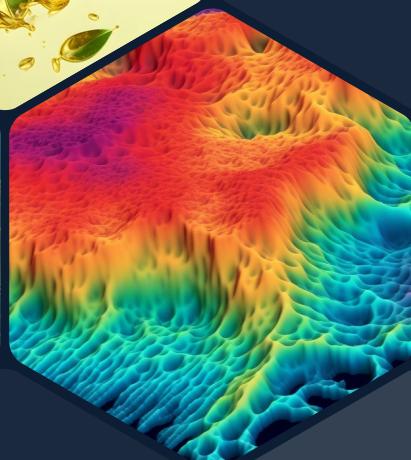
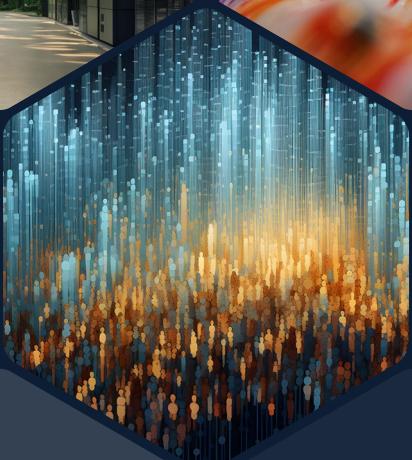
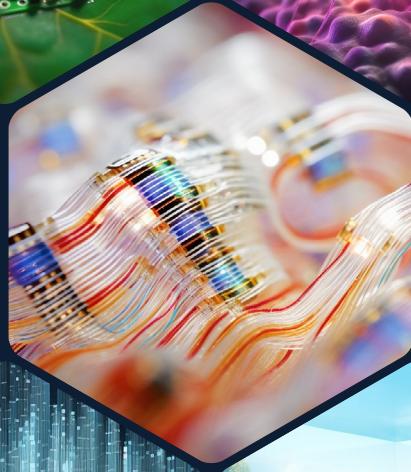


Top 10 Emerging Technologies of 2023

FLAGSHIP REPORT
JUNE 2023



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Preface



Jeremy Jurgens
Managing Director,
World Economic Forum

For more than a decade, the Forum has been surveying academics, industry leaders and futurists on the emerging technologies set to transform economies and societies. In doing so, the *Top 10 Emerging Technologies of 2023* report seeks to help professionals across sectors and industries anticipate exponential technologies, interpret their implications and champion industry-shaping and society-serving applications.

Since the first edition in 2011, the annual report has identified little-known technologies that have gone on to have global impact. For example, the precise genetic-engineering tool, CRISPR-Cas9, featured in 2015, went on to become Nobel Prize-winning science five years later and is now being used to create insect and drought-resistant crops in harsh growing conditions around the world. Messenger ribonucleic acid (mRNA) vaccines, which earned their place in the 2017 report, became the technology underpinning the majority of COVID-19 vaccines protecting lives worldwide. In the few years since AI-led molecular design made it onto the 2018 list, Deepmind's AlphaFold has predicted the structure of 200 million proteins, and the first AI-discovered drugs have entered clinical trials.

Now in its 11th year, the *Top 10 Emerging Technologies of 2023* report outlines the technologies poised to positively impact society in the next three to five years. The report broadens its scope beyond describing the top 10 technologies and associated risks and opportunities to include a qualitative assessment of how each technology is set to impact people, the planet, prosperity, industry and equity. Unique for each technology, these “impact fingerprints” are meant to stimulate further analysis and debate about how emerging

technologies – some of which you might never have heard of – can and will shape our collective future in the years ahead. Also new for the 2023 edition is a collection of transformation maps from the Forum’s Strategic Intelligence Platform, which provide deeper insights and context on each technology by showcasing how they connect to other topics on the global agenda and surfacing the latest trusted publications for further reading.

This year’s report brings together the perspectives of over 90 experts in 20 countries from all world regions. This report would not be possible without their openness to contributing their insights, and we sincerely thank them all. We greatly appreciate, too, the leadership of our Top 10 Emerging Technologies Steering Group Co-Chairs, Mariette DiChristina and Bernard Meyerson, who, along with many members, have been loyal collaborators since the inception of the Top 10 Emerging Technologies report series. We would additionally like to thank our knowledge partner for this year’s edition, Frontiers, for the deep expertise and scientific rigour of their journal editors – across the articles, impact fingerprints and transformation maps. Our thanks also to the project team: Greta Keenan, Saemoon Yoon, Minji Sung and Sebastian Buckup, as well as the wider team at the Centre for the Fourth Industrial Revolution for their input.

New technologies have the power to disrupt industries, grow economies, improve lives and safeguard the planet – if designed, scaled and deployed responsibly. We hope that this year’s report serves as a powerful tool for business leaders and policy-makers to unlock the transformative potential of emerging technologies and shape their inclusive adoption.

Introduction

A message from the Co-Chairs of the Top 10 Emerging Technologies report steering committee.



Mariette DiChristina
Dean and Professor of the Practice in Journalism,
Boston University College of Communication



Bernard Meyerson
Chief Innovation Officer
Emeritus, IBM

In the [introduction](#) of his 2016 book, *The Fourth Industrial Revolution*, Klaus Schwab advised that humanity should “take dramatic technological change as an invitation to reflect about who we are and how we see the world”. The *Top 10 Emerging Technologies of 2023* report is an ongoing response to that invitation to improve the state of the world and the humans inhabiting it. The driving forces behind the innovations featured in this special report are the acceleration of global connectivity, the rise of AI, along with the convergence of the physical, digital and biological worlds.

Consistent with the Fourth Industrial Revolution, several of the technologies cited use data and computing to enhance public health. The list explores how AI is enabling improvements in healthcare delivery, especially to those who live in less well-resourced areas; how flexible batteries are powering wearable technologies and bendable displays that enable wearable medical devices and biomedical sensors; and next-generation neural electronics that can interact with millions of cells at once more safely. With mental health issues more pressing in the post-pandemic world, virtual shared spaces in the metaverse are facilitating global outreach to serve those in need.

In this report, you’ll learn about how spatial omics is creating a new generation of molecular-level “cell atlases” to help unlock life’s mysteries. In a new approach to treatment, researchers are engineering viruses, called phages, to augment human, animal and plant health.

Beyond the understanding and treatment of disease, the rapid public emergence of artificial intelligence (AI) shows a potential to vastly enhance access to and implementation of human knowledge. Generative AI, embodied in ChatGPT and Bard, has demonstrated the creation of original social and technical content in seconds. Those abilities developed from models trained on vast information content ingested from the web. It is, however, important to be cognizant of the societal issues created by these “super-human” capabilities.

Human well-being also ultimately requires a healthy planet. Addressing this need, the “top 10” includes wearable plant sensors, which enable increased food production by improving plant health. With the impact of climate change ever-more dire, two cited innovations offer progress: sustainable aviation fuel, made from biological or non-biological sources, and sustainable computing, which is paving the way towards net-zero carbon data centres. However, far more innovation is required to mitigate this existential threat to humanity.

Methodology

Choosing the top 10 list for 2023

Technologies for consideration for the 2023 list were collected via a survey distributed to the steering group and wider expert network, as well as the World Economic Forum's Innovator Communities from December 2022 to January 2023. Survey respondents were asked to complete the following fields:

- Technology name
- Description of the technology
- Fields impacted by the technology
- Description of the impact of the technology on these fields, including benefits and risks to society
- Justification for why the technology should be on the 2023 list.

The 95 valid technology nominations were reviewed, debated and ranked by the steering group over the course of three meetings between January and February 2023, eventually whittling the list down to the final 10 based on the judging criteria:

- **Novelty:** the technology is emerging and at an early stage of incipient development, not already widely used.
- **Applicability:** has the potential to be of significant use and benefit to societies and economies in the future; is not of only marginal concern.
- **Depth:** is being developed by more than one company and is the focus of increasing investment interest and excitement within the expert community; likely to have a significant impact in the next 3-5 years.
- **Power:** is potentially powerful and disruptive in altering established ways and industries.

Members of the steering group volunteered to author the articles in the report, consulting specialists in their networks for added input. All articles were fact-checked and edited by Frontiers.

“Impact fingerprint”

The content of the *Top 10 Emerging Technologies of 2023* report is built upon the contributions of experts from academia and industry. The methodology of this edition is based on the previous 10 editions but incorporates “impact fingerprint” survey data for the first time.

To achieve this, expert groups of academics and industry leaders were curated for each of the 10 technologies listed in the 2023 report. They were then asked to predict the future impact of their respective technology, rating the projected influence on a scale from 1 to 10, should these technologies achieve widespread adoption in the next 3-5 years. The survey aimed to assess the potential effect of these technologies across five distinct metrics:

A. People

Participants rated their expectations regarding each technology's potential to enhance security and dignity—spanning areas such as food security, access to clean water, and improvements in healthcare outcomes—over the next decade.

B. Planet

Participants gauged the extent to which they envisage the technologies could help protect and restore our planet. This included considerations such as restoring biodiversity, minimizing waste, and reducing greenhouse gas emissions.

C. Prosperity

Survey respondents were asked to evaluate the potential of each technology to improve the quality of life for individuals worldwide. Factors considered included job creation, enhanced connectivity, and increased leisure time.

D. Industry

Participants assessed the potential of these technologies to disrupt existing industries and generate new markets over the next decade.

