Centre for the Fourth Industrial Revolution

WORLD ECONOMIC FORUM

In collaboration with Frontiers

Top 10 Emerging Technologies of 2025

FLAGSHIP REPORT

JUNE 2025

Images: Midjourney, Studio Miko. All images in this report were generated using artificial intelligence.

Contents

Foreword

Frederick Fenter
Chief Executive Editor,
Frontiers

Jeremy Jurgens
Managing Director,
World Economic Forum

Every year, remarkable innovations emerge from research labs around the world. Many hold tremendous promise, yet too few successfully make the critical leap from scientific discovery to real-world application. For 13 years, the World Economic Forum's Top 10 Emerging Technologies report has aimed to change that by shining a spotlight on breakthrough technologies with the potential not only to cross this threshold but also to help societies adapt and thrive in the face of complex challenges.

This report serves a clear purpose: to catalyse forward-looking dialogues and shape technology agendas by connecting cutting-edge research with those who can help advance it. By identifying technologies at their turning point – where scientific achievement meets practical potential – we provide leaders in government, business and science with the insights needed to make forward-thinking decisions in a rapidly evolving landscape.

Our work arrives at a pivotal moment. The global innovation landscape continues to evolve, with shifting trade relationships, supply chain reconfigurations and regional dynamics creating new strategic considerations. In this context, the technologies highlighted in this report take on additional dimensions of importance. Some may offer pathways to greater self-sufficiency and resilience; others could serve as bridges for essential international collaboration despite broader tensions. Many represent areas where shared global interests matter more than short-term differences.

Each technology in this report has been carefully evaluated based on its novelty, development progress and transformative potential. From materials that store energy within their structure to new treatments for neurodegenerative diseases, these innovations have moved beyond theory and demonstrated the capacity to strengthen society's ability to adapt and thrive.

What makes this report valuable is that we look beyond what these technologies are to envision what they could create. Each entry includes a strategic outlook that illustrates possible futures if these innovations reach their full potential. Developed in collaboration with the Dubai Future Foundation, these forward-looking scenarios help readers see transformative possibilities and inspire the commitment needed to move these technologies from promising concepts to widespread implementation.

The technologies in this edition reveal exciting patterns: combining energy systems with advanced materials, using biological approaches to improve human health, reimagining industrial processes for sustainability and creating new foundations for trust in connected systems. Each represents not just a technical advance, but a path towards more resilient and sustainable societies.

This work would not be possible without Mariette DiChristina and Bernard Meyerson, co-chairs of our Emerging Technologies Steering Committee. Their leadership has been essential in shaping both this report and the selection process behind it. We are equally grateful to our steering committee members, whose diverse expertise ensures we identify truly groundbreaking technologies with the potential to transform our world.

As the report continues to evolve, this year we've also introduced ecosystem readiness maps that provide practical guidance on the specific actions needed to scale these technologies from promise to impact.

We offer this report not as an endpoint, but as a call to action – a catalyst for the collaboration essential to help these technologies fulfil their promise. In an era of unprecedented challenges and uncertainty, these innovations give us powerful tools to adapt, overcome and thrive.

Building strategic foresight

H.E. Khalfan Belhoul
Chief Executive Officer,
Dubai Future Foundation

Strategic foresight is the deliberate exploration of possible futures to inform today's decisions. In an era of accelerating change, foresight enables leaders to move beyond short-term thinking, anticipate disruption and uncover opportunities that lie beyond the immediate horizon.

At its core, strategic foresight recognizes that technological innovation cannot be understood through a single, linear perspective. At the Dubai Future Foundation (DFF), we assess emerging technologies through three simultaneous and interconnected lenses:

As an assumption

Technological progress will continue to accelerate.

As an uncertainty

Technologies are shaped by complex constraints – infrastructure limitations, energy demands, policy shifts and societal readiness.

As an enabler

Technologies that underpin emerging megatrends and future opportunities.

Beyond merely predicting outcomes, strategic foresight unpacks the various pathways through which different possibilities might unfold, revealing how innovations can transform our collective future.

In exploring these technologies, we invite readers to look beyond technical specifications. Each innovation represents more than an isolated advancement – it is a signal of broader transformations taking shape across our global systems. These are not just technologies, but potential catalysts for reimagining how we address complex global challenges.

