job postings by title, 2019–23, thousands

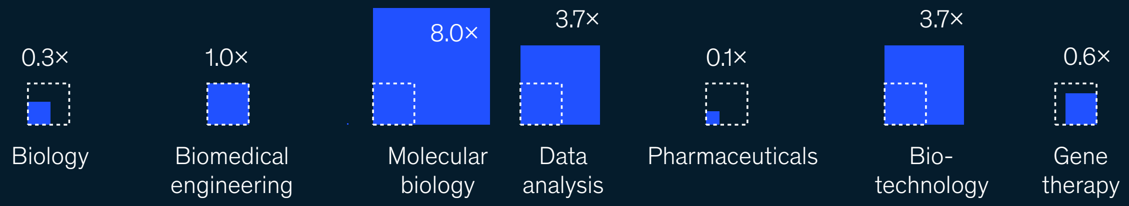


Skills availability

While the supply of talent in molecular biology is high relative to demand, the supply of talent for more specialized areas—such as gene therapy and pharmaceuticals—is low.

Talent availability, % share of postings requiring skill

Talent availability, ratio of talent to demand



‘The momentum of progress in bioengineering remains strong, driven by breakthroughs in generative AI technologies that have unlocked new pathways for innovation. The excitement surrounding these advancements has already led to notable developments, particularly in areas like protein engineering and drug repurposing. We can only expect more, and faster, adoption of these technologies as biopharma and other industries continue advancing their use of generative AI.’

– Erika Stanzl, partner, Zurich

Adoption developments across the globe

The adoption of bioengineering technologies is low relative to other trends, as they are specific to certain industries and have higher up-front capital investment needs as they reach commercialization. The energy and materials industries have seen a relatively high percentage of respondents demonstrating that they have at least started experimenting with bioengineering. This likely arises from its potential in both well-established and nascent use cases—for example, improved fermentation processes, bio routes to develop novel materials with entirely new properties (for instance, alternatives to traditional leather), and broadening biofuels production to new feedstock sources.

Adoption dimensions

Advancements along the following dimensions could enable the next level of adoption:

— continued investments in scientific research and development to support bioengineering innovation

— an increase in regulatory approvals of bioengineering innovations across most major economies (currently, medicine developed through the use of CRISPR is approved in the European Union, the United Kingdom, and the United States)

— improved public perception and broader social acceptance of the technologies

— a complex infrastructure to support advanced bioengineering activities and the ability to scale operations and production to meet market demands

In real life

The following are real-world examples involving the future of bioengineering:

— After acquiring Elixirgen Scientific in 2022, Ricoh, a Japanese digital-services company, sought to leverage its expertise in digital technologies and AI to create more reliable disease models, leading to shorter drug development timelines and increased success rates. Ricoh accordingly entered into a CRISPR/CRISPR-Cas9 license agreement with ERS Genomics for access to gene editing technology patents. The initiative aimed to accelerate personalized medicine, drug discovery research, and regenerative medicine.

— Japan became the first country to approve a self-amplifying mRNA vaccine that instructs the body on how to make more mRNA, as trial results have shown signs of an increased antibody response relative to traditional mRNA boosters. This advance could potentially allow for lower effective dosages and a more resilient immune response, leading to fewer side effects and longer-lasting vaccines.

— Tropic, an agricultural biotech company based in the United Kingdom, used CRISPR to genetically modify bananas so they stay fresh longer. Conventional techniques for creating a genetically engineered organism involve the introduction of foreign DNA from other organisms, whereas CRISPR offers a more targeted and precise approach to gene editing. The Philippines Department of Agriculture has since classified these bananas as non-GMO and approved their production.

- Insilico Medicine is evaluating its potentially first-in-class antifibrotic small-molecule inhibitor on lung function in patients with idiopathic pulmonary fibrosis (IPF). The cause of IPF, a progressive lung disease characterized by the formation of scar tissue in the lungs, is unknown, which makes it challenging to treat effectively. Researchers at Insilico Medicine used a combination of machine learning and generative AI to identify a new therapeutic molecule to create a compound that demonstrated antifibrotic properties. While this process usually takes five to eight years, the compound was able to progress to human trials in only 18 months.
- Unilever announced that it will launch a version of its Breyers ice cream that consists of whey protein produced by precision fermentation. The company has partnered with Perfect Day, a food-tech start-up, to produce the whey protein to meet its sustainability goals.
- Norfolk Plant Sciences released a genetically altered purple tomato with high levels of anthocyanins, a type of antioxidant shown to have anti-cancer and anti-inflammatory effects. The company began selling the seeds to farmers and gardeners alike, allowing regular consumers to "grow biotech" in their own backyard.

Underlying technologies

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

- *Omics.* Biological sciences ending in the suffix "-omics," such as genomics and proteomics, focus on a different class of molecule and its functions. Omics are central to the development of bioengineering applications such as viral-vector gene therapy (which uses modified viruses to permanently replace poorly functioning genes that cause genetic diseases) and mRNA therapy (which uses messenger RNA to trigger the synthesis of proteins that can help prevent or fight disease).
- *Gene editing.* A subset of genomics, gene editing comprises techniques for modifying an organism's DNA, usually using tools such as CRISPR-Cas9.
- *Tissue engineering.* This technology enables the modification of cells, tissues, and organs. Tissue engineering supports various human applications, such as development of transplantable biomaterials and the generation of human tissue replicas for drug studies. Cultivated meat is an example of a product produced via tissue engineering methods. It is made by taking a sample of animal cells and growing it in a controlled environment to produce tissue that is similar to meat from whole animals.
- *Biomaterials.* Materials made using bioengineering technology are known as biomaterials. They fall into several different categories: bio-based drop-in chemicals (which can replace chemicals traditionally made from petrochemicals without changing surrounding operations), bioreplacements (new materials made from bio-based chemicals that provide similar quality and cost but better environmental performance than traditional chemicals), and biobetter materials (completely new materials produced via biochemical synthesis).

Key uncertainties

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

- *Regulation of bioengineering technology and products* will play a part in governing the pace of advancements.
- *Public perceptions and ethical concerns* regarding the safety, cost, and quality of bioengineered products could determine how quickly markets develop. Concerns about modifying living organisms could also challenge advancements.
- *Unintended consequences* could occur, as biological systems are self-replicating, self-sustaining, and highly interconnected, and changes to one part of a system can have negative cascading effects across an entire ecosystem or species.

Big questions about the future

Companies and leaders may want to consider the following questions when moving forward with bioengineering technologies:

- How will society, in light of its diverse values and principles, determine an appropriate extent for genome editing?
- In conjunction with business adoption, how will the public perceive and adopt bioengineering? For example, how does cultivated meat fit within existing diets?
- How long will it take for a variety of CRISPR-based gene therapies to come to fruition and become more socially accepted for a range of ailments?

Future of space technologies

The trend—and why it matters

Rapidly decreasing technology costs over the past decade have given rise to an increase in the viability and relevance of space technologies. Lower costs, attributable to reductions in the size, weight, and power needs of satellites and launch vehicles, have led to a growing number of launches and applications for space technologies. We have seen the rise of wide-scale satellite internet connectivity—pioneered by SpaceX-owned Starlink, with more than 5,000 low-Earth-orbit (LEO) satellites—and increased private-market involvement and innovation around launch vehicles. The growing number of use cases has also attracted the attention and investment, of non-space-technology companies that see a series of opportunities within the realms of remote connectivity, Earth observation across a spectrum of frequencies, and more. Revenues of the industry's "backbone"—that is, space hardware and service providers—could potentially grow to more than $750 billion by 2035, but adoption of different space technologies varies widely.[1] While some technologies are deployed and scaling rapidly, many activities of the future space industry, such as space mining and on-orbit manufacturing, are still nascent and will have to navigate an array of technological and geopolitical hurdles in the coming years.

[1] "Space: The $1.8 trillion opportunity for global economic growth," McKinsey, April 8, 2024.