E. Equity

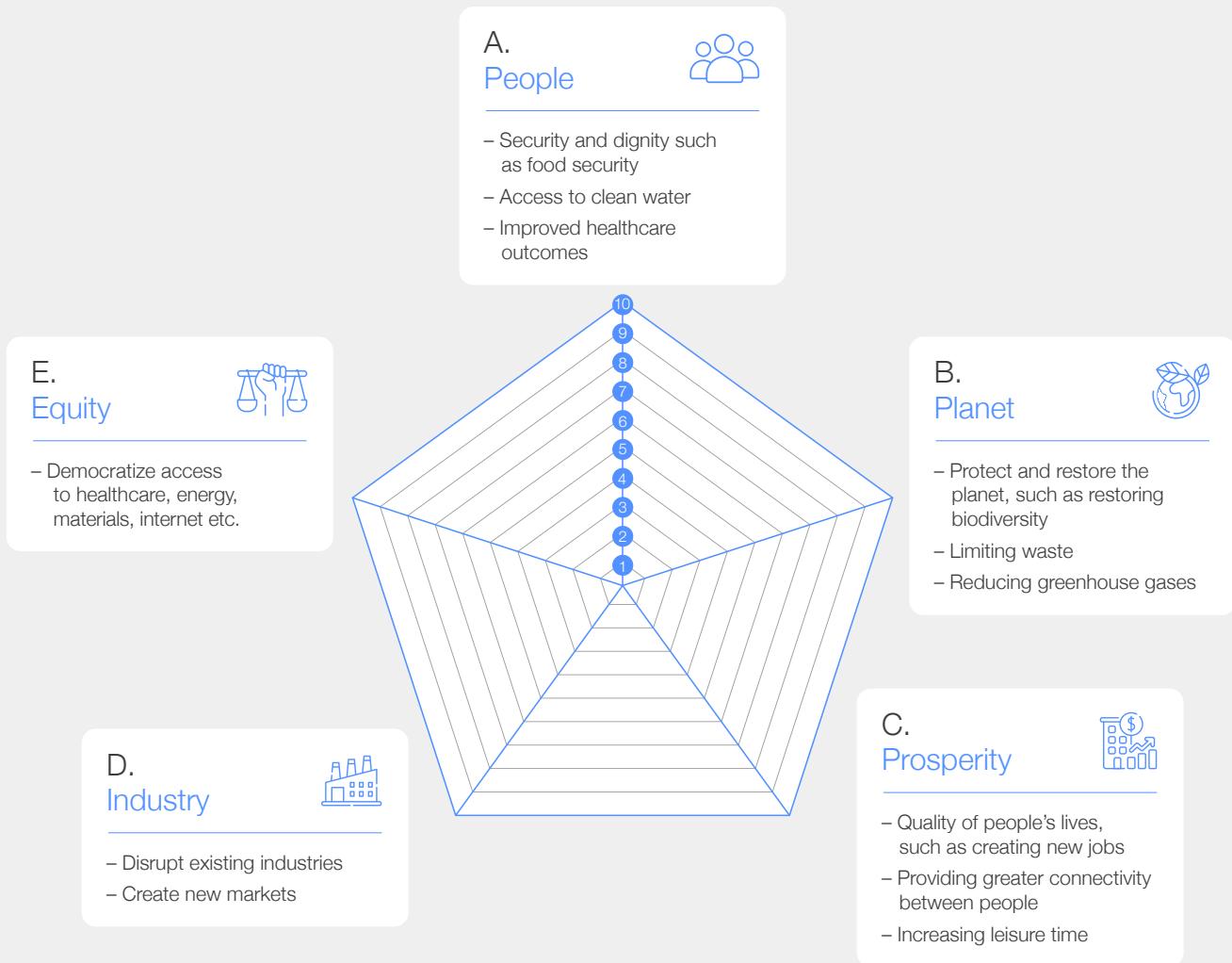
Finally, the survey asked participants to rate the potential for these technologies to promote global societal equity. This involved estimating their capacity to democratize access to essential resources and services like healthcare, energy, materials, and the internet.

Academics were mainly selected from Frontiers' network of scientific journal editors, while industry leaders were selected from the Forum's Innovator Communities.

Of the 100+ experts invited to contribute to one of the 10 technology surveys, 69 respondents from 18 countries contributed their assessment. Scores were averaged for each dimension of the impact fingerprint for each technology, with optional comments collated for additional context to scores.

The results have been visualized using radar charts (see Figure 1) and are present in each section.

FIGURE 1 | “Impact fingerprint” radar chart



Methodological limitations

This methodology was designed to be rigorous within a range of constraints.

First, given that some of the technologies on the list are truly emerging, there were limitations to how many academics and industry leaders in the Forum and Frontiers extended networks could be considered experts on these topics for participation in the impact fingerprint survey.

Second, response rates varied across the technologies, with different ratios of respondents from industry and academia.

Third, qualitative scores varied within technologies, partly due to different interpretations of the impact dimensions and partly due to different vantage points.

On balance, the impact fingerprint data visualizations provide a complementary qualitative dimension to the articles for each technology in this year’s report and prompt further analysis and debate about how emerging technologies are likely to shape the collective future in the years ahead.

Strategic Intelligence transformation maps

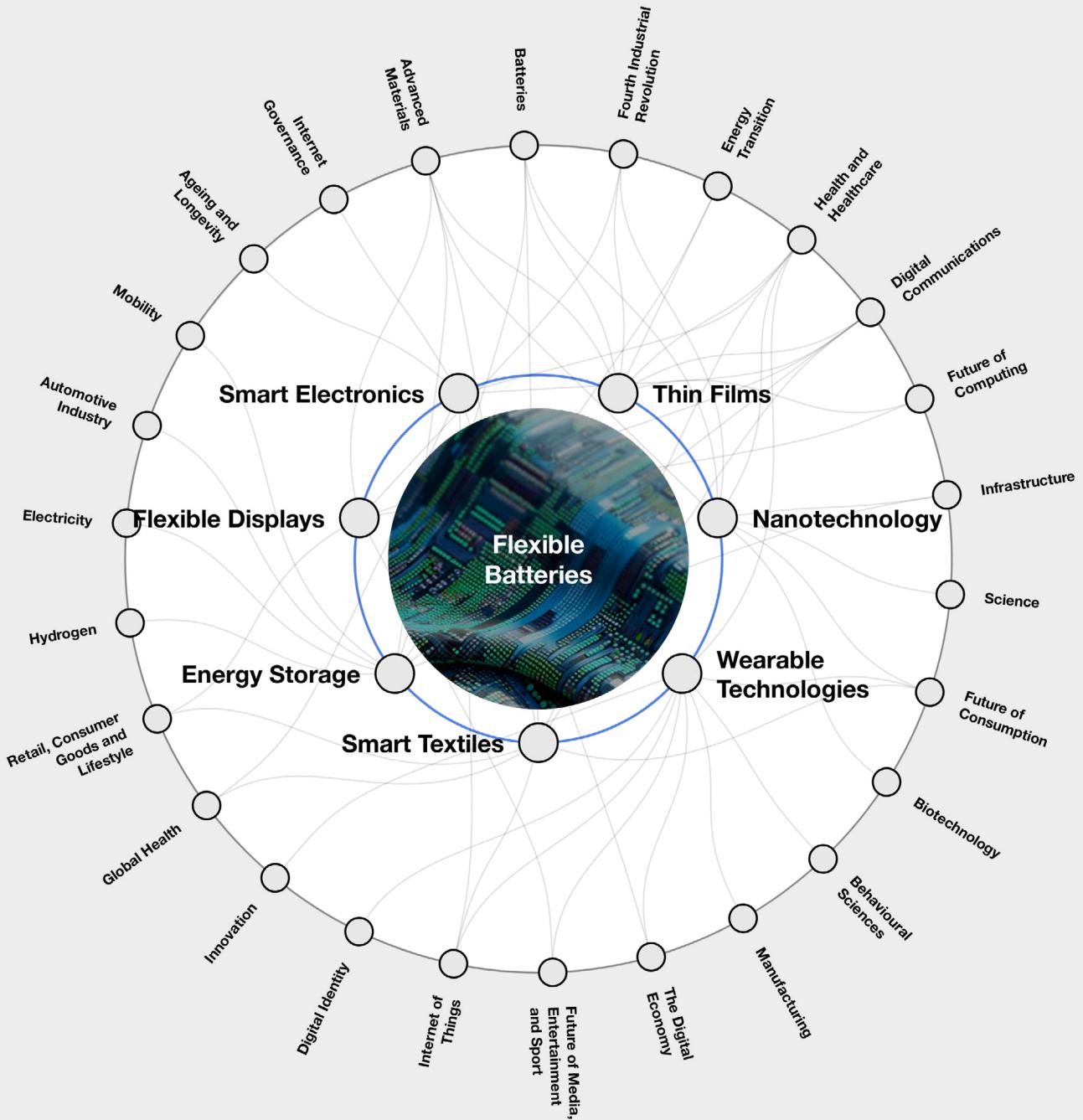
Another ambition for the 11th edition of the report was to facilitate deeper reader engagement with each of the technologies beyond the short articles included. To achieve this, Frontiers co-curated transformation maps for each technology, housed on the Forum's Strategic Intelligence Platform, where

readers can learn more about the key issues of each technology and how it connects to other topics on the global agenda as well as find the latest articles on the topic from trusted sources.

The descriptions were predominantly based on the articles in this report. Key issues were determined based on guidance from the steering group authors and the input of Frontiers' editors. Key issue descriptions were researched and written by Frontiers' editors.

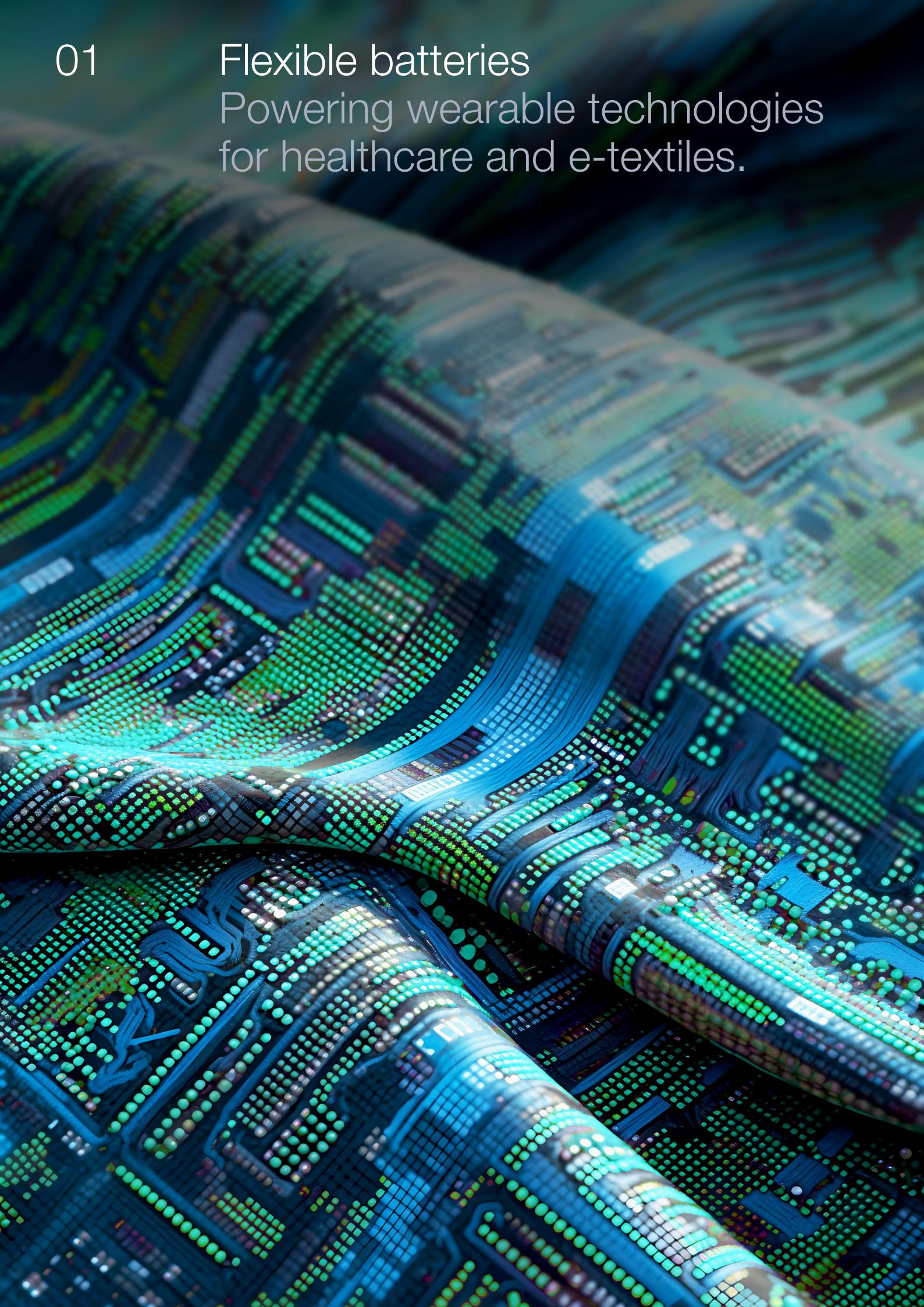
FIGURE 2

Example Strategic Intelligence transformation map



01

Flexible batteries Powering wearable technologies for healthcare and e-textiles.