For those interested in a deeper exploration of each technology's potential, the strategic outlook sections that follow each description offer a comprehensive view of transformative possibilities and strategic implications. To ground these technologies in the context of global change, every entry is tagged with two of the DFF megatrends that are most likely to enable, and be enabled by, the respective technology within the next decade.

By connecting these emerging technologies to wider contextual frameworks, we aim to provide a comprehensive view that bridges technical potential with human aspiration. Our goal is not to present a definitive roadmap, but to spark imagination, encourage dialogue and consider multiple futures that might emerge from some of today's most promising innovations.

Introduction

A message from the Top 10 Emerging Technologies Steering Group Co-Chairs.

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

Bernard S. Meyerson
Chief Innovation Officer
Emeritus, IBM

The Fourth Industrial Revolution continues apace, filling this year's Top 10 Emerging Technologies report with a striking array of integrative advances that address global gaps and concerns. Our selection reflects the diverse nature of technological emergence – some technologies, like structural battery composites, represent novel approaches to longstanding challenges, while others, such as GLP-1s (glucagon-like peptide-1) for neurodegenerative diseases and advanced nuclear technologies, demonstrate how established innovations can find transformative new applications. Each represents a critical inflection point where scientific achievement meets practical potential for addressing global needs. (For more on how the Fourth Industrial Revolution sparks "waves of further breakthroughs", see the final chapter of this report, "From weak signals to societal transformation".)

Take, for instance, the integration of energy systems and materials, which provides dramatic improvements in functionality and efficiency as seen in this year's list. In structural battery composites, transport gets an upgrade with "massless" energy systems that blend into the load-bearing elements. Turning to other sources of energy, advances in materials for semipermeable membranes enable "salt power" in osmotic power systems. Finally, in the search for non-carbon energy sources, new designs for next-generation nuclear power plants are coming online.

Biotechnology also offers some striking additions to human health in this year's top 10. Biologically based interventions are gaining momentum as both treatment and monitoring solutions, moving beyond traditional pharmaceutical approaches. Witness engineered living therapeutics, microbes genetically engineered into living factories that could produce medicines and other therapeutic substances as needed by the body. A new class of drugs, called GLP-1s, well-known in weight-loss medications and management of type 2 diabetes, are now being brought to bear on brain-related diseases such as Alzheimer's and Parkinson's. It is anticipated that autonomous biochemical sensing, where analytical devices continuously monitor chemical or disease markers, will soon replace single-use tests at scale.

Core industrial processes are being fundamentally reimagined for sustainability and efficiency. Examples in this year's top 10 include green nitrogen fixation, in which atmospheric nitrogen is converted into crop-feeding ammonia for fertilizer with a vastly lowered carbon footprint. Meanwhile, nanozymes, laboratory-produced nanomaterials with enzyme-like properties that act as catalysts in important industrial processes, offer increased stability, lower production costs and simpler synthesis processes.

Trust and safety in connected systems are clearly essential to our networked future. Collaborative sensing, for example, will rely on that. Sensors distributed in homes, vehicles and workspaces are increasingly being connected to each other and used by artificial intelligence (AI)-infused systems. Last and not least, this year, the World Economic Forum's *Global Risks Report 2025* again highlighted misinformation and disinformation as key current risks. Generative AI watermarking, which embeds invisible markers to verify authenticity and origins, may help offer a way forward.

Applied collaboratively and wisely, as always, emergent innovations inspire more confidence in humanity's ability to improve the state of the world. We invite you to engage with this year's list in detail and welcome your feedback.

Methodology

The 2025 emerging technologies were selected through expert nominations, AI analysis, readiness assessment and strategic evaluation.

Technologies were nominated for the *Top 10 Emerging Technologies of 2025* report through a survey distributed to the World Economic Forum's Global Future Councils Network, the Frontiers network of chief editors, comprised of editors from top institutions worldwide, and the Top 10 Emerging Technologies Steering Committee members.

The report's definition of "emerging technologies" encompasses both entirely novel innovations and established technologies being applied in transformative new ways. This inclusive approach recognizes that technological emergence occurs through multiple pathways – whether through groundbreaking new discoveries or through applying existing technologies to solve different problems in ways that could create significant new impact.

Survey respondents, representing a global community of trusted academics and researchers, provided information about the technology nominated, including the technology name, description, key breakthroughs, case studies and how it will impact economies, the environment and society, as well as potential risks that accompany the technology.