CUTTING-EDGE ENGINEERING

Future of space technologies

Scoring the trend

Space technology momentum scores have remained modest—but shown steady increases—across all dimensions since 2019.

Adoption score, 2023

Frontier innovation → Fully scaled

Equity investment, 2023, $ billion

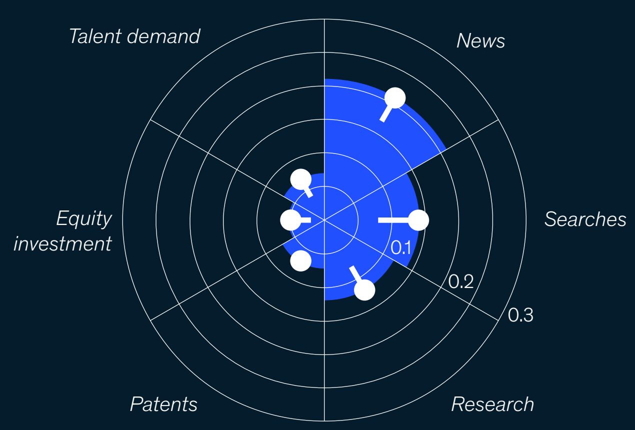
$9

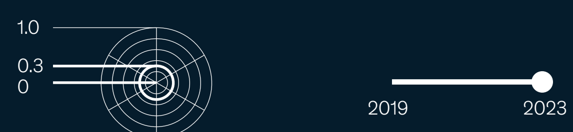
Job postings, 2022–23, % difference

–9%

Industries affected: *Aerospace and defense; Agriculture; Aviation, travel, and logistics; Telecommunications*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

Latest developments

Recent developments involving space technologies include the following:

— *LEO satellite communications constellations see continued growth.* LEO satellite constellations are in various stages of planning and deployment, with multiple companies launching and deploying constellations for commercial and government use. After only a few years of commercial operation, Starlink saw rapid growth in 2023, reaching more than 2.3 million subscribers in over 60 countries and launching new satellites into orbit every few days.[2] Potential competitors, such as Amazon's Project Kuiper, are testing their products in hopes of introducing commercial service soon.

— *Interest and expected expansion of direct-to-device connection continues.* Following Apple's release of its direct-to-device (D2D) emergency connection on its iPhone, companies have increased their focus on the technology to broaden their coverage to remote areas. SpaceX has completed successful tests in partnership with T-Mobile. Viasat and Skylo announced the world's first global D2D network with industries such as agriculture, mining, and logistics as target customers.

— *Global launch activity increased.* Excitement and attention about launches continued in 2023, with an estimated 223 attempted launches versus 186 in 2022, a 20 percent increase.[3] Most of these launches are from US-based companies, primarily SpaceX. However, there was a significant uptick in activity from other countries, such as France and India, as they are starting to invest more in space exploration and involvement. The debut of *Vulcan Centaur*—a new methane-fueled rocket from United Launch Alliance—in early 2024 marked the beginning of two certification missions, adding a new launch alternative to the market.

— *Lunar activity continued within the private and public sectors.* In January 2024, Japan successfully completed the country's first and the world's most precise moon landing ever. This event represents the expanded interest in lunar landings across geographies between the private and public spheres. A series of private companies, such as Astrobotic Technology and Intuitive Machines, have focused heavily on constructing lunar landers, with Intuitive Machines' *Odysseus* managing to land the first US spacecraft on the moon since 1972. NASA has recently selected Intuitive Machines, along with Lunar Outpost and Venturi Astrolab, to advance capabilities for the lunar terrain vehicle for Artemis astronauts, enabling them to conduct scientific research on the moon and prepare for future Mars missions.[4]

— *Integration of offerings into end-to-end solutions is driven by increased interest from non-space-technology sectors.* Space technology companies are increasingly focusing on providing end-to-end (E2E) solutions as the market matures and customers, particularly enterprises, demand seamless integration with their existing infrastructure and less complexity with implementation. We see this through single partnerships between space tech companies (such as those offering D2D technology or remote sensing analytics) and enterprises in industries such as mining, agriculture, and sustainability that are seeking both hardware and software solutions. For example, Planet Labs has contracts with Swiss Re and other insurers to use their satellites and software to both observe and provide analytics to support parametric agriculture insurance.[5]

'Space continues to accelerate in the public consciousness, yet adoption is uneven, and funding is increasingly flowing to "winners." Real progress is being made to deliver on the promises of 2020–21.'

– Jesse Klempner, partner, Washington, DC

[2] Magdalena Petrova, "Starlink's rapid growth and influence has made it an indispensable part of Elon Musk's SpaceX," CNBC, November 11, 2023.
[3] Jonathan McDowell, "Space activities in 2023," January 15, 2024.
[4] "NASA selects companies to advance moon mobility for Artemis missions," NASA press release, April 3, 2024.
[5] "How satellite data is changing agriculture insurance," Planet Labs, December 6, 2023.

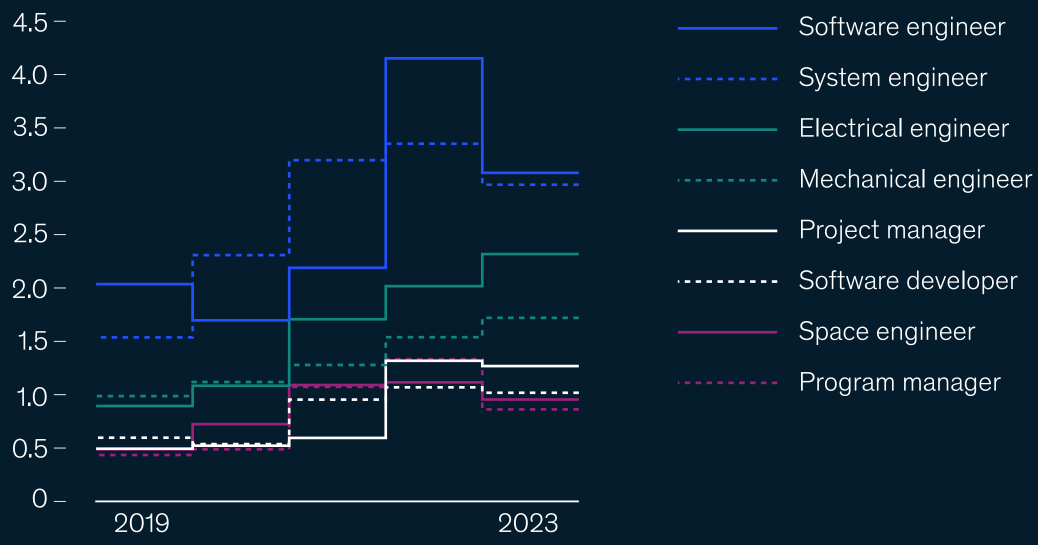
Talent and labor markets

Future of space technologies

Demand

In 2023, the prolonged growth streak of the space technology labor market tapered off. Previously, from 2019 to 2022, the market had consistently seen double-digit growth. Notably, job postings surged during the height of private-capital investment in 2021, peaked in 2022, and experienced a slight decline in 2023.
Postings for electrical and mechanical engineers have seen growth, while all other major segments have declined since 2022. Currently, the space industry job market is witnessing a decline in job postings, though the expectation for long-term growth persists, with established and emerging space disruptors contributing to the growth.