Javier García Martínez
Professor of Chemistry and Director, Molecular Nanotechnology Lab, University of Alicante

Joseph Costantine
Associate Professor of Electrical and Computer Engineering, American University of Beirut

From rollable computer screens to “smart” clothing, the future of electronics looks to be increasingly flexible. The rapidly escalating development of wearable devices, flexible electronics and bendable displays demands power sources that match the agility of these systems. Standard, rigid batteries may soon be a thing of the past as thin, flexible batteries – made of lightweight materials that can be easily twisted, bent or stretched – reach the market.

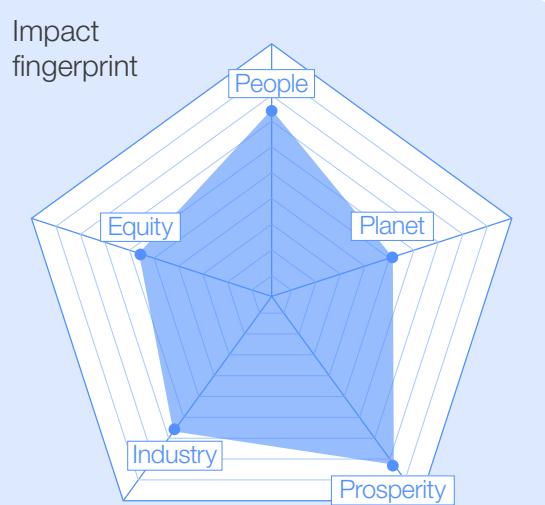
Several types of flexible batteries are currently available. These batteries are rechargeable and include lithium-ion or zinc-carbon systems placed on conductive polymer current collectors. In some cases, additives enhance conductivity and flexibility.¹ The electrodes of flexible batteries can be coated with – or even printed onto – flexible substrates, including carbon-based materials like graphene, carbon fibres or cloth.

Flexible batteries have applications in a growing number of fields, including wearable medical devices and biomedical sensors, flexible displays and smartwatches. Health-related applications powered by these batteries could transmit data wirelessly to healthcare providers, facilitating remote patient monitoring. Further, flexible batteries that can be integrated into the fabric of jackets, shirts or other apparel will be required to power emerging textile-based electronics with capabilities ranging from built-in heating systems to health monitoring.

The flexible battery market is expected to expand rapidly in the coming years. One study forecasts that the global flexible battery market will grow by \$240.47 million from 2022-2027, accelerating at a compound annual growth rate of 22.79% during this period.² The primary drivers of growth are expected to be the increasing demand for wearable devices and the growing trend towards miniaturization and flexibility of electronics.

Several companies are actively developing and commercializing flexible battery technology, including LG Chem, Samsung SDI, Apple, Nokia, Front Edge Technology, STMicroelectronics, Blue Spark Technologies and Fullriver Battery New Technology.³ However, there is still room for innovation in this space, and new players are likely to enter the market as the technology evolves.

The ability of flexible batteries to be bent, twisted and stretched makes them ideal for use in wearable devices. As the market demand for wearable technologies continues to grow, the future of flexible batteries is promising, and further advances are likely. As with all batteries, one hurdle to overcome is their safe disposal and recycling, which should come as the technology and associated applications become circular. Revolutionary advances in flexible-battery technologies and their accompanying industries are expected to continue for many years to come.



22.79%
Compound annual growth rate between 2022-2027

\$240 million
Forecasted growth of the global flexible battery market between 2022-2027

↑ Image:
A new generation of flexible batteries may allow for the seamless integration of technology into fabrics and clothes.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated):
“Technology fabric with interwoven digital elements”.

Read more:
Discover expert analysis related to [flexible batteries](#) on the Strategic Intelligence Platform.

02

Generative artificial intelligence Expanding the boundaries of human endeavour.



Olga Fink

Professor of Intelligent Maintenance
and Operations Systems, EPFL

Julien Weissenberg

Founder, Deep Tech Experts

Generative artificial intelligence (AI) is a powerful type of AI that can create new and original content by learning patterns in data, using complex algorithms and methods of learning inspired by the human brain. While generative AI is still currently focused on producing text, computer programming, images and sound,⁴ this technology could be applied to a range of purposes, including drug design, architecture and engineering.

For example, at the time of this writing, initial work has been published on generating candidate drug molecules targeting particular conditions⁵ and on creating [pictures of imaginary buildings or on generating interior design](#). NASA engineers are currently working towards AI systems that can construct lightweight spaceflight instruments, achieving a 10-fold reduction in development time while simultaneously improving structural performance.⁶ Generative AI technologies may even impact the food industry and the design of everyday objects, from furniture to appliances. In scientific research, generative models could facilitate breakthroughs by improving experimental design, identifying relationships between data elements and creating new theories. For example, recently developed AI algorithms can [translate a mathematical formula](#) into plain English or analyse brain activity data to generate drawings of the objects that human participants are holding in mind.^{7,8}

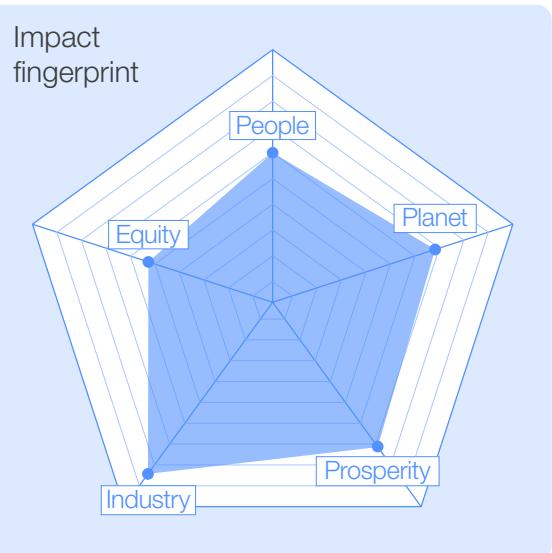
High school and university students are using generative AI more frequently, with some institutions forbidding their use while others are integrating generative models into teaching practices⁹ or even training students to master these tools. Used properly, generative AI can create personalized curricula that adjust to student skills and learning progress while encouraging critical thinking, igniting creativity and harnessing novel ideas.

In the workplace, the use of AI-based language models like the recently popular ChatGPT or its successors can increase productivity and improve output quality, restructuring human tasks towards idea generation and editing as opposed to rough drafting.¹⁰ Generative AI technologies specifically benefit low-ability workers and can increase job satisfaction and self-efficacy. Given the potential for productivity gains resulting from adopting these new technologies, it's crucial to acknowledge the likelihood of job displacement. As such, policies and programmes that support workers in their efforts to upskill and reskill are essential in ensuring that the benefits of technological innovation are widely shared and that workers are equipped with the skills needed to thrive in the changing job market.

The newest developments involve autonomous AI systems that can make important decisions or take significant actions. For instance, [AutoGPT](#) is an autonomous AI application using the GPT-4 language model. AutoGPT can automatically accomplish a user-identified goal by dividing the goal into smaller tasks and employing tools like internet searches or text-to-speech technology. The growing integration of generative AI technologies, particularly autonomous AI, into multiple aspects of people's daily lives, is generating both public excitement and concern.

To build public trust in generative AI, applications should meet agreed-upon professional and ethical standards. Generative AI systems represent the data they were trained on and the conventions governing society at that time. Care should be taken to mitigate AI bias based on training data, with a focus on including "outlier" data and novel societal conventions. Further, the decision-making processes of an application should be easy to understand, an application's goals should be clearly disclosed to operators and end users, and individual privacy should be respected. Ethical guidelines and governance structures must be developed to mitigate potential harm and ensure that technical progress is balanced with responsible use. Finally, copyright attribution must be addressed so that proper credit is given to AI designers, creators of training data and authors of instructions for using the applications.

With the correct controls in place, generative AI can provide more time for creativity, demonstrate the boundaries of knowledge, and act as a sparring partner to challenge conventional thinking.



↑ Image:

Generative AI can synthesize what it has learnt from gigantic data sets to create and intuit new information in novel ways.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated):
"Glitched image overlaying various styles of painting, photography and 3D renderings".

Read more:
Discover expert analysis related to [generative artificial intelligence](#) on the Strategic Intelligence Platform.

03

Sustainable aviation fuel Moving the aviation industry towards net-zero carbon emissions.



Mariette DiChristina

Dean and Professor of the Practice in Journalism,
Boston University College of Communication

Lee Sang-Yup

Senior Vice-President for Research, Korea Advanced
Institute of Science and Technology

Lauren Uppink Calderwood

Head, Climate Strategy, Centre for Nature and Climate,
World Economic Forum

Aviation accounts for 2-3% of global CO₂ emissions annually, with concerning “business-as-usual” projected emissions of 39 gigatonnes between 2022-2050.^{11,12} While the use of electric vehicles for ground transport is rapidly increasing, the aviation sector has struggled with decarbonization because energy-dense fuels are required for long-distance flights. Additionally, the high price of replacing aircraft means that the current fleet will remain in operation for decades, and electric or hydrogen-fuelled planes may not be viable for long-distance flight in any case.