In 2025, more than 250 valid technology nominations were submitted by experts across industry and academia. To screen these submissions, the AI Trend Analyzer – developed by Frontiers – mapped nominations to key concepts and matched these concepts to their frequency in academic articles over a rolling 10-year period. From this analysis, an average "trendiness" score was established, indicating each technology's growing presence and momentum in research literature.

Each technology was also evaluated using the World Economic Forum Resilience Consortium's *Resilience for Sustainable, Inclusive Growth* (2022) framework, focusing on their potential to address systemic challenges and contribute to building adaptive capacity for future generations.

The ranked technologies were then filtered by removing those featured in previous editions of the report. Business funding data was added to support the analysis for each of the top 20 technologies, providing insight into market confidence and commercialization potential.

This refined shortlist of 20 technologies was then assessed by a steering committee of experts, who applied the following selection criteria:

– **Novelty:** Early adoption is emerging, but widespread use is not yet achieved.

– **Impact:** Potential for significant societal and economic benefit.

– **Depth:** Developed across multiple entities, with broad and sustained interest.

This rigorous, multi-phase selection process ensures a comprehensive and objective assessment of each technology's readiness and transformative potential.

Ecosystem readiness

This year introduces an ecosystem readiness map for each technology. This analysis evaluates how prepared the societal infrastructure is for these technologies to scale and achieve their projected impact.

For each technology, insights were gathered from the Top 10 Emerging Technologies Steering Committee, Frontier's network of chief editors and futurists from the Dubai Future Foundation. These experts evaluated readiness across five key dimensions, commonly known as STEEP (social, technological, environmental, economic and political) analysis:

Social: Public awareness, acceptance, education levels and cultural values that support the technology

Technological: Maturity of underlying technologies, research needs and supply chain readiness

Environmental: Access to required resources, sustainability of materials and alignment with emission regulations

Economic: Market demand, investment trends and business model viability

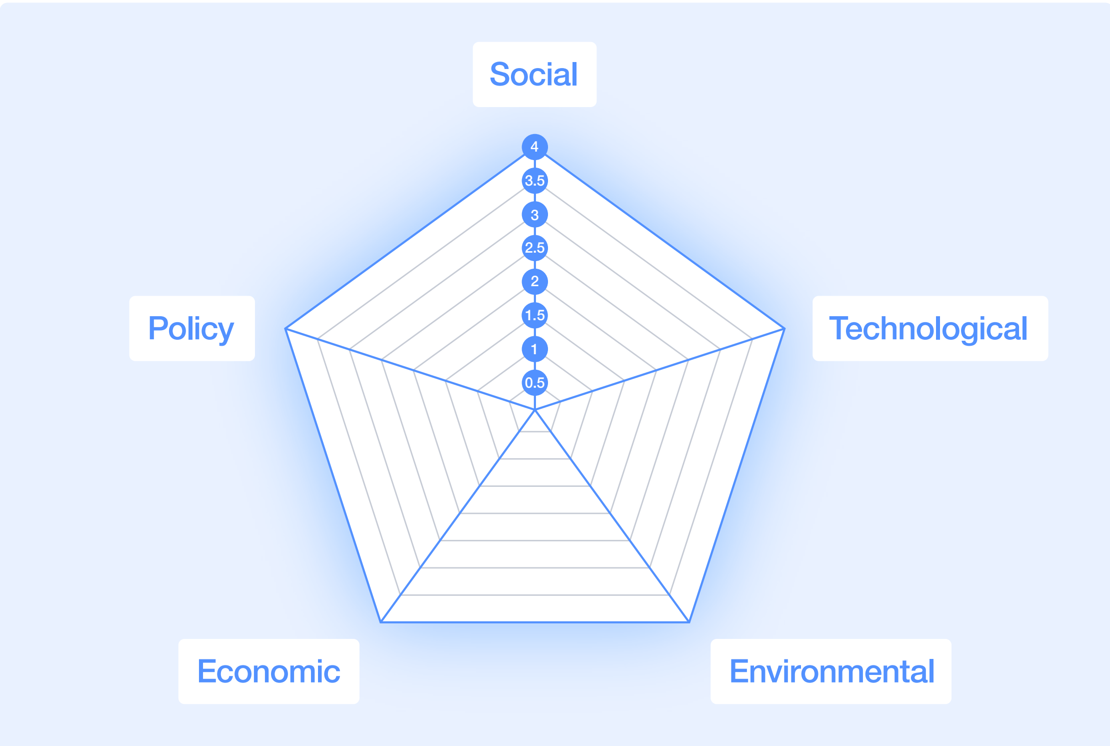
Policy: Regulatory frameworks, international policy alignment and trade barriers

Each dimension was rated on a four-point scale from "no readiness" to "high readiness". The results are displayed in radar charts (see Figure 1) in each technology section, accompanied by key actions required to achieve scale.