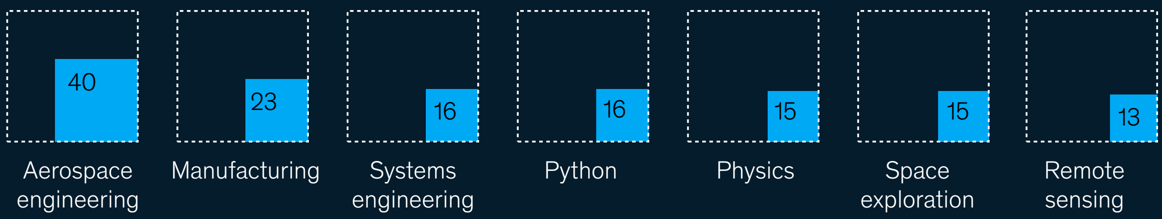
Job postings by title, 2019–23, thousands



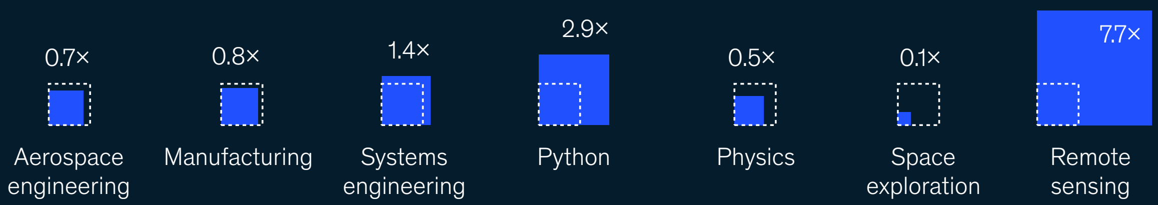
Skills availability

Job listings within the space technology sector feature numerous technical positions, notably in aerospace engineering and manufacturing. Additionally, as the use of space technology expands, there is a growing need for expertise in engineering and data-related fields.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Space technology tools are more specific to some industries and, therefore, experience relatively low levels of reported adoption across the broader market. Perhaps unsurprisingly, respondents from energy and materials and telecommunications, media, and technology companies self-reported that they are scaling or have fully scaled more than other industries, owing to how central connectivity and remote sensing are to these sectors.

Adoption dimensions

The adoption trajectory for advanced technologies varies for each technology and each use case within that technology. Advancements along the following dimensions could enable the next level of adoption:

— Technological evolution facilitates easier access and harmonization of space data and creates opportunities for new revenue streams to emerge. Improved accessibility and usability enable non-space-technology commercial players to embrace space data, breaking down technical barriers and fostering innovative use cases.

— Demand increase—for instance, through regulatory requirements for observation of key metrics—could be accomplished by space-based remote sensing in a broader range of verticals. Substantial legislation where third-party verification of emissions is either required or beneficial, such as the EU Deforestation Regulation, can create incentives for enterprises to use space-based technologies to monitor their environmental impact. Growth in demand is also enabled by an increasingly connected and mobile world, generating demand for satellite internet, positioning, and navigation services, and AI- and machine learning–powered insights for various applications, including disaster response and early trendspotting.

— Considerable decrease of implementation costs for companies, aided by further E2E integration of data, hardware, software, and science-based methods would enable more enterprises to access the technology, integrating not only satellite data but also other relevant insights. For example, it can help in the sustainability field, with certifiable Scope 3 emissions calculations or certification needs.

In real life

Real-world examples involving the use of space technologies include the following:

— John Deere formed a commercial partnership with SpaceX's Starlink to bring D2D connectivity to its agricultural machinery. This will allow new features on new and existing machines, such as real-time data sharing, enhanced self-repair options (for example, connected support and software updates), and machine-to-machine communication for farmers in remote locations.[6]

— Qatar Airways announced that it will begin installing Starlink on select planes for passenger Wi-Fi. The company claims that customers will be able to achieve speeds of up to 350 megabits per second, which is faster than in many homes in North America.[7] Other airlines incorporating Starlink include JSX, Hawaiian Airlines, airBaltic, and ZIPAIR.

— India successfully landed its *Chandrayaan-3* lunar lander on the moon in August 2023. This makes India the fourth nation to successfully land a spacecraft on the moon[8] and the first to land on the unexplored south side.[9]

— With the *International Space Station* currently slated to be retired around late 2030, several commercial companies are vying to build and operate LEO space stations.

— The Australian government enlisted the geospatial-analytics company HawkEye 360 to use its remote-sensing satellites and radio-frequency data analytics on a pilot program to detect and prevent illegal and unregulated fishing activity in the Pacific Islands. HawkEye 360 operates a constellation of 21 satellites, with plans to expand to 60 satellites by 2025.[10]

— Nanosatellite start-up Fleet Space Technologies purchased equity in mineral exploration company Thor Energy after raising $33 million in its Series C round in mid-2023. Together, the companies will perform mineral exploration tests using Fleet Space's ExoSphere technology, which uses their satellites and seismic array technologies to create 3D models of mineral exploration sites.

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6 "John Deere announces strategic partnership with SpaceX to expand rural connectivity to farmers through satellite communications," John Deere press release, January 16, 2024.
7 "Qatar Airways selects Starlink to enhance in-flight experience with complimentary high-speed internet connectivity," Qatar Airways press release, October 13, 2023.
8 Nivedita Bhattacharjee, "Chandrayaan-3 spacecraft lands on the moon in 'victory cry of a new India,'" Reuters, August 23, 2023.
9 Jeffrey Kluger, "How India became the first country to reach the moon's south pole," *Time*, August 23, 2023.
10 "HawkEye 360 working with the Pacific Islands Forum Fisheries Agency for greater maritime visibility in the Pacific Islands," HawkEye 360 press release, July 6, 2023.

‘For so long, space has been fascinating yet far from reality. But now, it is one of the biggest influences on our daily lives—from guiding us on our daily commutes to facilitating disaster relief operations. Space technologies enable impact on Earth.’

– Giacomo Gatto, partner, London

Underlying technologies

Foundational space technologies include the following:

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

— *Remote sensing.* Full-spectrum imaging and monitoring are used to observe Earth’s features, such as oceanography, weather, and geology.

— *SWaP-C advancements.* Reductions in the size, weight, power, and cost (SWaP-C) of satellites and launch vehicles have increased the cost-effectiveness of space technology and associated use cases.

— *Launch technology advancements.* Technology advancements (for example, computer-aided design and material sciences), the reuse of booster structures and engines, the advent of new lower-cost heavy launch vehicles, and the increases in launch rates are opening access to space. We see potential for more advanced launch technologies, such as nuclear propulsion.

— *Advanced-connectivity technologies.* These technologies, including laser communications, electronically scanned antennas, and automated satellite operations, are expected to progress in the coming years.

Key uncertainties

The major uncertainties affecting the future of space technologies include the following:

— *Cost-effectiveness* of space technologies is required to enable further scalability.

— *Governance* mechanisms need to better define the allocation of spectrum and orbit usage rights to accommodate the increasing number of players, satellites, and applications.

— *Cyber risks,* including data breaches, malware, and other cyberattacks, are growing in number and complexity because of the proliferation of commercial players.

Big questions about the future

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

— How can leaders define ownership and access rights to space and space technologies?

— How can the industry build governance structures around key domains (for example, reducing unintentional interference, promoting safe operations, protecting property rights and usage, determining liability, and encouraging equitable data sharing)?

— How can stakeholders coordinate to manage space debris and traffic effectively?

— What will future satellite distribution look like (for example, balance across orbits)?

— How will the market evolve, given a variety of factors (macroeconomic, the push for E2E solutions, et cetera)?

— How will competition evolve, within the private-launch market?

— With increasing competition and the risk of interference and gridlock in spectrum usage, could the current spectrum allocation system endure?

A sustainable world

Electrification and renewables

The trend—and why it matters

Electrification and renewable-energy technologies are crucial for reducing global carbon emissions in accordance with the Paris Agreement. Achieving the agreement's goals requires a 45 percent reduction in global emissions by 2030 and net-zero emissions by 2050.[1]

Fortunately, many of the technologies required to achieve these reductions already exist today and encompass the entire value chain of energy production, storage, and distribution. These increasingly important solutions include renewable sources such as solar and wind power; clean firm-energy sources such as nuclear and hydrogen, sustainable fuels and bioenergy, and energy storage; and distribution solutions such as long-duration battery systems and smart grids.