Enter a solution that does not require large-scale changes to current aviation infrastructure and equipment: sustainable aviation fuel (SAF), produced from biological (e.g. biomass) and non-biological (e.g. CO₂) resources. Combined with other decarbonization strategies, including system-wide operational efficiencies, new technologies and carbon offsets, SAF should move the airline industry towards reaching net-zero carbon emissions in the coming decades.

Today, SAF makes up less than 1% of global jet fuel demand, but this must increase to 13-15% by 2040 to put the aviation industry on the path to net zero by 2050.¹³ Such an increase will require the creation of 300-400 new SAF plants; and airlines, manufacturers and fuel companies are working around the clock to enable this level of scale.

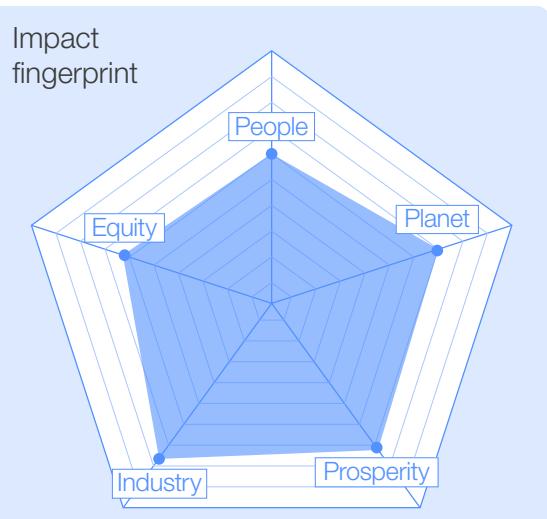
Fortunately, the production of SAF from biogenic raw materials using renewable energy is steadily increasing. According to the International Air Transport Association, SAF production reached at least 300 million (optimistically 450 million) litres in 2022, nearly triple that produced in 2021.¹⁴ An increasing number of airlines have committed to using SAF, a trend that will be accelerated through global efforts such as the World Economic Forum’s Clean Skies for Tomorrow initiative¹⁵ and [First Movers Coalition](#).

The American Society of Testing and Materials (ASTM) has approved nine SAFs for blending at a ratio of up to 50% with conventional petroleum-based jet fuel.¹⁶ The first SAF, approved by ASTM in 2009, is produced by converting syngas (a mixture of carbon monoxide and hydrogen) into hydrocarbons through a series of chemical

reactions. Syngas can be prepared from biomass or wastes or, better yet, from captured CO₂ and green hydrogen using renewable energy.

The second SAF, approved in 2011, is produced from plant oil and animal fat. The availability and collection of raw materials, along with the need for sustainably produced green hydrogen, remain major challenges for this option. Metabolically engineered microorganisms that can break down abundant, non-edible biomass could potentially reduce dependence on plant oils and animal fats.¹⁷

Over the past several years, seven more SAFs have been approved, with other exciting candidates still in active development. One example uses engineered bacteria to improve the SAF’s energy profile.¹⁸ In 2023, a consortium of actors in the United Kingdom is poised to deliver the first net-zero transatlantic flight using solely sustainable aviation fuel, demonstrating the potential of this rapidly evolving technology and moving the world closer to net-zero aviation.



2-3%

of annual global CO₂
emissions are from aviation

↑ Image:

Sustainable aviation fuel, created from biomass and combined with other decarbonization strategies, plot a reliable course to net-zero aviation.

Credit: Midjourney and Studio Miko.

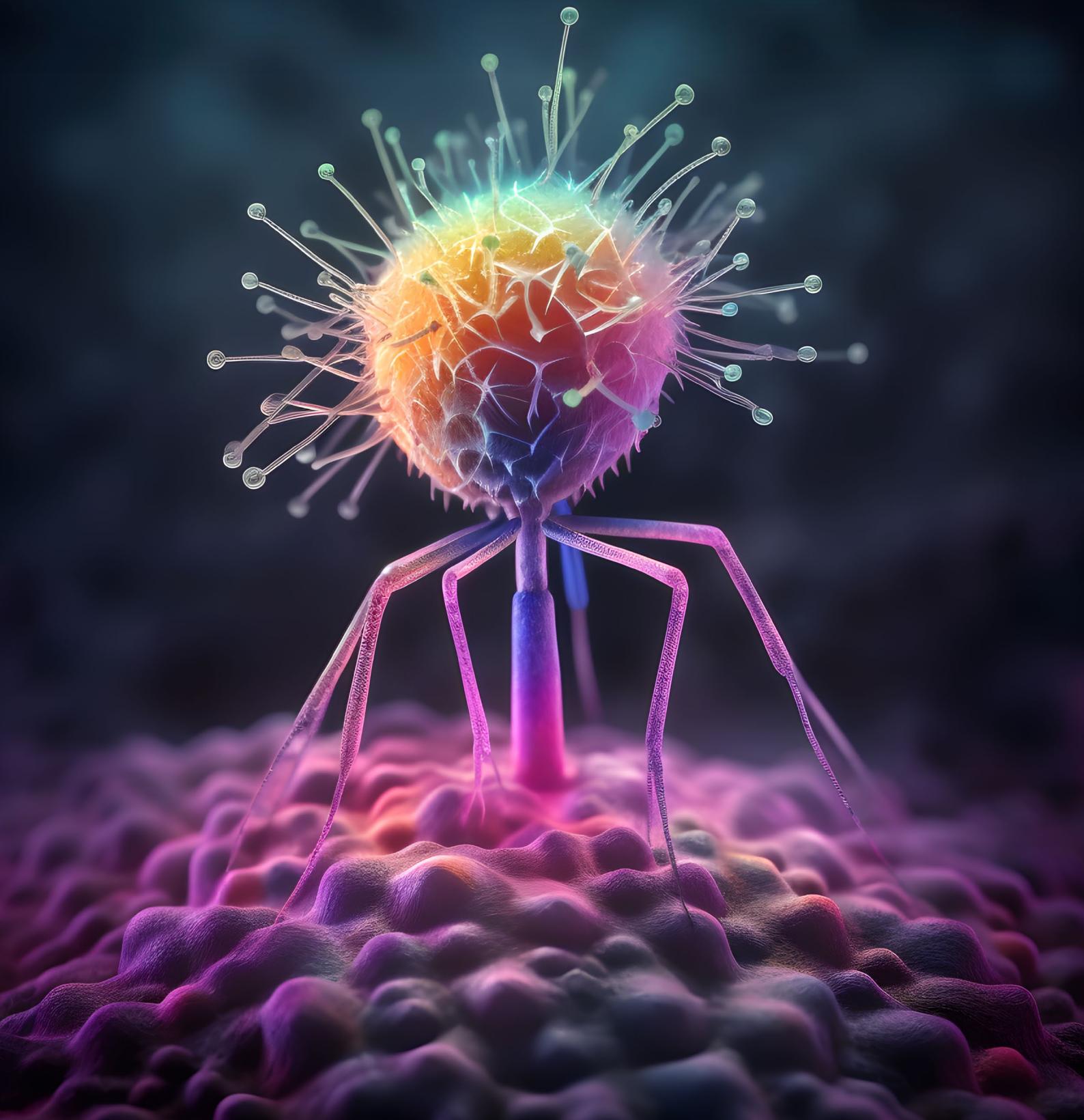
Prompt (abbreviated):
“Drops of fuel splashing in the shape of leaves”.

Read more:
Discover expert analysis related to [sustainable aviation fuel](#) on the Strategic Intelligence Platform.

04

Designer phages

Engineering viruses to augment human, animal and plant health.



Mine Orlu

Professor of Pharmaceutics, University College London (UCL) School of Pharmacy, Faculty of Life Sciences, UCL

Wilfried Weber

Scientific Director, Leibniz Institute for New Materials

The number of microbes living on and within the human body matches, and may even exceed, the number of human cells.¹⁹ The community of microbes an organism harbours is called its microbiome, and the microbiomes of humans, animals and plants play important roles in the health of these organisms.^{20,21}

Recent advances allow engineering of the microbiome to benefit human well-being and agricultural productivity. Key to this engineering are phages – viruses that selectively infect specific types of bacteria. Upon infection, a phage injects its genetic information into the bacterium. Using synthetic biology tools, the genetic information of phages can be reprogrammed so that infected bacteria execute a bioengineered set of genetic instructions. With bioengineered phages, scientists can change a bacterium's functions, causing it to produce a therapeutic molecule or to become sensitive to a certain drug, for example. As phages generally only infect one type of bacteria, individual bacterial species within the complex microbiome can be targeted.

Designer phages are showing potential for treating microbiome-associated diseases such as hemolytic uremic syndrome (HUS) – a rare but serious condition that affects the kidneys and blood-clotting functions, caused by a certain species of *E. coli*. Scientists engineered the genetic material of an *E. coli*-infecting phage to encode genetic “scissors” that can chop up the *E. coli* genes that lead to HUS. Animal studies demonstrated that administration of these designer phages significantly reduced the presence of the HUS-causing strain of *E. coli* in the microbiome and alleviated HUS symptoms.²² This approach was recently granted an orphan drug designation by the U.S. Food and Drug Administration, paving the way for clinical trials.²³ Phages are also being designed as feed supplements to enhance the growth of livestock, treat certain plant diseases and eliminate dangerous bacteria in food supply chains, in alignment with the World Health Organization's “One Health” approach.

↑ Image:

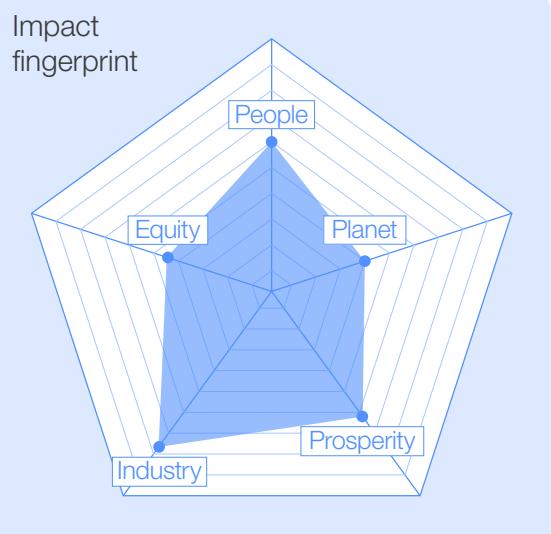
Engineered viruses could allow for hyper-targeted therapies that can selectively affect specific bacteria.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated):
“A microscopic image of a virus attacking a cell”.

Read more:
Discover expert analysis related to [designer phages](#) on the Strategic Intelligence Platform.