These assessments help identify critical gaps that must be addressed before technologies can reach their full potential, providing valuable context for decision-makers across sectors.

FIGURE 1

Ecosystem readiness map



Strategic outlooks

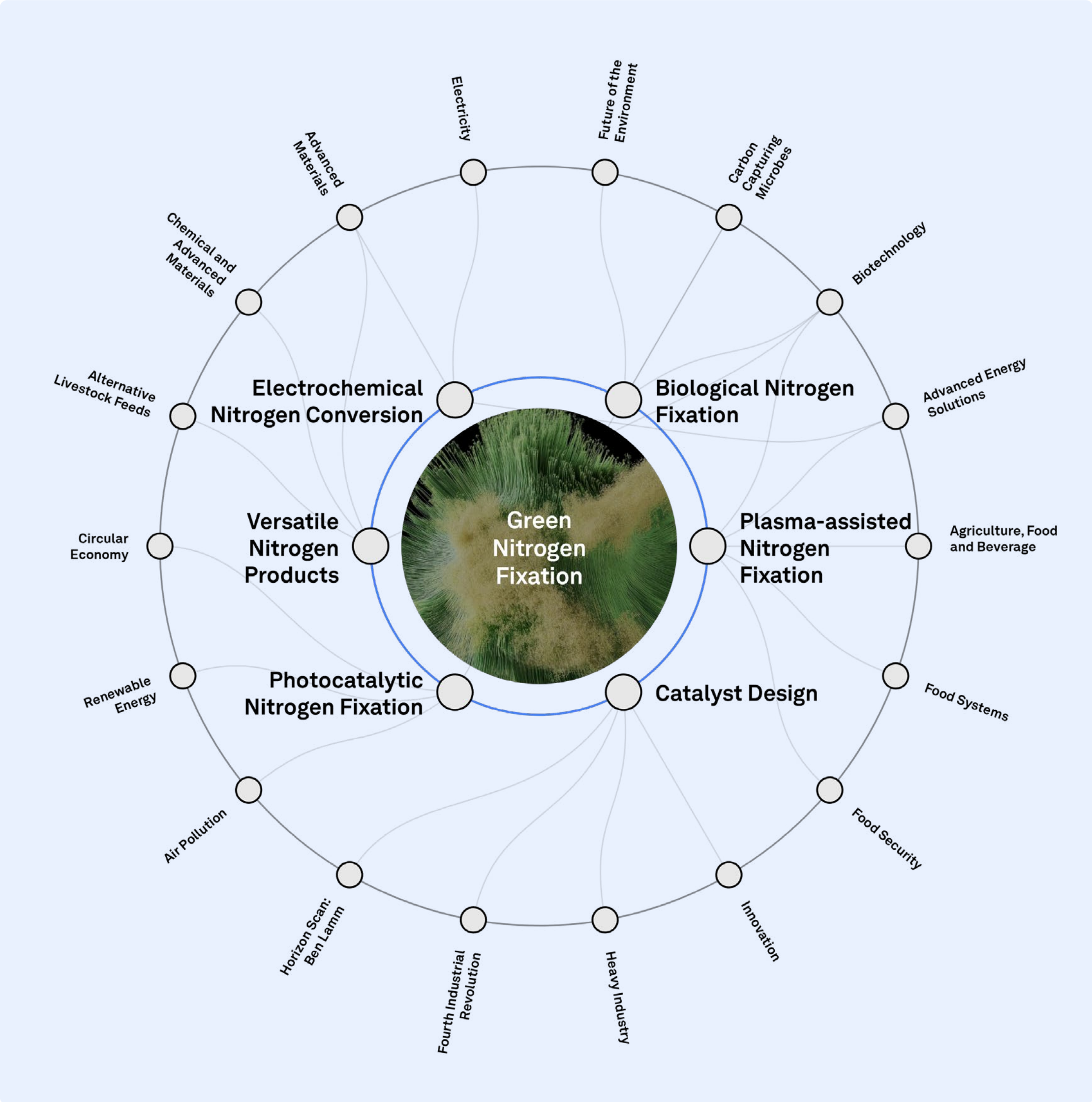
The strategic outlooks in this report were developed by the Dubai Future Foundation (DFF). For each selected technology, inputs included academic research literature, market analyses and an in-depth foresight analysis of key drivers and implications. The development process involved an initial assessment of each technology's transformative potential, followed by a systematic analysis of cross-sector applications and implementation barriers. Parameters for evaluation included potential impact across economic, social and environmental dimensions, with particular attention to scaling requirements, governance implications and system-level changes. Each technology was also categorized according to its relationship with two of DFF's megatrends framework categories to position these innovations within broader evolutionary patterns. This methodical approach ensures consistent evaluation across diverse technological domains.