The shift to clean energy will have far-reaching effects on both energy-producing and energy-intensive sectors, and it will require substantial investments in physical assets for energy and land-use systems. So far, the total investment in physical assets for energy and land-use systems is still well below the $9.2 trillion annual investment required to reach net zero by 2050.[2] While capacity, reliability constraints, and rising interest rates could slow the uptake of clean energy, growing capital spending can help accelerate adoption. Increased government support on infrastructure and permitting could likely accelerate adoption as well. As these technologies become more widespread, closing the talent gap will also be critical: McKinsey research estimates that climate technology value chains will require approximately 200 million skilled workers globally by 2050.[3]

1 "For a livable climate: Net-zero commitments must be backed by credible action," United Nations Environment Programme, November 2023.
2 Mekala Krishnan and Lola Woetzel, "Infrastructure for a net-zero economy: Transformation ahead," McKinsey, April 6, 2022.
3 "What would it take to scale critical climate technologies?," McKinsey, December 1, 2023.

A SUSTAINABLE WORLD

Electrification and renewables

Scoring the trend

The electrification and renewables trend had the highest investment and interest scores among all the trends we evaluated, with innovation scores close to the group average.[1] These positions align with the maturity and scaling of renewable technologies, particularly photovoltaic-solar and wind power. Moreover, they reflect the level of investment required to meet global net-zero pathways.

Adoption score, 2023

Frontier innovation → Fully scaled

Equity investment, 2023, $ billion

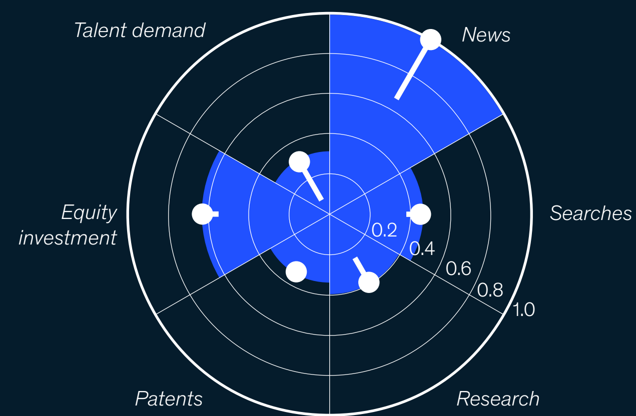
$183

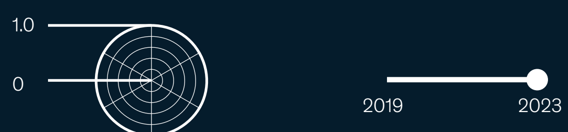
Job postings, 2022–23, % difference

+1%

Industries affected: *Agriculture; Automotive and assembly; Aviation, travel, and logistics; Chemicals; Construction and building materials; Electric power, natural gas, and utilities; Metals and mining; Oil and gas; Real estate*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

[1]PitchBook data for closed deals across all investment types, based on keywords (consistent with the *2022 Global Energy Perspective* report).

Latest developments in 2023

Recent developments involving electrification and renewables include the following:

— *Renewable generation grows amid challenges.* Despite high interest rates and an increased focus on energy security, particularly in Europe, 2023 was a record year for renewable-capacity installation. An estimated 50 percent more renewable-generation capacity (totaling 507 gigawatts) was added globally compared with 2022.[4] This rapid deployment was underscored at COP28, where countries committed to tripling renewable-energy capacity and doubling energy efficiency by 2030.[5] Utilities for Net Zero Alliance (UNEZA), an international platform for cooperation in power and utilities, confirmed the difficulty of achieving that goal without grid buildout. Further innovation, government support, and funding, particularly for emerging economies, will be necessary to continue the momentum toward global decarbonization by 2050, especially considering that emissions and gas consumption were at all-time highs in 2023.

— *Public sector support for hydrogen increases, but implementation still lags.* Green hydrogen remains an important piece of the clean-energy puzzle—for example, hydrogen is used in processes such as hydrocracking or hydrotreating at refineries. Recent incentives such as the US Clean Hydrogen Production Tax Credit, the EU Important Projects of Common European Interest, and the UK Low Carbon Hydrogen Agreement demonstrate growing interest in public sector support for advancing the green-hydrogen ecosystem and ultimately allow for economies of scale despite existing cost barriers.[6] Despite the new incentives, private sector hydrogen adoption remains relatively small, with only 1.0 percent of global production (and 0.7 percent of demand in existing applications) coming from low-emission hydrogen.[7] Factors contributing to slow adoption include the challenge to balance clean-hydrogen production with the growing demand for power, the high-interest-rate environment, and incentives that mainly target new applications instead of scaling existing uses.

— *Global battery storage capacity is scaling rapidly.* In 2023, lithium-ion battery pack prices dropped by 14 percent and are expected to decline further in 2024, with demand for mobile and stationary battery storage increasing by more than 50 percent year over year.[8] McKinsey analysis projects that demand for lithium-ion batteries will scale up to six times to 4,700 gigawatt-hours by 2030, with mobility applications encompassing a vast majority of the market.[9] Established policy incentives, including Europe's Fit for 55 program, the US Inflation Reduction Act, the European Union's 2035 ban on internal-combustion-engine vehicles, and India's scheme for faster adoption and manufacture of hybrid vehicles and electric vehicles (EVs), demonstrate public sector interest in continued EV adoption. However, widespread adoption of EVs will likely hinge on the expansion of charging infrastructure, as well as improvements in mileage and performance. Innovations such as solid-state batteries, which promise significant enhancements, are still years away from commercialization.

— *Policy incentives look to spur stalled heat pump adoption.* In 2023, global heat pump installations declined (approximately 3 percent) from their peak at 111 gigawatts in 2022,[10] with a 17 percent decline in the United States alone.[11] While studies have shown that heat pumps can drive long-run cost and energy savings for residential applications, high installation costs and variable natural gas prices have created a hesitancy in further consumer adoption.[12] However, existing subsidies for heat pump installation throughout the European Union[13] and new tax credits in 2023–24 through the US Inflation Reduction Act[14] could look to reinvigorate demand.

4 Johnny Wood, "Energy transition: The world added 50% more renewable capacity last year than in 2022," World Economic Forum, February 8, 2024.
5 *A world energy transitions outlook brief: Tracking COP28 outcomes: Tripling renewable power capacity by 2030*, International Renewable Energy Agency, March 2024.
6 "Global Hydrogen Review 2023: Executive summary: Low-emission hydrogen production can grow massively by 2030 but cost challenges are hampering deployment," International Energy Agency, 2023.
7 Ibid.
8 "Lithium-ion battery pack prices hit record low of $139/kWh," BloombergNEF, November 26, 2023.
9 Kersten Heineke, Philipp Kampshoff, and Timo Möller, "Spotlight on mobility trends," McKinsey, March 12, 2024.
10 "Executive summary: Heating is a fundamental service to society that needs to be decarbonised further" in *The future of heat pumps in China*, International Energy Agency, 2024.
11 Casey Crownhart, "This chart shows why heat pumps are still hot in the US: Sales slowed in 2023, but heat pumps are gaining ground on fossil fuels," *MIT Technology Review*, February 12, 2024.
12 "Benefits of heat pumps detailed in new NREL report: Millions of homes can benefit today, but installation costs keep technology out of reach for some," National Renewable Energy Laboratory news release, February 12, 2024.
13 *Subsidies for residential heat pumps in Europe*, European Heat Pump Association, April 2023.
14 "This chart shows why heat pumps are still hot in the US," *MIT Technology Review*, 2024.