Promising early results of designer phage therapies are attracting significant venture capital that will help to facilitate clinical testing of engineered phages. Potential applications of designer phages are numerous and diverse. [Locus Biosciences](#) is using engineered phages to combat antibiotic-resistant bacteria, whereas [Eligo Biosciences](#) is pursuing similar approaches to make certain bacteria less pathogenic. Of the 44 phage-related clinical trials with therapeutic intent, 29 have been posted since the beginning of 2020.²⁴ Phage-based therapies involving both natural and designer phages will continue to emerge as a powerful method to engineer microbiomes, enhancing the health of humans, animals and plants.



“

Phages are showing potential for treating microbiome-associated diseases and revolutionizing the engineering of microbiomes for human, animal and plant health.

05

Metaverse for mental health

Shared virtual spaces to improve mental health.



Corinna Lathan

Co-Founder and former Chief Executive Officer,
AnthroTronix

Geoffrey Ling

Professor of Neurology, Johns Hopkins Hospital

The Surgeon General of the United States recently declared war on what he calls “[one of the country’s most pressing public health issues of our time](#)”.

Excess screen time and social media can decrease psychological well-being,²⁵ but they can also enhance well-being when used responsibly.²⁶ Screen time spent building connections in shared virtual spaces might help combat the growing mental health crisis as opposed to contributing to it.

Virtual shared spaces are digital environments where people can interact professionally and socially. The future of these spaces is commonly referred to as the metaverse, which may include virtual shared spaces enhanced with augmented or virtual reality (AR/VR). Just as multiple shared virtual platforms currently exist, there will likely be multiple metaverses, differing in purpose and level of immersiveness.

The mental health crisis that existed prior to the COVID-19 pandemic has since increased to unprecedented levels,²⁷ making conditions ripe for metaverse-enabled mental health treatment. The number of mental health providers is insufficient to meet the escalating crisis,²⁸ and, in the United States, a federal reimbursement opportunity for tele-mental health services is in the works to combat this shortage.²⁹ Ideally, a mental health-centred technology-based infrastructure will support all aspects of mental health: prevention, diagnostics, therapy, education and research.

Gaming platforms are already being leveraged for mental health treatment. Such platforms not only increase patient engagement but also help destigmatize mental health issues. For example, [DeepWell Therapeutics](#) has created video games to treat depression and anxiety; UK-based Xbox studio [Ninja Theory](#) has incorporated mental health awareness into mass-market games and plans to expand into treatment with their [Insight Project](#);

↑ Image:

The metaverse may be used to provide a shared virtual space for people to connect and access therapy.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated):
“People boating on lake in a glass cube”.

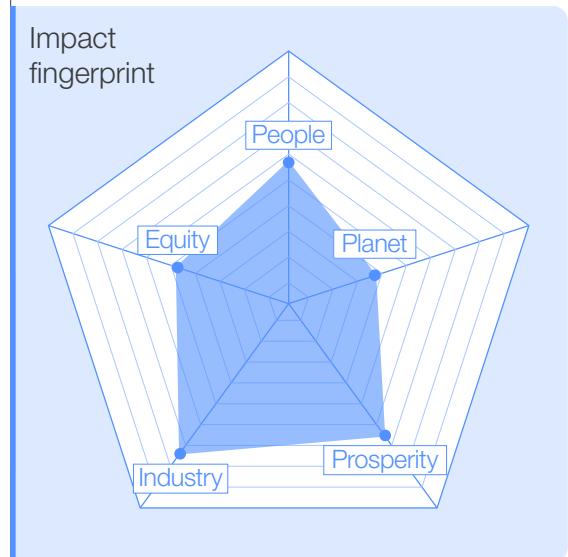
Read more:

Discover expert analysis related to [metaverse for mental health](#) on the Strategic Intelligence Platform.

and [TRIPP](#) has created Mindful Metaverse, which enhances well-being through VR-enabled guided mindfulness and meditation.³⁰

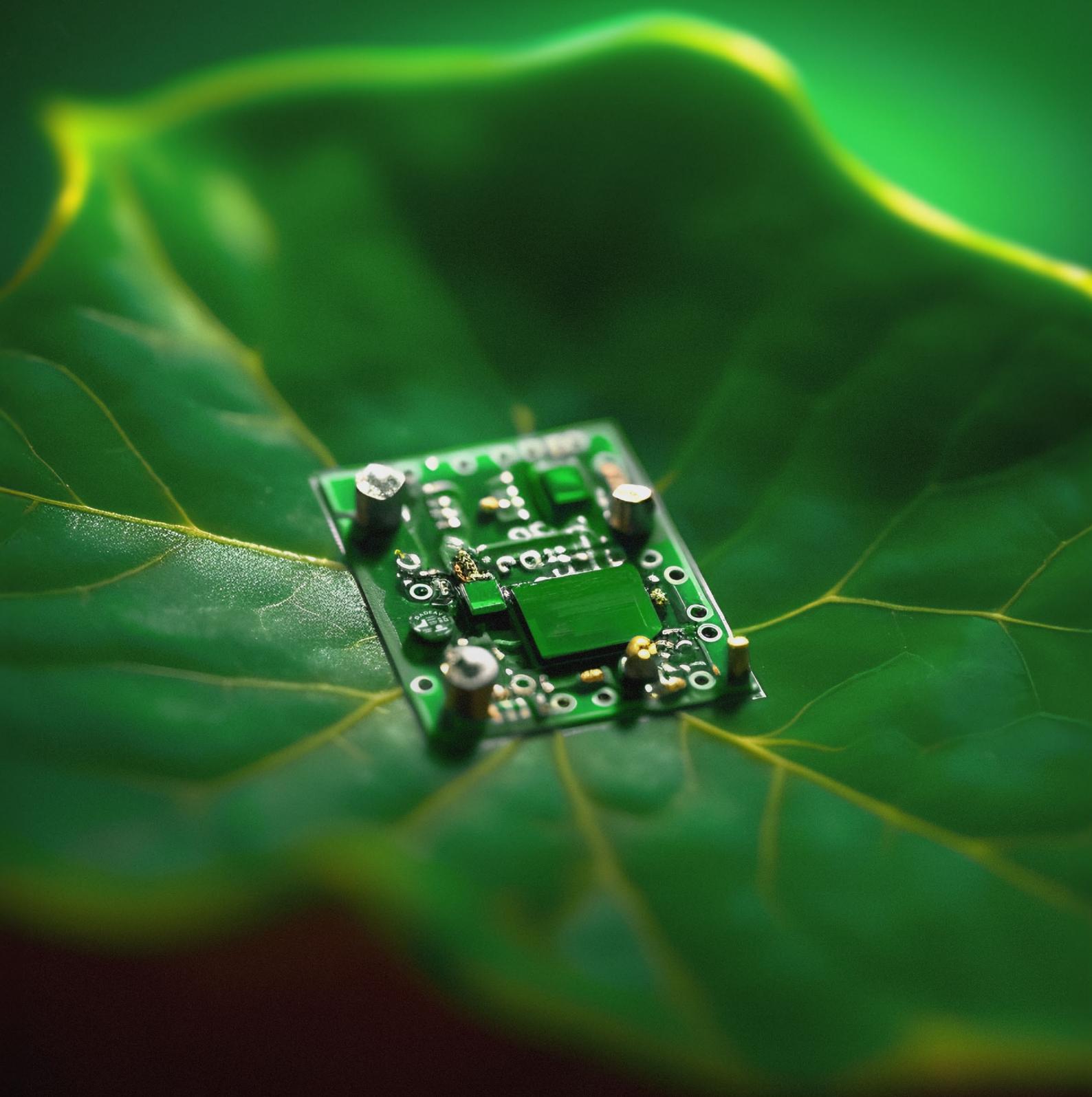
Maturing interface technologies could further augment social and emotional connections between distant participants. For example, [Emerge Wave 1](#) is a tabletop device that uses ultrasonic waves to simulate touch, enhancing users’ social experience. Noninvasive neurotechnologies can even provide feedback attuned to a user’s emotional state. For example, [Neurable](#) headsets use electrodes to measure emotion and can adjust music accordingly. Eventually, the metaverse will also connect to therapeutic neurotechnologies, such as direct brain stimulation to treat intractable depression.³¹

Leveraging the metaverse for the continuum of mental healthcare needs could be a win-win. Not only would patients benefit, but grounding the metaverse in a practical, necessary application could drive the emergence of this advancing virtual space.



06

Wearable plant sensors Revolutionizing agricultural data collection to feed the world.



Rona Chandrawati

Associate Professor, University of New South Wales

Carlo Ratti

Director, Massachusetts Institute of Technology (MIT)
Senseable City Lab

The United Nations Food and Agriculture Organization states that world food production will need to increase by 70% to feed the world's population in 2050.³² Technological innovations in agriculture will be a key step towards meeting this dramatic escalation and improving the world's food security.

Traditionally, crops have been monitored via soil testing and visual inspections, both of which are expensive and time-consuming. Recent technological advances have improved the ease of crop monitoring, enabling farmers to monitor crop conditions at a larger scale. For several years, the health of farmland has been monitored using low-resolution satellite data.³³ Now, sensor-equipped drones and tractors are providing higher-resolution information about crop conditions.^{34,35} Resultant information from all forms of monitoring can be processed using AI. The next frontier in crop monitoring is even higher resolution: the monitoring of individual plants.

Wearable plant sensors promise to improve plant health and increase agricultural productivity. These sensors are small, non-invasive devices that can be attached to crop plants for continuous monitoring of temperature, humidity, moisture and nutrient levels. Data from plant sensors can optimize yields, reduce water, fertilizer and pesticide use, and detect early signs of disease.

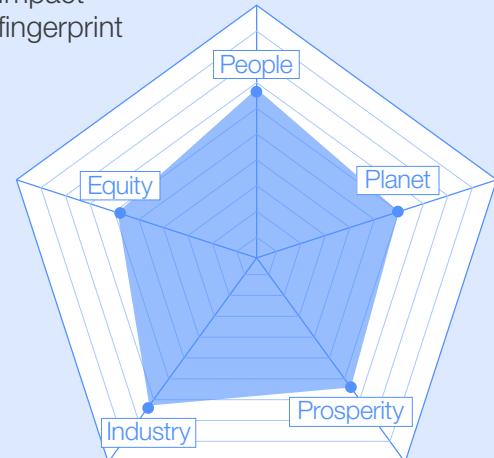
Two companies, [Growvera](#) and [Phytech](#), have independently developed micro-sized needle sensors that insert into a plant's leaves or stems to measure changes in electrical resistance. Data are transmitted wirelessly to a computer or mobile device, where they are analysed to generate insights about plant health. Farmers can thus monitor crops in real time and perform precise interventions based on the specific demands of plants, such as adjusting irrigation or fertilizer application in response to moisture levels or nutrient data.