Transformation maps

To complement this year's report, transformation maps have been developed in partnership with Frontiers' chief editors. These digital tools visualize how each technology connects to broader systems and global priorities. Hosted on the Forum's Strategic Intelligence Platform, the maps illustrate intersection points between emerging technologies and related topics, providing curated content from trusted sources. They offer decision-makers a practical resource for exploring potential impacts, understanding cross-domain relationships and tracking ongoing developments.

Explore the maps here →

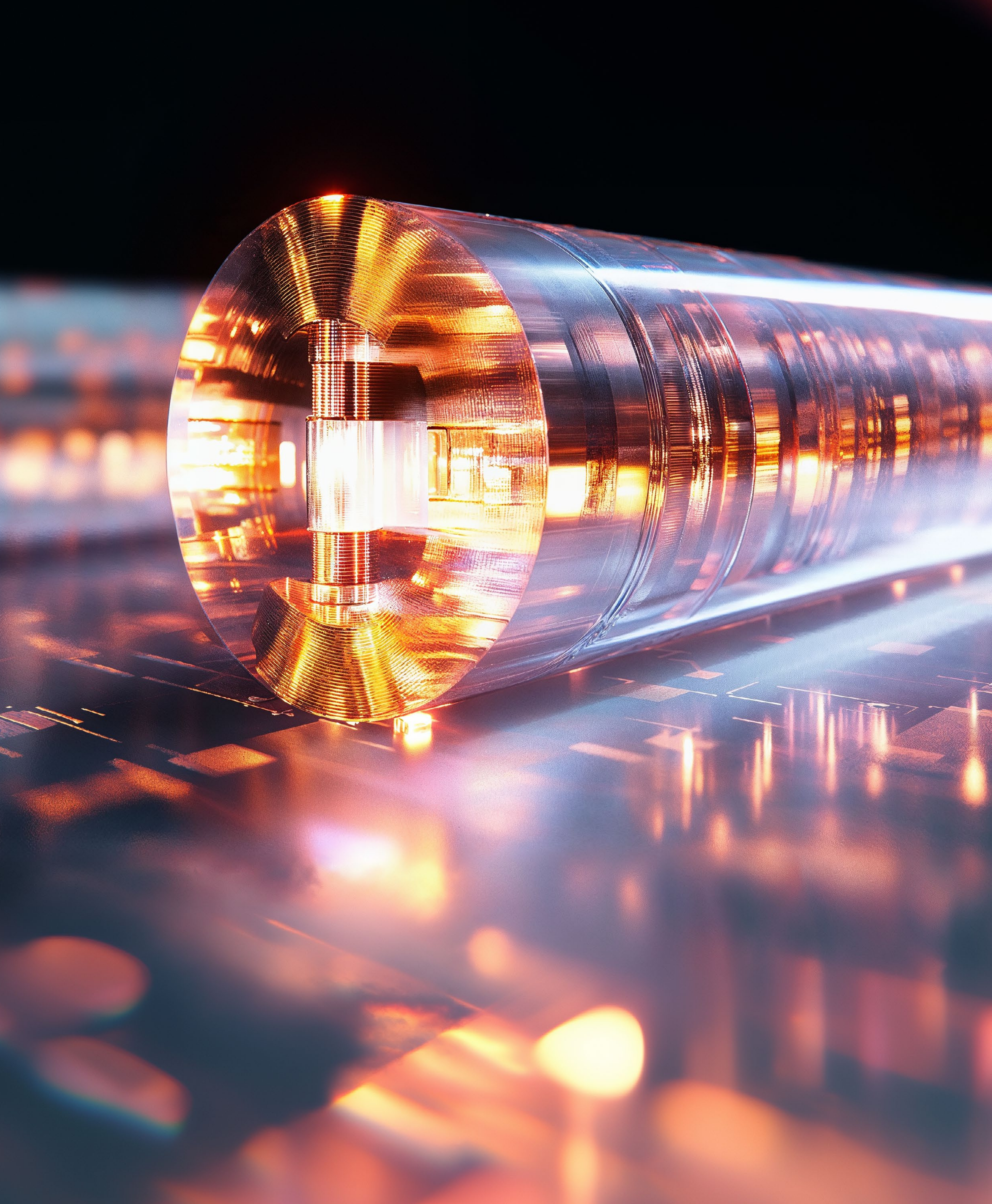
FIGURE 2 **Example: Green nitrogen fixation transformation map**