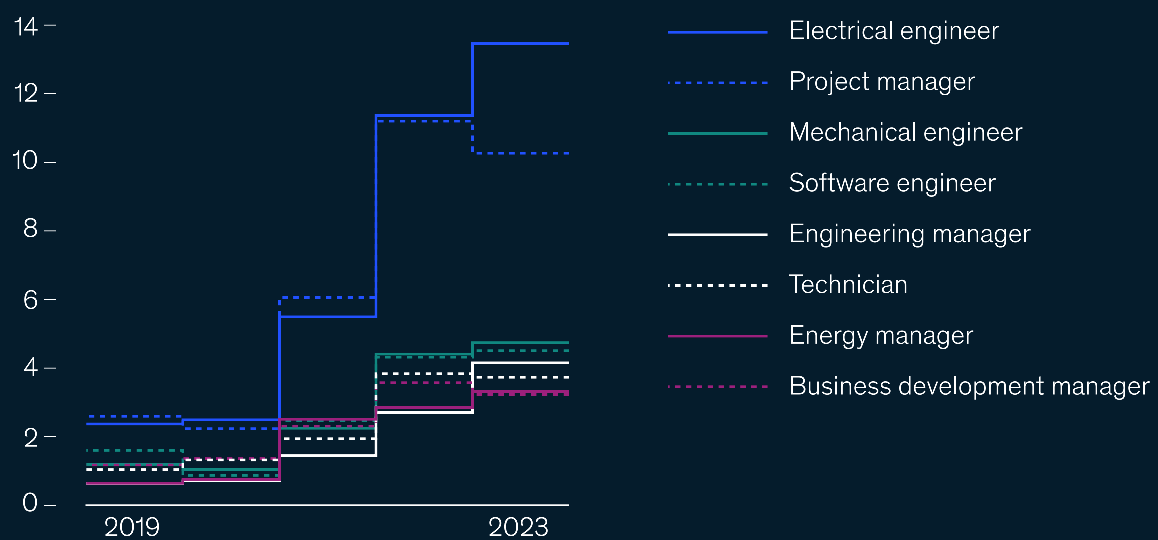
Talent and labor markets

Electrification and renewables

Demand

Between 2019 and 2022, electrification and renewable-energy technologies saw tremendous growth, withjob postings increasing more than 250 percent (37 percent CAGR). The trend also demonstrated a noteworthy lack of cyclicality, as job postings increased approximately 1 percent between 2022 and 2023, compared with the average 26 percent reduction across all trends over the same period. This growth coincides with public sector incentives that have allocated capital toward infrastructure improvements.

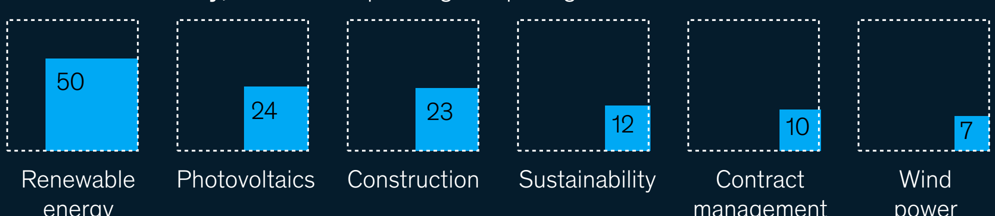
Job postings by title, 2019–23, thousands



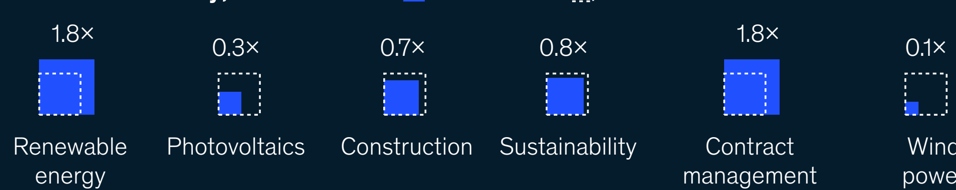
Skills availability

There is a broad shortage of experienced talent throughout electrification and renewable-energy technologies, with gaps for professionals with deep knowledge of specific renewable technologies (for example, photovoltaics and wind power) and installation (for instance, construction). To scale electrification and renewable-energy technologies to meet global decarbonization timelines, the supply of experienced construction and maintenance professionals will need to increase in line with projected clean-energy capacity demand.

Talent availability, % share of postings requiring skill



Talent availability,[1] ratio of talent to demand



[1]The ratio of talent supply to demand is based on skills listed in McKinsey's Organization Data Platform (ODP) job postings compared with LinkedIn users' skills, filtered by a set of keywords specific to each trend.

Adoption developments across the globe

More than 40 percent of survey respondents self-reported that they already are piloting, are scaling, or have fully scaled their electrification and renewable-energy technologies. Energy and materials and technology companies showed the greatest adoption across industries, indicating the significant impact electrification and renewables will have throughout the energy value chain.

Adoption dimensions

Advancements along the following dimensions could enable the next level of adoption:

— Further adoption of electrification and renewable-energy technologies depends on reducing costs, which can be achieved through tech advances and investments to scale. Material efficiency will then become more relevant, since the supply of materials such as lithium, steel, and copper could become constraints if the speed of low-carbon energy generation increases to the levels required to keep pace with global net-zero commitments.

— The future energy mix may involve ramping up infrastructure development for production of emerging technologies such as green hydrogen, batteries, and sustainable fuels.

— Accelerating innovation and investment in infrastructure for power transmission and distribution, battery storage, EV charging, and smart-grid load management can facilitate the clean-energy transition. Streamlined permitting processes can reduce project lead times and facilitate rapid scale-up.

— Deploying electrification and renewable-energy technologies at the speed and scale required for global decarbonization commitments could be achieved through a step-change increase in the supply of clean-energy technology professionals.

— Cross-regional collaboration can help harmonize standards, accelerate the global adoption of renewable-energy technologies, and align on global energy security policies.

In real life

Real-world examples involving the use of electrification and renewables include the following:

— Aira is a Swedish-founded, UK-based clean-energy technology company disrupting the European heat pump market with a vertically integrated, subscription-based business model. The company overcomes consumer concerns about navigating complex regulation and high installation costs by providing end-to-end customer support through home energy assessments, grant application assistance, installation, and lifetime system maintenance while spreading up-front costs over monthly installments. Aira heat pumps can be fully controlled using the Aira app and deliver significant energy and cost savings. Over the next ten years, the company has set the goal of serving five million homes with its clean-energy technology solutions.

— EV OEMs are forming strategic partnerships to be at the forefront of battery technology. Stellantis has made an investment in Lyten to accelerate the commercialization of 3D Graphene applications to lithium–sulfur EV battery technology. The technology produces lithium–sulfur batteries without using nickel, cobalt, or manganese, which could potentially result in an estimated 60 percent lower carbon footprint than current best-in-class batteries.[15] The rate of innovation for lithium–graphene batteries is spurred by a rapid increase in related patent filings.[16] Adoption potential is significantly boosted by anticipated decreases in graphene costs as production scales up, making these advanced batteries more economically viable for broader markets.

— Cloud hyperscalers are investing heavily in renewable energy. For example, Amazon directly invested in more than 100 new renewable-energy projects in 2023, increasing its total portfolio to over 500 projects globally, with a total installed generation capacity of more than 77,000 gigawatt-hours per year.[17]

[15] "Stellantis invests in Lyten's breakthrough lithium–sulfur EV battery technology," Stellantis press release, May 25, 2023.
[16] Oliver Gordon, "Graphene is set to disrupt the EV battery market," Energy Monitor, February 5, 2024.
[17] "Amazon is the world's largest corporate purchaser of renewable energy for the fourth year in a row," Amazon press release, January 16, 2024.

Underlying technologies

Foundational technologies in electrification and renewables include the following:

— *Batteries.* These devices store chemical energy and convert it into electricity. They are applicable to traditional energy sources as well as renewables such as wind and solar.

— *Heat pumps.* These devices extract heat from a source (that is, from air, ground, or water) and transfer that heat from evaporator to condenser, proving to be 2.0 to 4.5 times more efficient than a traditional furnace or boiler.[18] They also function as air conditioners, transferring heat from internal spaces to outside.