Much work remains. Wearable sensors can be expensive to install and maintain, and interpretation

of sensor data may require specialized expertise. Improved data analytics tools are needed to help farmers make informed decisions about crop management from sensor data. The long-term effects of wearable sensors on plant growth and development also warrant investigation.

Despite these challenges, wearable plant sensors are poised to revolutionize crop production and management. By providing real-time data about plant health and environmental conditions, these devices can help farmers optimize agricultural productivity, reduce waste and minimize agriculture's environmental impact – all while helping to feed the world's growing population.

Impact
fingerprint



70%

increase in world food production will be required to feed the global population by 2050.

↑ Image:

Individual plant monitoring would allow for the harvesting of extremely high-resolution data on a farmer's crop.

Credit: Midjourney and Studio Miko.

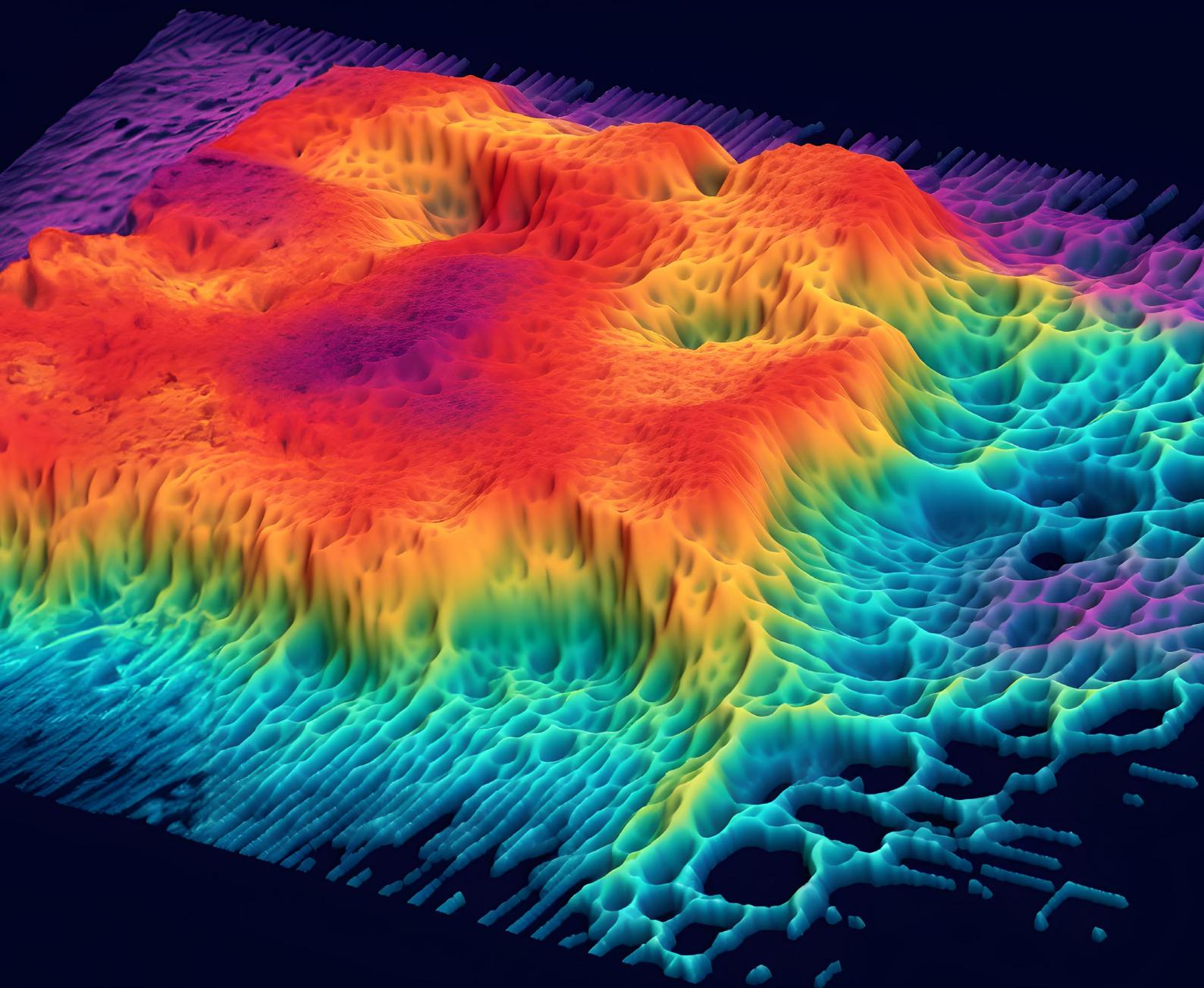
Prompt (abbreviated):
"Microchip attached to a leaf".

Read more:
Discover expert analysis related to [wearable plant sensors](#) on the Strategic Intelligence Platform.

07

Spatial omics

Molecular-level mapping of biological processes to unlock life's mysteries.



Elizabeth O'Day

Chief Executive Officer and Founder, Olaris

Angela Ruohao Wu

Associate Professor, Hong Kong University of Science and Technology

Xu Xun

Director, BGI Research

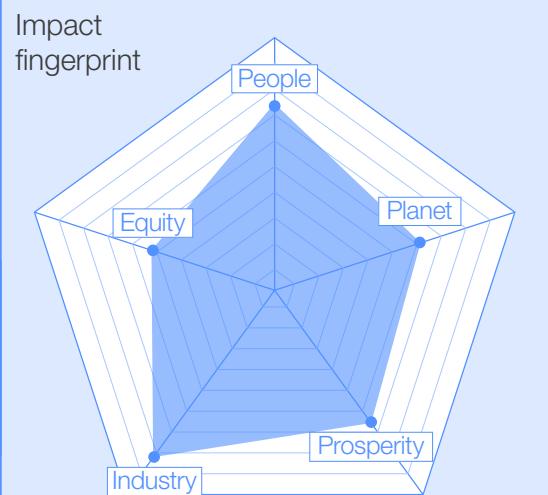
The human body is composed of approximately 37.2 trillion cells. How do they all work together to keep us alive and healthy? Spatial omics may provide researchers with an answer. By combining advanced imaging techniques with the specificity and resolution of DNA sequencing, this emerging method enables the mapping of the what, where and when of biological processes at the molecular level. Starting with an organ of interest (such as a mouse brain), scientists slice tissue into sections only one cell thick. Innovative techniques are then used to visualize the locations of specific biomolecules in each slice.^{36,37,38} Spatial omics allows previously unobservable cell architecture and biological events to be viewed in unprecedented detail.

A new generation of molecular-level “cell atlases” are under development thanks to spatial omics, detailing the myriad biological processes occurring in humans and other species.^{39,40} For example, using spatial omics, scientists constructed a three-dimensional cell atlas of fruit fly larvae and unlocked the black box of organ development in mouse embryos.^{41,42,43} Another study revealed that the injured amphibian axolotl brain heals itself using mechanisms mirroring those activated during brain development.⁴⁴ Spatial omics also shows promise in therapeutic discovery. Using this technique, scientists identified a population of neurons in the spinal cord that appears to be responsible for recovery after spinal cord injury. Stimulating these neurons in paralysed mice sped up their recovery to walking.⁴⁵ Additional health-related applications include characterizing the various cell types in a tumour to customize treatment and unravelling the mechanisms of complex diseases like Alzheimer’s disease and rheumatoid arthritis.⁴⁶ Infectious diseases can also be investigated using spatial omics. For example, a spatial omics study of samples from people who died from COVID-19 revealed that SARS-CoV-2 causes widespread disruption of cellular pathways across all tissues.⁴⁷

The need to democratize and scale up spatial omics technologies is pressing. With a total market value of \$232.6 million in 2021 and an estimated revenue of \$587.2 million in 2030, a growing list of public and private companies are seeking to provide spatial omics solutions.⁴⁸ While academic and translational research centres made

up 89% of the market in 2020,⁴⁹ the market is dramatically expanding to include pharmaceutical and biotech industries.

To realize the full promise of spatial omics, technical challenges around data acquisition, processing, storage and standardized reporting must be addressed. Further, applications should be expanded to map other biomolecules, such as metabolites, and other organisms, including plants and invertebrates, to further illuminate the underlying biology. In the brief time since *Nature Methods* selected spatial omics as the method of the year in 2021,⁵⁰ it has evolved from a niche technique to one that is poised to become standardized and widely employed, revolutionizing the understanding of life.



\$232 million

Spatial omics technologies
total market value in 2021

\$587 million

Estimated revenue in 2030

↑ Image:

New imaging techniques may allow for unprecedented access to the previously unobservable.

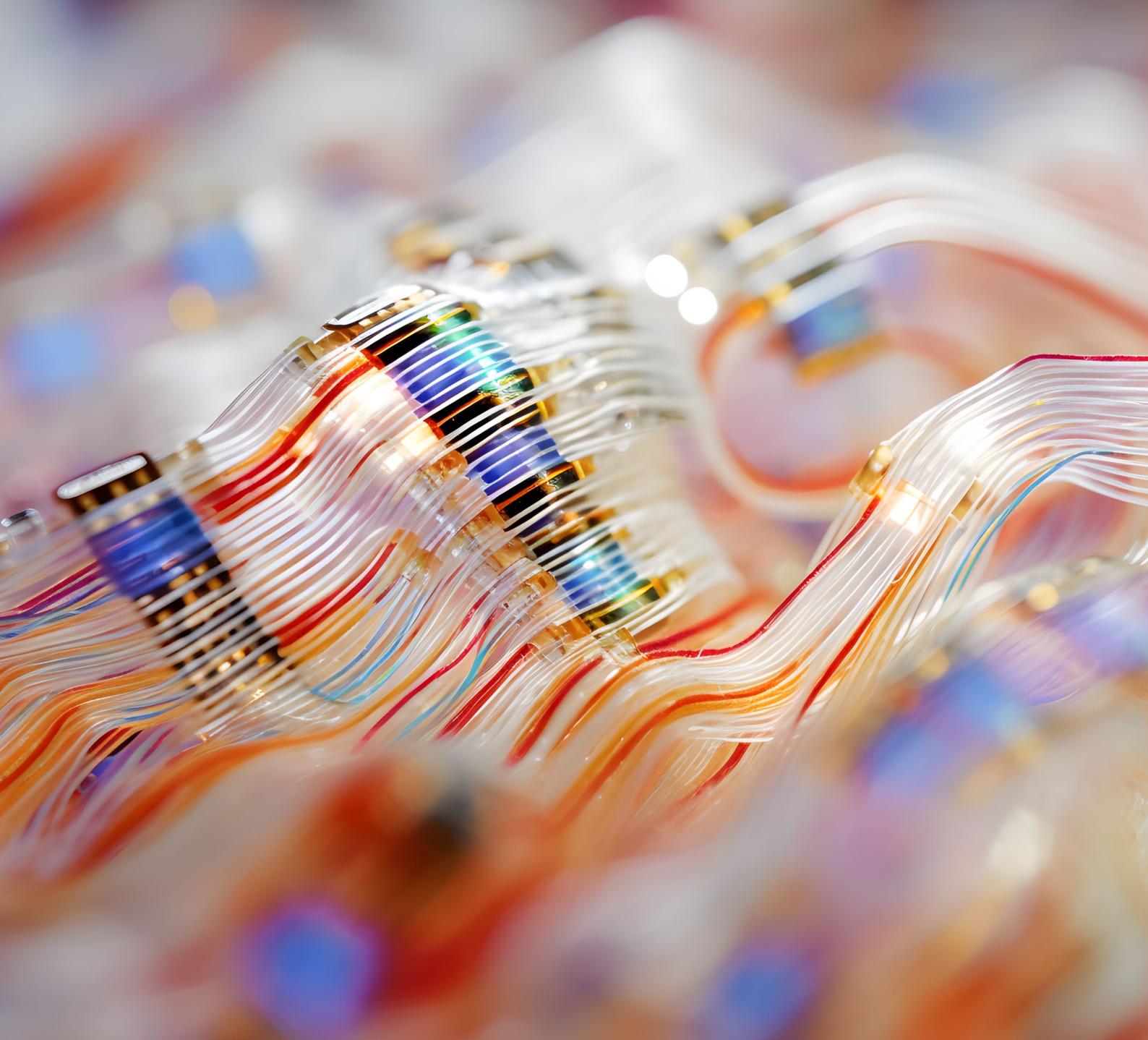
Credit: Midjourney and Studio Miko.