01

Structural battery composites

Merging energy and engineering in motion.



Doug Arent

Executive Director, National Renewable Energy Laboratory Foundation

Andrew Maynard

Professor, School for the Future of Innovation in Society, Arizona State University

David Parekh

Chief Executive Officer, SRI International

Structural battery composites (SBCs) integrate load-bearing mechanical components and rechargeable energy storage. This means structural battery composites can store energy the same way as traditional lithium-ion batteries, while also being rigid components of the vehicle or building that the battery is powering.[1] In contrast, the electrochemical components of a traditional battery system are housed in a container that adds weight without providing any structural benefit. SBCs may include carbon fibre, epoxy resin or other lightweight, high-strength materials and can be 3D printed and optimized for surface area and structural strength to enhance efficiency.[2] SBCs have uses in a wide variety of applications, ranging from electric vehicles (EVs) to aerospace technologies.

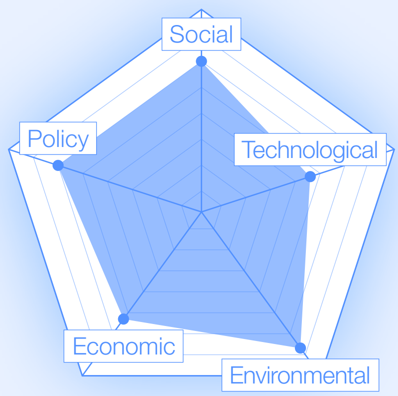
The concept of structural battery composites arose in the past couple of decades from advances in material science, particularly in the fields of composite materials, batteries and electrochemistry.[3] The technology is still in the early stages of commercialization but has made significant progress. EVs already use batteries as part of the vehicle's structure, but SBCs will take that to the next level by enabling body panels of all shapes and sizes to perform both functions.

In the future, SBCs could enable all rigid vehicle body panels to similarly store energy. For example, Airbus is experimenting with SBCs for use in aircraft,[4] whereas academic research continues to explore new materials and methods to enhance performance. Applications currently being explored include energy-storing vehicle body panels and drone frames, with some potential future applications including aircraft fuselages.

As transformative as its potential is, SBC technology has yet to achieve widespread adoption due to technical challenges such as achieving high energy storage density, long-term stability, safety, durability and cost-effectiveness.[5] Regulatory hurdles also remain. As structural battery composite materials mature, a new set of safety regulations and standards must be developed before wide-scale adoption is possible. Key milestones include the integration of lightweight materials like carbon fibre with battery technology, creating multilayer composites that can function as both structural components and energy storage units.

The impact of SBCs will be substantial. Economically, they promise to cut manufacturing costs by reducing the amount of structural materials, which, in turn, can lower the overall weight of vehicles and aircraft; lighter-weight vehicles require less fuel to operate as well. Environmentally, SBCs could lead to energy-efficient designs that reduce material requirements, and make reuse, repurposing and recycling faster and cheaper, if developed appropriately. Their use in industries including aviation and transport could contribute to more reliable and sustainable operations.

Ecosystem readiness map



KEY ACTIONS TO ACHIEVE SCALE

Develop industry-specific demonstration platforms – Collaborate with key transport manufacturers (automotive, aerospace, marine) to build functional prototypes that quantify weight reduction, range improvement and structural integrity benefits.

Establish specialized manufacturing capacity – Invest in pilot production facilities that combine battery manufacturing expertise with advanced composite fabrication techniques to address the unique production challenges of structural battery components.

↑ **Image:**
SBCs combine energy storage and structural strength, enabling lighter, multifunctional components for transport and aerospace.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Golden layered quantum disks refining and filtering organic data into a single light stream."

Read more:
For more expert analysis, visit the SBCs transformation map. Authored by: Lief Erik Asp, Björn Johansson and Johanna Xu.