— *Energy storage.* These technologies, including batteries, capture energy from various sources, such as electrochemical, thermal, mechanical, and chemical systems, to be used later.[19]

— *Nuclear fission.* Nuclear fission, the process of splitting large atoms to create energy, is a proven zero-carbon power source. Concerns about accidents and radioactive waste persist. However, the growing demand for clean energy is reinvigorating efforts to expand nuclear power capabilities. (There is also growing interest in nuclear fusion, the process of combining small atoms to produce energy, but significant technical challenges remain to be solved.)

— *Renewables.* These are energy sources produced by natural power resources. New technologies such as advanced solar photovoltaics and both onshore and offshore wind turbines are driving significant growth from traditional renewable sources.

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

— *Sustainable fuels.* These are fuel alternatives to traditional fossil hydrocarbon fuels, including both low-carbon fuels and fuels derived from natural or alternative feedstock (for example, biomass, hydrogen, e-ammonia, and e-methanol-based fuels).

Opportunities to leverage other tech trends with electrification and renewables technologies include the following:

— *Future of mobility.* There are expanded applications of electrification and renewables in transportation; for example, innovative battery technologies can transform micromobility applications.

— *Applied AI.* Real-time smart-grid monitoring enables dynamic energy pricing models and more efficient charging.

— *Industrialized machine learning.* Predicting green-hydrogen production potential from organic waste can enhance efficacy and yield.

— *Immersive reality.* Blueprints combined with augmented reality headsets could allow heat pump installers to see necessary ductwork changes and installation steps.

'The technologies that enable the transition to clean energy are critical to delivering approximately 50 percent of the required solution for net zero. Acceleration of these technologies is critically important. Above all, we need ambition to accelerate the transition.'

– Mark Patel, senior partner, Bay Area

[18] "How a heat pump works," in *The future of heat pumps*, International Energy Agency, December 2022.
[19] "Energy storage: How it works and its role in an equitable clean energy future," Union of Concerned Scientists, October 4, 2021.

Key uncertainties affecting the trend

The major uncertainties affecting electrification and renewables include the following:

— *Concerns exist about the high costs* of scaling renewables, generating clean firm power, and supporting infrastructure.

— *Balancing necessary transmission and distribution investments with uncertain adoption timelines* for EVs, heat pumps, and other electrification technology could create challenges for efficient capital deployment.

— *Government climate policies and regulation* can dramatically alter the timeline of climate technology adoption.

— *Reskilling and transitioning skilled labor from legacy industries to electrification and renewables* will be a massive workforce challenge but could also present an incredible opportunity for inclusive job growth around the world.

Big questions about the future

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

— How will innovations in battery storage technology influence the adoption of EVs and renewable assets?

— How can public–private stakeholders collaborate to manage existing and emerging energy systems in parallel while ensuring energy security and grid stability?

— How will regions and organizations leverage the new comparative advantages brought on by an electrified world while increasing energy access and ensuring job security for employees of legacy industries?

— How will the power sector increase the talent pool of workers with skills specific to electrification and renewable-energy technology?

— Will emerging economies choose to supply growing populations with clean energy despite existing infrastructure hurdles[20] and cost competition from hydrocarbons?[21]

‘Scaling renewables and electrification technologies requires cost reductions, substantial investments, and talent. Despite challenges, 2023 marked significant strides in renewables, battery storage, and hydrogen support. However, cost competitiveness, raw materials, manufacturing capacity, labor transition, and infrastructure remain hurdles to leaping ahead.’

– Sebastian Mayer, partner, Munich

[20] Gracelin Baskaran and Sophie Coste, “Achieving universal energy access in Africa amid global decarbonization,” Center for Strategic & International Studies, January 31, 2024.
[21] Carl Greenfield, “Energy system: Fossil fuels: Coal,” International Energy Agency, March 26, 2024.

Climate technologies beyond electrification and renewables

The trend—and why it matters

Climate technologies beyond electrification and renewables cover technologies related to circularity and resources and carbon capture and removal. The production of sustainable goods and services can support companies in terms of complying with emerging regulations, creating growth opportunities, and attracting talent. While many technologies that mitigate the environmental impact of consumption are technically viable, few have become cost-effective enough—or have overcome other hurdles, such as labor upskilling and funding—to achieve mass scale. The scope of the challenge is also unprecedented: according to some estimates, an additional removal capacity of 0.8 to 2.9 metric gigatons of CO_2 per year is required by 2030 (to be on the pathway to net-zero emissions by 2050)—three to ten times more than the volumes currently estimated to be onstream by that date.[1] However, opportunities for innovators to capture value through scale are apparent, since a carbon removal market capable of enabling gigaton-scale removals at net-zero levels could be worth up to $1.2 trillion by 2050.[2] To close the gap between aspirations and commitments, a step change in investment equal to about 0.1 percent of global annual GDP (about $120 billion) could be necessary.[3]

[1] *Carbon removals: How to scale a new gigaton industry*, McKinsey, December 4, 2023.
[2] Ibid.
[3] “Global Energy Perspective 2023: CCUS outlook,” McKinsey, January 24, 2024.

A SUSTAINABLE WORLD

Climate technologies beyond electrification and renewables

Scoring the trend

Despite a decline in private investment since 2021, the investment score for climate technologies beyond electrification and renewables remains above average compared with other tech trends, which highlights the importance of climate solutions in mitigating the challenges brought on by climate change.[1] Interest and innovation have maintained their momentum of increasing scores year over year, with a slower pace of innovation being indicative of how the capital intensity of and long development timelines for new projects are creating challenges for scaling technologies.

Adoption score, 2023

Frontier innovation → Fully scaled

Equity investment, 2023,
$ billion

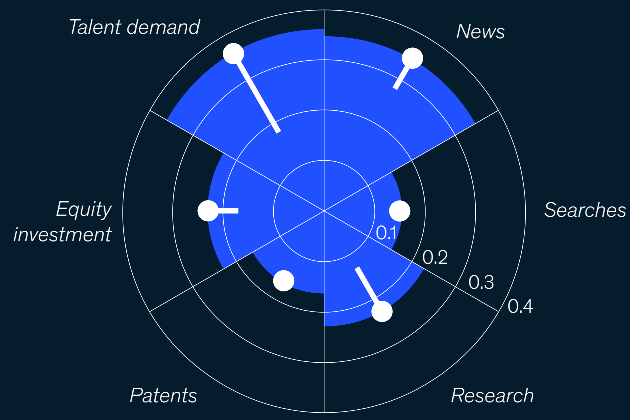
$68

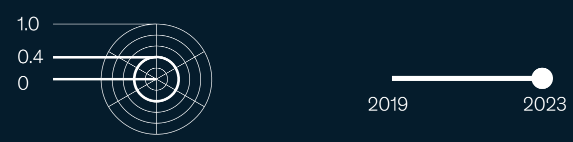
Job postings, 2022–23,
% difference

–11%

Industries affected: *Agriculture; Automotive and assembly; Aviation, travel, and logistics; Chemicals; Construction and building materials; Electric power, natural gas, and utilities; Metals and mining; Oil and gas; Real estate*

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





Talent demand Ratio of skilled people to job vacancies

News Press reports featuring trend-related phrases

Equity investment Private- and public-market capital raises for relevant technologies

Searches Search engine queries for terms related to trend

Patents Patent filings for technologies related to trend

Research Scientific publications on topics associated with trend

[1] PitchBook data for closed deals across all investment types, based on keywords (consistent with 2023 report).