Prompt (abbreviated):
“Organic cell structure at the molecular level taken through microscopic imaging in a heatmap style”.

Read more:
Discover expert analysis related to [spatial omics](#) on the Strategic Intelligence Platform.

08

Flexible neural electronics
Better engineered circuits to
interface with the nervous system.



Wendy Ju

Associate Professor, Cornell Tech

Geoffrey Ling

Professor of Neurology, Johns Hopkins Hospital

Ruth Morgan

Vice-Dean (Interdisciplinary Entrepreneurship),
Faculty of Engineering Sciences, UCL

Angela Ruohao Wu

Associate Professor, Hong Kong University
of Science and Technology

In recent years, brain-machine interfaces (BMIs) have gained visibility, igniting collective imaginations regarding the power and potential of one day controlling machines with thoughts. BMIs allow electrical signals the brain produces to be captured by sensor hardware. Algorithms then decode these electrical signals into instructions that a computer can understand and execute. BMI-like systems are already used to treat patients with epilepsy, and in neuroprosthetics – prosthetic limbs use electrodes to interface with the nervous system.^{51,52}

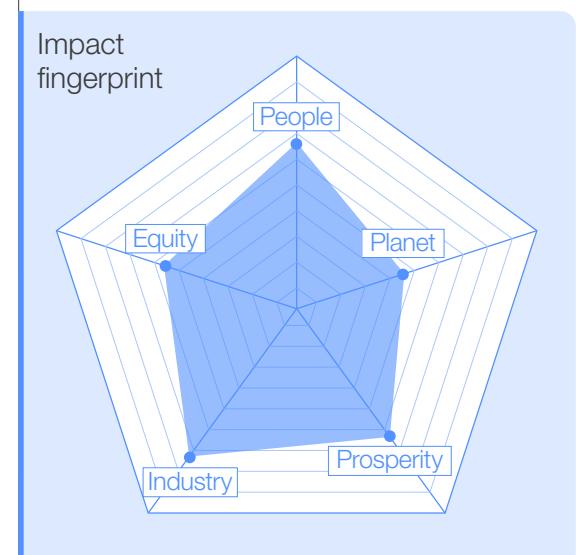
Despite initial successes, there are challenges to these technologies. Current implants used by doctors are made of hard materials, like the chips inside a laptop or phone, and they can trigger long-term scarring and cause substantial discomfort. They cannot bend or adapt to brain movements so, over time, they “drift” in position, decreasing the accuracy of the captured signals. Non-invasive methods, like electrodes placed on the outside of the skull, do not require surgical implantation but provide only muffled, difficult-to-decode signals – like listening to a person talk through a thick face mask.

Researchers have recently developed brain interfacing circuits on biocompatible materials that are soft and flexible. Flexible circuits can conform to the brain, reducing scarring and sensor drift, and they can be packed with enough sensors to stimulate millions of brain cells at once, vastly outperforming the scale and timeframe of hard probes.⁵³

When used in neuroscience research, flexible BMIs could deepen understanding of neurological conditions such as dementia and autism. In the clinic, flexible BMIs could provide greater control of neuroprosthetics without requiring frequent

recalibration.⁵⁴ Applications of flexible BMIs^{55,56} are already undergoing US Food and Drug Administration (FDA)-approved clinical trials, rapidly making this technology a reality. In the future, other implantable devices, such as cardiac pacemakers, could adopt similar types of materials.

Looking forward, advances in materials manufacturing and soft-circuit printing could further improve flexible BMI technologies, eventually leading to true human-AI interfacing. As with many emerging technologies, broad ethical issues must be considered prior to the wide implementation of these interfaces. Potential health outcomes must be balanced with public acceptance and trust. Further, given the sensitive nature of brain-derived data, privacy and ethical use guidelines must establish how these data can be used in the short, medium and long term.



↑ Image:

Breakthroughs in flexible electronics may pave the way for neurological treatments.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated):
“bright-white, flexible electronics”.

Read more:

Discover expert analysis related to [flexible neural electronics](#) on the Strategic Intelligence Platform.

09

Sustainable computing Designing and implementing net-zero-energy data centres.

A photograph of a modern data center. On either side of a central aisle are rows of server racks. A large glass wall on the right side of the aisle offers a view of a dense, lush green forest. The lighting suggests it's either sunrise or sunset, with warm light filtering through the trees. The overall theme is the integration of technology and nature.

Olga Fink

Professor of Intelligent Maintenance and Operations Systems, EPFL

Andrew Maynard

Professor of Advanced Technology Transitions, Arizona State University

While the Earth is indisputably facing a worsening environmental crisis, increasing reliance on data may not seem to play much of a role. Yet data centres, which facilitate Google searches, email, the metaverse, AI and myriad other aspects of an increasingly data-based society, consume an estimated 1% of the electricity produced globally,⁵⁷ and this amount will only increase with growing demand for data services. While there is no single “green data” magic bullet, it is expected that the coming decade will boast substantial strides toward net-zero-energy data centres as emerging technologies are combined and integrated in innovative ways – rapidly making the dream of net-zero-energy data centres an achievable reality.

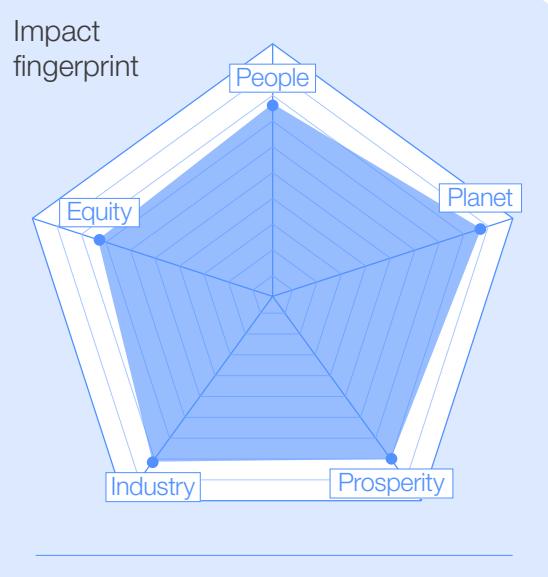
First, to address heat-management issues, liquid cooling systems are being developed that use water or dielectric coolant to dissipate heat, and excess heat is being repurposed for applications including space heating, water heating and industrial processes. For instance, the city of Stockholm is implementing projects to harness waste heat from data centres to heat homes.⁵⁸

Second, AI is being used to analyse and optimize energy use in real-time, maximizing efficiency without compromising performance. DeepMind has successfully demonstrated the potential of AI-powered energy management, achieving up to a 40% reduction in energy consumption at Google’s data centres.⁵⁹

Third, the technological infrastructure supporting net-zero-energy data centres is becoming more modular and demand-based. For instance, cloud and edge computing systems allow data processing and storage to be spread across multiple devices, systems and even locations.^{60,61} As an example, Crusoe Energy installs its modular data centres at sites where methane flaring occurs to enable cloud computing infrastructure to be powered by methane gas that would otherwise have been released directly into the atmosphere. These and other prefabricated units can be easily deployed, expanded or relocated, allowing data centre operators to optimize energy use and adapt to their companies’ changing needs. Additional innovations in software and hardware include novel computing architectures like systems on a chip;⁶² and optimizations such

as energy-proportional computing, in which computers use energy proportional to the amount of work being performed.⁶³

Achieving net-zero-energy data centres will involve innovative approaches to integrating the above mentioned approaches with new electricity generation, storage and management technologies. Given the wave of innovation and investment in this area, there is reason to be optimistic about the years ahead.



“

Data centres, which facilitate Google searches, email, the metaverse, AI and myriad other aspects of an increasingly data-based society, consume an estimated 1% of the electricity produced globally, making the dream of net-zero-energy data centres an achievable reality.

↑ Image:

Innovations in heat management and energy optimization can help data centres switch to a more environmentally friendly future.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated):
“Futuristic data centre with nature inside and surrounding”.

Read more:
Discover expert analysis related to [sustainable computing](#) on the Strategic Intelligence Platform.

AI-facilitated healthcare

New technologies to improve the efficiency of healthcare systems.



Daniel E. Hurtado

Associate Professor, Pontifical Catholic University of Chile

Andrew Maynard

Professor of Advanced Technology Transitions, Arizona State University

Bernard S. Meyerson

Chief Innovation Officer Emeritus, IBM

The shortcomings of healthcare systems all over the world became abundantly and horrifyingly clear during the early days of the COVID-19 pandemic when the sustainable workloads of many hospitals were rapidly exceeded. In response, government-based and academic teams have been created to integrate AI and machine learning (ML) into healthcare – both to anticipate impending pandemics and to aid in effectively addressing them ([AI4PEP](#)).^{64,65} These emergent efforts to enhance the efficacy of national and global healthcare systems in the face of major health crises, and to democratize access to care, are in their initial stages but will rapidly scale up by integrating quality data into the AI and ML models.⁶⁶

AI-based technologies could also help to tackle a related challenge – the long delays many patients experience when attempting to obtain medical care through the healthcare system.⁶⁷ Surprisingly, delays often arise not from a lack of capacity but due to uneven access to – and resultant underutilization of – existing facilities. When applied to a curated data set of existing medical facilities, AI, ML and data analytics, techniques dramatically improved patient access to treatments. Medical Confidence, a subsidiary of CloudMD, used such technology to optimally align patient treatment needs with facility availability, enabling dramatic reductions in treatment wait times – in some cases, from many months down to only weeks.⁶⁸ An AI-based approach to optimizing access to care is becoming broadly adopted in Canada and will likely be replicated elsewhere.