Strategic outlook
Structural battery composites

By Dubai Future Foundation

The convergence of materials science and energy technology through structural battery composites represents a critical inflection point for global industries. Over the next decade, these innovative materials have the potential to fundamentally restructure how infrastructure, energy storage and product design are conceived across multiple sectors.

With 85% of lithium currently refined by just three countries,[6] the geopolitical landscape of critical minerals currently stands at a pivotal moment. SBCs offer a strategic pathway to diversify and decentralize energy material supply chains. This technological shift could reshape global economic dependencies, transforming how nations approach energy infrastructure and technological sovereignty.

Beyond supply chain impacts, transformative potential is most evident in transport. In the automotive sector, a 10% reduction in vehicle weight can improve fuel efficiency by 6-8% and increase EV range by 70%.[7,8] Aviation presents an equally compelling opportunity, with potential fuel efficiency improvements of 15% over a 1,500 km flight.[9] These are not merely incremental improvements, but potential catalysts for systemic change in transport design and energy consumption.

To realize benefits at scale, strategic leaders must recognize challenges that extend beyond technological innovation. Existing regulatory frameworks do not fully account for dual-function materials. Safety standards, testing protocols and building codes will require comprehensive reimagining to accommodate materials that simultaneously provide structural integrity and energy storage.

Sustainability is both a critical challenge and an opportunity. Carbon fibre, while five times stronger than steel, currently faces significant environmental constraints due to carbon-intensive production and recycling challenges.[10,11] However, advances in AI-driven composite material design suggest the emergence of more scalable, bio-based alternatives.[12]

The most forward-thinking organizations will view this technology as more than a product improvement. It represents a fundamental redesign of how material functionality is conceived. In construction, this means buildings that are not just shelters, but active energy systems. In electronics, it translates to devices that seamlessly integrate structural integrity and power storage.

Strategic decision-makers face a critical choice. Those who proactively invest in understanding and developing these technologies will be positioned to:

- **Redesign entire product categories**
- **Reduce energy consumption across industrial sectors**
- **Create more resilient and adaptive infrastructural systems**
- **Develop new economic models that challenge existing technological paradigms**

The next decade will offer significant advantages to organizations that look beyond incremental improvements and recognize SBCs as a transformative technological platform. Success will depend on unprecedented collaboration across materials science, design, energy systems and regulatory frameworks.

→ **Related DFF megatrends:** Materials and Energy Boundaries[13]

02 Osmotic power systems

Channelling salt into energy.

Katherine Daniell

Director and Professor, School of Cybernetics, Australian National University

Alison Lewis

Dean of the Faculty of Engineering and the Built Environment, University of Cape Town

Osmotic power systems use a variety of means to generate energy from salinity (salt content) differences in two sources of water. Such systems are clean, renewable and low-impact – and they provide a steady source of energy. In contrast, the energy produced by renewables such as solar and wind power may fluctuate greatly during the course of a day, depending on weather conditions.

Although the concept was first proposed in 1975,[14] osmotic power systems could not be adopted at the time due to limitations of membrane performance, including inadequate flows through the membrane and insufficient power produced even in larger area systems.[15] To address both issues, recent advances have yielded new materials,[16,17] and system designs[18] that facilitate flow through membranes.

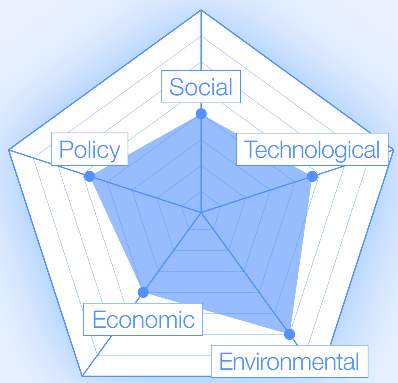
There are two general designs for osmotic power systems. One, called pressure retarded osmosis (PRO), uses a specially designed semipermeable membrane that only allows water to move from a low- to high-salinity environment. The increased amount of water on one side of the membrane generates a pressure difference that can be used to drive a turbine that spins a generator to produce electricity.

Another type relies on reverse electrodialysis (RED),[19] which uses ion-exchange membranes that selectively allow cations (positive charge) and anions (negative charge) to move to opposite sides of the membrane – the impetus to do so again being differences in the salt content between two sides of the membrane. That flow of charge in this instance directly generates electricity.