Latest developments in 2023

Recent developments involving climate technologies beyond electrification and renewables include the following:

— *Companies are expanding their commitments.* This is evidenced by a moderate increase in targets across various dimensions and a more notable surge in corporate climate commitments. Currently, about 80 percent of companies in the Fortune Global 500 have set carbon reduction targets. Beyond carbon, the dimensions attracting the most attention include water, chemicals and plastic, biodiversity, and forests. The year 2023 witnessed a 30 percent year-over-year increase in the number of companies setting targets in three or more dimensions of nature (for example, air, water, land).[4] Europe has the greatest share of companies with nature targets, likely galvanized by a set of nature-related regulations, including the Corporate Sustainability Reporting Directive, EU Deforestation Regulation, and—most recently—the EU Nature Restoration Law. Similar public sector action in other regions could encourage companies in all sectors to implement nature-positive levers with opportunities for an annual net benefit of up to $700 billion.[5]

— *The adoption of agriculture technology (agtech) solutions for sustainable farming is growing, though penetration is currently relatively low.* While sustainable agricultural practices that require behavior change (such as cover crops and afforestation of degraded cropland) have the highest adoption, practices that leverage technology and require a product or equipment change are not adopted at full scale yet, according to the latest US farmer survey.[6] However, we see advances in these agtech solutions. For example, variable-rate fertilizer applications (VRA) benefit from advances in AI to generate high-precision VRA maps to account for field variability. This can help reduce the amount of fertilizer applied, which, in turn, reduces greenhouse gas emissions caused by excess nitrogen. Similarly, weed control robots are advancing and allow for the reduction of tillage and herbicide applications, which benefits carbon sequestration and reduces water pollution. Satellite-enabled remote-sensing technologies help to assess reduced tillage, sustainable practices for cover crops, and plant health. Further adoption of these technologies requires helping farmers overcome operational challenges and the risks that new technologies might entail—for example, through insurance and the promotion of potential yield, cost, and revenue benefits (such as carbon credits).

— *Public sector support for carbon management initiatives is increasing.* Government agencies across the globe are leveraging a number of instruments, including grants, regulations, and tax breaks, to support the development and adoption of carbon management technologies. For example, in addition to other investments, the US Department of Energy recently awarded $13 million in funding to 23 projects focused on R&D in carbon capture through the Office of Fossil Energy and Carbon Management.[7] This funding aims to support innovative solutions and advancements in carbon capture technologies. Furthermore, the US Department of Energy has allocated up to $1.2 billion, through the Office of Clean Energy Demonstrations, to support two direct air capture (DAC) projects in Louisiana and Texas.[8] These DAC hubs could play a crucial role in developing and demonstrating large-scale carbon removal technologies. These initiatives from the Department of Energy may indicate a significant focus on addressing carbon management challenges and accelerating the development of sustainable solutions in the fight against climate change.

— *Carbon capture, utilization, and storage (CCUS) has seen a step change in interest.* In the past year, the global CCUS market has seen a step change in interest. If all announced projects in the pipeline are realized by 2030, current capacity could increase by 12 times.[9] However, many of these projects still need confirmed funding and final decisions on executing the buildout. This projected increase in interest coincides with a proliferation of CCUS start-ups, new technologies, and private sector interest in forward agreements and long-term carbon offtakes. These agreements allow developers to finance CCUS infrastructure more easily, since they can demonstrate proof of an existing customer base prior to construction. Such market dynamics are encouraging signs for global net-zero ambitions, considering the expectation that CCUS capacity needs are expected to increase by over 100 times by 2050.

4 "Companies are broadening their commitments to nature beyond carbon," McKinsey, December 8, 2023.
5 *Nature in the balance: What companies can do to restore natural capital*, McKinsey, December 5, 2022.
6 "Voice of the US farmer 2023–24: Farmers seek path to scale sustainably," McKinsey, April 9, 2024.
7 "DOE invests over $13 million for projects that capture carbon emissions from industrial facilities, power plants, air, and oceans," Office of Fossil Energy and Carbon Management, August 9, 2023.
8 "Biden-Harris administration announces up to $1.2 billion for nation's first direct air capture demonstrations in Texas and Louisiana," US Department of Energy, August 11, 2023.
9 "Global Energy Perspective 2023," January 24, 2024.

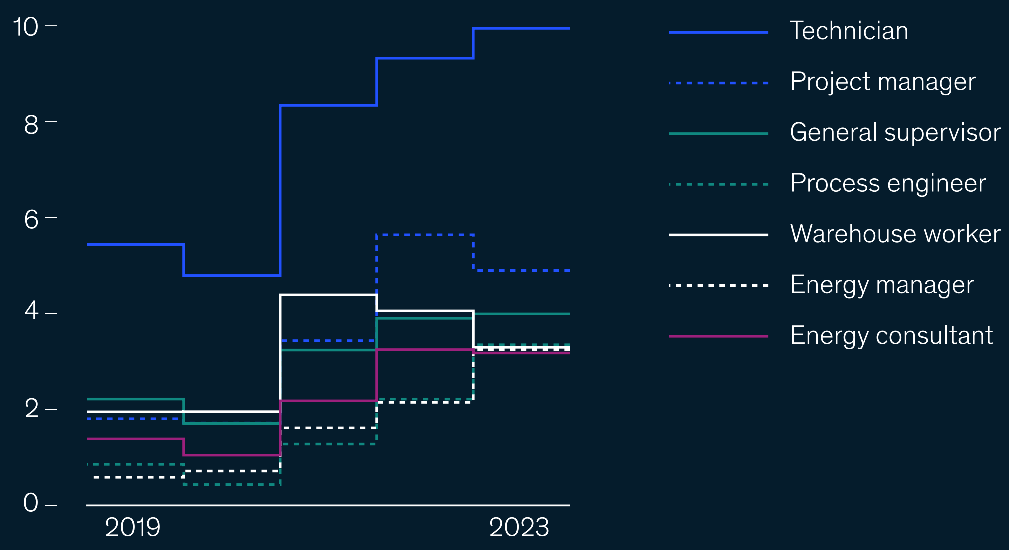
Talent and labor markets

Climate technologies beyond electrification and renewables

Demand

Between 2019 and 2022, climate technologies beyond electrification and renewables saw significant growth, with job postings increasing by over 96 percent (25 percent CAGR). Climate technology jobs were also less affected by macroeconomic conditions, as they declined by only 11 percent from 2022 to 2023, compared with the average 26 percent reduction across all trends over the same period. This relatively strong labor demand is supported by significant public sector incentives, such as the Inflation Reduction Act, and initiatives like the European Union's Net-Zero Industry Act, providing increased public sector support for the reduction of greenhouse gas emissions and for sustainable production methods.

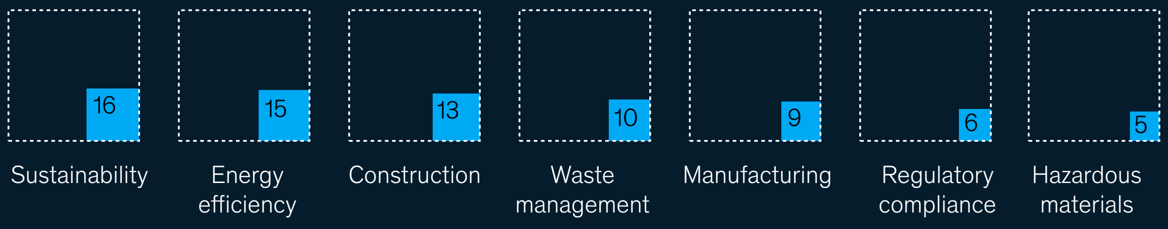
Job postings by title, 2019–23, thousands



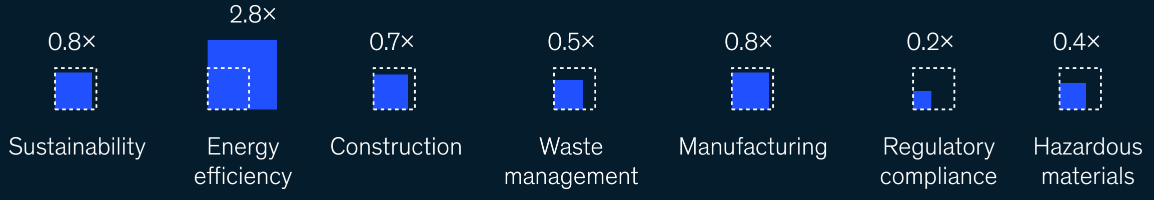
Skills availability

Climate technologies beyond electrification and renewables face shortages of workers with industry-specific and manufacturing or construction skills. To meet global net-zero timelines, the supply of skilled workers with climate-tech-specific skills will need to scale in line with the overall trend.