The impact of AI-based healthcare could be even more profound in developing nations, which often lack the infrastructure and personnel to deliver health services to much of their populations. Intelligent tools to assist in the identification, monitoring and treatment of new or ongoing medical conditions – such as an AI-based system to facilitate the reading of radiological data⁶⁹ – are a first step in leveraging AI and ML to enhance healthcare capabilities in locations where care is currently inadequate. India, for example, has a widely dispersed population of over 1.4 billion and

Mine Orlu

Professor of Pharmaceutics, UCL School of Pharmacy, Faculty of Life Sciences, UCL

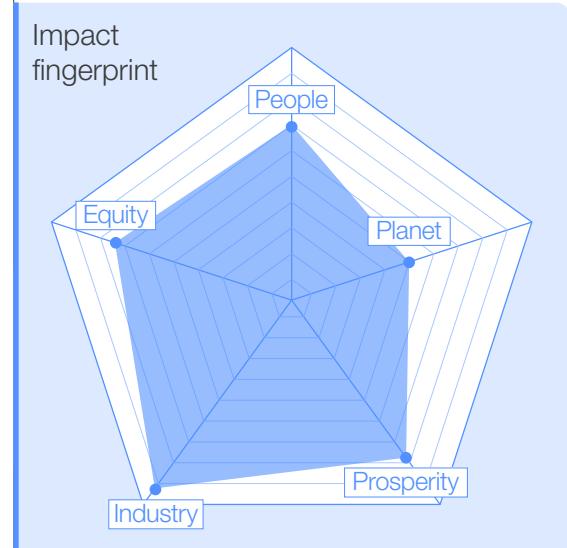
Landry Signe

Senior Fellow, Brookings Institution

has embraced an AI-based approach to enhance medical outreach. The Indian government has enabled physicians to engage remote communities through assistive technologies, with requisite privacy safeguards in place.

In addition to protecting data privacy and gathering quality data needed to generate these insights, other challenges to implementing AI-facilitated healthcare approaches include bolstering public acceptance and universal adoption of such technologies, assuring patient compliance and addressing possible national security concerns. While these remaining hurdles may be challenging to overcome, the risks of inaction are clear.

Moreover, any system that curates personal data on the health and welfare of a vast population must function within the bounds of a carefully crafted legal and ethical framework. Such considerations are already the topic of extensive discussion,⁷⁰ and legal frameworks are beginning to emerge in anticipation of the global application of AI and ML to healthcare. AI-based healthcare solutions will become ever-more pervasive in the next three to five years, to the great benefit of human health – particularly for those in underserved populations.



↑ Image:

One of the most effective ways emerging AI systems may impact healthcare is through the treatment of data and analytics.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated):
"Abstract population data".

Read more:
Discover expert analysis related to [AI-facilitated healthcare](#) on the Strategic Intelligence Platform.

Contributors

World Economic Forum

Centre for the Fourth Industrial Revolution

Sebastian Buckup
Head, Network and Partnerships

Greta Keenan
Strategic Impact and Communications Lead

Saemoon Yoon
Lead, Innovator Communities

Strategic Intelligence Platform

James Landale
Head, Content and Partnerships

John Letzing
Digital Editor

Stephan Mergenthaler
Head

Minji Sung
Specialist, Content and Partnerships

Centre for Nature and Climate

Lauren Uppink Calderwood
Head, Climate Strategy

Frontiers

Susan Debad
Consultant

Frederick Fenter
Chief Executive Editor

George Thomas
Public Affairs Manager

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Frontiers in Medical Technology
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Frontiers in Membrane Science and Technology
Frontiers in Microbiology
Frontiers in Plant Science
Frontiers in Systems Biology
Frontiers in Virtual Reality

Production

Laurence Denmark
Creative Director, Studio Miko

Sophie Ebbage
Designer, Studio Miko

Martha Howlett
Editor, Studio Miko

George Messer
Designer, Studio Miko

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Steering group

Co-Chairs

Mariette DiChristina

Dean and Professor of the Practice in Journalism,
Boston University College of Communication

Bernard S. Meyerson

Chief Innovation Officer Emeritus, IBM

Members

Enass Abo-Hamed

Chief Executive Officer, H₂GO Power

Jeff Carbeck

Vice-President, Corporate Innovation, Eastman

Rona Chandrawati

Associate Professor, University of New South Wales

Liming Chen

Chair of Greater China, World Economic Forum

Joseph Costantine

Associate Professor of Electrical and Computer
Engineering, American University of Beirut

P. Murali Doraiswamy

Professor of Psychiatry and Medicine,
Duke University School of Medicine

Sarah E. Fawcett

Senior Lecturer, University of Cape Town

Olga Fink

Professor of Intelligent Maintenance and
Operations Systems, EPFL

Javier García Martínez

Professor of Chemistry and Director, Molecular
Nanotechnology Lab, University of Alicante

Daniel E. Hurtado

Associate Professor, Pontifical Catholic University
of Chile

Wendy Ju

Associate Professor, Cornell Tech

Jeremy Jurgens

Managing Director, World Economic Forum

Corinna Lathan

Co-Founder and former Chief Executive Officer,
AnthroTronix

Lee Sang-Yup

Senior Vice-President for Research, Korea
Advanced Institute of Science and Technology

Geoffrey Ling

Professor of Neurology, Johns Hopkins Hospital

Andrew Maynard

Professor of Advanced Technology Transitions,
Arizona State University

Ruth Morgan

Vice-Dean (Interdisciplinary Entrepreneurship),
Faculty of Engineering Sciences, University College
London (UCL)

Elizabeth O'Day

Chief Executive Officer and Founder, Olaris

Mine Orlu

Professor of Pharmaceutics, UCL School of
Pharmacy, Faculty of Life Sciences, UCL

Carlo Ratti

Director, Massachusetts Institute of Technology
(MIT) Senseable City Lab

Barry Shoop

Dean of Engineering, Albert Nerken School
of Engineering, The Cooper Union for the
Advancement of Science and Engineering

Landry Signe

Senior Fellow, Brookings Institution

Wilfried Weber

Scientific Director, Leibniz Institute for New Materials

Angela Ruohao Wu

Associate Professor, Hong Kong University
of Science and Technology

Xu Xun

Director, BGI Research

Academics

Mark Billinghurst

Professor, University of South Australia

Cristina Botella

Full Professor, Universitat Jaume I

Yohann Boutté

Research Director, Centre National de la Recherche
Scientifique (CNRS)

Kim Bullock

Clinical Professor, Stanford

Mouloud Denai

Senior Lecturer, University of Hertfordshire

Anirban Dutta

Associate Professor in Biomedical Engineering,
University of Lincoln

Issam El Naqa

Chair and Senior Member, Moffitt Cancer Center

Sanket Goel
Professor, BITS Pilani, Hyderabad Campus

Chenghong Gu
Reader, University of Bath

Thomas Hartung
Professor, Johns Hopkins University

Paul Hyman
Professor of Biology, Ashland University

Xiuliang Jin
Professor, Institute of Crop Sciences,
Chinese Academy of Agricultural Sciences

Kumaran Kannaiyan
Associate Professor, Guangdong Technion Israel
Institute of Technology

Farah Kidwai-Khan
Senior Data Scientist, Yale

George Kouvas
Chief Technology Officer, Wyss Center for Bio and
Neuroengineering

Oliver Kröcher
Head of the Bioenergy and Catalysis Laboratory,
Paul Scherrer Institut

Eungje Lee
Staff Scientist, Argonne National Laboratory

Yongliang Qiao
Research Fellow, The University of Adelaide

Deborah Richards
Professor, Macquarie University

Stefano Rinaldi
Associate Professor, Università degli
Studi di Brescia

Dwayne Roach
Assistant Professor, San Diego State University

Philippe Roux
Professor, Université de Montréal

Yasir Saleem
Lecturer in Computer Science,
Aberystwyth University

Michael Short
Professor, Teesside University

Lei Shu
Professor, Nanjing Agricultural University

Mel Slater
Distinguished Investigator, University of Barcelona

Lena Smirnova
Assistant Professor, Johns Hopkins University

Daobilige Su
Associate Professor, China Agricultural University

Vincent Quoc-Huy Trinh
Clinical Assistant Professor, Université de Montréal

Julien Weissenberg
Founder, Deep Tech Experts

Alicja Wegrzyn
Professor, University of Gdańsk

Yaolin Xu
Researcher, Helmholtz-Zentrum Berlin für
Materialien und Energie (HZB)

Guo Zhao
Associate Professor, Nanjing Agricultural University

Innovator Community members

Marissa Ruby Brock
Senior Director, Policy and Government Affairs,
Sourcemap

Jamie Burrows
Founder and Chief Executive Officer, Vertical Future

Isaac Castro
Co-Founder and Co-Chief Executive Officer, Emerge

Jim Flatt
Co-Founder and Chief Executive Officer,
Brightseed Bio

Adam Hildreth
Founder, Crisp

Igor Jablakov
Chief Executive Officer, Pryon

Bu Gi Kim
Chief Executive Officer, Standard Energy

Sky Kurtz
Founder and Chief Executive Officer,
Pure Harvest Smart Farms

Ben Lamm
Chief Executive Officer, Colossal Biosciences

Kevin Lang
Chief Executive Officer, Agerpoint

Maarten Michielssens
Founder and Chief Executive Officer, EnergyVision

Tsuyoshi Stuart Oda
Founder and Chief Executive Officer,
Alesca Life Technologies

Joe Paluska
Chief Marketing Officer, One Concern

Joris Poort
Founder and Chief Executive Officer, Rescale

Felix Reinshagen
Chief Executive Officer, NavVis

Umesh Sachdev
Chief Executive Officer, Uniphore

Jimmy Samartzis
Chief Executive Officer, LanzaJet

Ritwik Sinha
Strategy Analyst, Our Next Energy (ONE)

Didier Toubia
Co-Founder and Chief Executive Officer, Aleph Farms

Raj Verma
Chief Executive Officer, SingleStore

Ellie Wood
Chief of Staff to the Chief Executive Officer,
LanzaTech

Josef Zankowicz
Vice-President Corporate Development, Canvass AI

Endnotes

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org