Talent availability, % share of postings requiring skill



Talent availability, ratio of talent to demand



Adoption developments across the globe

Adoption levels for climate technologies beyond electrification and renewables currently sit in the middle of all our trends, with over 50 percent of companies reporting they have invested in the trend. As these technologies move down the cost curve, adoption is expected to increase. Respondents from energy and materials companies self-reported the greatest level of progress toward scaling capabilities, given the high relevance of circular-technology applications and carbon management to several industries within the sector.

Adoption dimensions

Climate technologies beyond electrification and renewables are diverse, each having unique development timelines and use cases. The adoption trajectory for advanced technologies will look different for each technology and each use case within that technology. Advancements along the following dimensions could enable the next level of adoption for these technologies:

— scaling of circular technologies, which require collaboration across the supply chain to administer collection, recycling, and reintroduction into the value chain

— regulatory clarity to promote investor and consumer confidence in alternative proteins and near-term innovation to maximize flavor and decrease costs for the many emerging alternatives that are still at the precommercial stage

— increased trust in and broader recognition of carbon abatement and removal schemes, including increased valuation of the environmental and human health cobenefits from nature-based carbon removal

— lower unit costs for measurable carbon abatement and removal projects, as well as for products and materials with low-carbon equivalents

— accelerated deployment of carbon capture and storage technologies to be achieved by enhancing funding, research, and international collaborations to improve feasibility and scalability

— pursuing net-zero or nature-positive operations over an extended time horizon, which requires an enduring ambition

In real life

Real-world examples involving the use of climate technologies beyond electrification and renewables include the following:

— The circularity solution led by Schneider Electric, a digital automation and energy management company, shows an example of how end-to-end operations can be set up in a circular approach. Through ecodesign, waste-to-resources sites, and a global network of refurbishment centers, this IoT-enabled architecture and platform has helped its customers to avoid more than 500 million metric tons of CO_2 since 2018 and to use 27 percent green material content across products.[10]

— A group of investors, including Equinor and TotalEnergies, partnered on the first phase of the Northern Lights project, a first-of-its-kind carbon capture and storage infrastructure open to third-party industrial emitters. The program will facilitate the transportation and permanent storage of liquefied CO_2 from the European continent to the reservoirs beneath the North Sea. Infrastructure completion and initial deliveries are on track for 2024.[11]

— Running Tide is an ocean health company that processes, quantifies, and provides carbon credits through ocean-based, natural climate solutions. The company uses two main carbon sequestration techniques—terrestrial biomass sinking and ocean alkalinity enhancement—to capture and store oceanic carbon. It then quantifies carbon removal, using in situ measurements, lab testing, and sophisticated ocean models to offer accredited carbon credits with high confidence in sequestration permanence. To date, the company has removed over 25,000 metric tons of CO_2 equivalent and sold about 22,000 carbon credits.[12]

— Among other agricultural and food companies, Cargill expanded its existing sustainable agriculture program, Cargill RegenConnect, to four European countries (France, Germany, Poland, and Romania). The program pays farmers to adopt agricultural techniques that pull carbon from the atmosphere into the soil—such as cover cropping and no-till farming—based on the market rate per ton of carbon sequestered in their soil and helps them leverage remote sensing and crop and soil health monitoring. It also helps connect farmers

[10] “Circular economy: How ‘lighthouses’ in the built environment can drive value,” World Economic Forum, January 15, 2024.
[11] “What we do,” Northern Lights, accessed May 31, 2024.
[12] “Carbon credits,” Running Tide, accessed May 31, 2024.

to other members of the downstream supply chain and provides training and mentorship on sustainable-farming techniques through agronomic experts. Cargill is committed to supporting farmer-led regenerative agriculture on ten million acres of farmland by 2030.[13]

Underlying technologies

There are varieties of climate technologies beyond electrification and renewables:

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

— *Natural climate solutions.* Nature-based projects can remove carbon or prevent emissions from being produced. Those can include terrestrial ecosystems (for example, afforestation), peatland restoration, fire management, and agricultural management (such as through optimizing grazing pathways and cover crops).

— *Alternative proteins.* These proteins can be produced from natural sources with significantly fewer emissions than animal proteins. These sources include plants (for instance, soybeans, wheat), microorganisms (such as through microbial fermentation), and cultivated animal cells.

— *CCUS.* CO_2 can be captured—before being emitted into the atmosphere—typically directly from the point of production, such as at industrial facilities and power plants that use fossil fuels. The utilization of CO_2 and its sale as a product offer a revenue source to offset the cost of capture. One of the primary uses of CO_2 today is enhanced oil recovery; other uses also are gaining momentum.[14]

— *Engineered carbon removal.* Various technologies can remove atmospheric CO_2, including direct air capture and storage, bioenergy carbon capture and storage, biochar and bio-oil, and enhanced weathering.

Opportunities for the integration of climate technologies beyond electrification and renewables with other tech trends include the following:

— *Applied AI.* AI technologies can be used to increase the efficacy and efficiency of carbon capture systems.

— *Advanced connectivity.* Advanced connectivity can improve real-time crop monitoring and automated micro-irrigation.

— *Future of bioengineering.* Bioengineering can help in the development of genetically modified varieties of trees, crops, and seaweed that absorb more carbon with fewer inputs.

— *Future of space technologies.* More advanced satellites can monitor CO_2 concentrations and soil and ocean health and validate, quantify, and authenticate carbon management schemes.

‘Carbon management technologies to reduce and remove carbon from the atmosphere will be an essential part of the world’s journey to net zero. Creating a gigaton-carbon-management industry in a few short decades to meet the climatic need presents an enormous challenge and an exciting opportunity for innovators, investors, and policy makers alike.’

– Emma Parry, partner and global colead of carbon management service line, London

[13] “Digging in: Cargill’s regenerative agriculture program brings healthier soil and profits to more European, U.S. farmers,” Cargill, May 23, 2023.
[14] “Scaling the CCUS industry to achieve net-zero emissions,” McKinsey, October 28, 2022.

Key uncertainties affecting the trend

The major uncertainties affecting climate technologies beyond electrification and renewables include the following:

— *Public sector incentives* such as potential policies and regulations could be pivotal in shaping investment decisions, business case viability, and public reactions to carbon management schemes.

— *Natural-capital valuation* through different carbon management incentive structures allows organizations to apply varying valuations for the cobenefits of natural-capital solutions, relative to pure CO_2 removal.

— *Coordination throughout the value chain* could be a challenge, as scaling carbon abatement and removal infrastructure is time and capital intensive. The need for coordination between public and private stakeholders at the local level could be an additional obstacle.

— *Standardization of the carbon market* could prove difficult, as it is unclear how recent commitments by independent carbon credit standards to enhance transparency and consistency will affect trust in carbon management schemes to follow through on promises.

Big questions about the future

Companies and leaders may want to consider a few questions when moving forward with climate technologies beyond electrification and renewables:

— How will carbon management schemes overcome potential bottlenecks (for instance, raw materials, land, and infrastructure) as R&D, experience, and economies of scale help propel adoption?

— How will debates about the efficacy of nature-based carbon removals compared with technology-based carbon removals affect investment decisions and public perception?

— Can innovations in CCUS technologies lead to significant cost reductions and expanded use cases?

— Can independent carbon credit agencies successfully meet certification criteria and increase scoring transparency to build trust and reliability in the voluntary carbon market?

— How will consumers react to the continued innovations in alternative proteins?

‘Nature is the technology that we have available today for the next critical decade and can help solve the net-zero equation. If you want to think about a cost-effective way of capturing carbon or avoiding carbon loss today, it is through natural systems. And nature’s import goes far beyond its role in the climate: let’s not forget we are dependent on it for our lives and livelihoods.’

– Joshua Katz, partner, Stamford