These advances are both in lab trials and being developed into commercial power plants. One commercial effort, for instance, the OsmoRhône 1 by Sweetch Energy, began system installations in 2024. A Danish company, SaltPower,[20] founded in 2015, already generates power using the super-concentrated salt solutions that well up from geothermal sites. In a form of circular economy, the Mega-ton Water System Project in Fukuoka, Japan[21] extracts energy from a seawater desalination plant's output of highly saline solution left over after purified water is produced.[22] In addition to power generation, techniques such as RED have been shown to potentially be relevant to producing purified water, and recovering lithium, nitrogen and carbon dioxide (CO_2) from the water employed in the process.

Remaining challenges to full emergence are largely technical and economic in nature. Previous generations of osmotic power stations suffered from membrane fouling and high costs, although recent advances have improved performance. The technology is otherwise based on clear and uncontroversial scientific principles for extracting energy from differences in salinity. Beyond licensing processes and effective environmental and social impact assessments, there appear to be relatively few hurdles to wide adoption once sufficient financial investments are made into osmotic power systems.

Ecosystem readiness map



KEY ACTIONS TO ACHIEVE SCALE

Establish demonstration projects – Create public-private partnerships to build pilot osmotic power plants in diverse geographic locations to validate the technology across different environments.

Develop community engagement programmes – Implement educational initiatives in potential host communities that clearly demonstrate osmotic power's dual benefits for clean energy generation and water management.

↑ Image: Osmotic power generates steady, renewable energy from salinity differences, with advancing membranes improving efficiency and viability.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Flow of energy between two sources of water, creating electricity."

Read more: For more expert analysis, visit the osmotic power systems transformation map. Authored by: Odne Burheim.

Strategic outlook
Osmotic power systems

By Dubai Future Foundation

Osmotic power systems could offer a unique approach to energy generation, with the potential to generate 5,177 terawatt-hours (TWh) annually – nearly a fifth of global electricity needs.[23,24] If developed at scale, this technology might transform how societies manage water resources while simultaneously creating new energy generation capabilities across coastal and estuarine environments.

The most compelling opportunity lies in the technology's ability to integrate energy production with water management. Utility companies might develop hybrid renewable systems that combine osmotic power with wind, solar and hydro technologies, creating more adaptive and resilient energy networks.[25] Coastal and estuarine communities could particularly benefit from decentralized energy solutions that enhance local energy resilience.[26]

As the technology matures, it could reshape global approaches to resource management. The growing research momentum – with 281 research papers published between 2022 and 2024, compared to 263 between 1968 and 2010 – suggests a critical inflection point.[27] Investments like Sweetch Energy's €25 million funding indicate increasing confidence in the technology's potential.[28]

Equally transformative is the potential that extends beyond energy generation to enable new approaches to water treatment and resource recovery. Osmotic power technologies could enable new approaches to desalination while recovering critical resources like lithium during the process. This could create interconnected systems where water management, energy production and resource extraction become deeply integrated.[29,30]

Imagine a future where water-intensive industries view water not as a waste stream, but as a strategic resource platform. Communities might develop economic models that transform geographical constraints into opportunities. These industries could reimagine their infrastructure to generate multiple forms of value – energy, purified water and recovered materials – from each interaction with water.

To realize benefits at scale, the most innovative organizations will recognize osmotic power as more than an energy technology – it represents a potential platform for reimagining how water-intensive industries create economic value. A desalination plant could evolve from a cost centre to a multi-purpose resource generator, simultaneously producing energy, purified water and recoverable minerals – transforming infrastructure from a linear process to an adaptive, value-creating ecosystem.

By integrating osmotic power systems, societies could develop more resilient, sustainable approaches to resource management. This technology might help transform how energy is generated, water is treated and economic value is created – potentially enabling infrastructure that serves multiple functions simultaneously across water management and energy production.

→ **Related DFF megatrends:** Materials and Energy Boundaries[31]

03

Advanced nuclear technologies

Bringing next-generation nuclear to power progress.

Doug Arent
Executive Director, National Renewable Energy Laboratory Foundation

Bernard Meyerson
Chief Innovation Officer Emeritus, IBM

Karen Hallberg
Principal Researcher, Bariloche Atomic Center (CONICET)

Energy demand is rapidly increasing, driven by the rise of electrified transport and emerging technologies like AI and a push for decarbonization to advance climate goals. Power grids globally must grow to meet the increased loads while maintaining reliability, resiliency and affordability.

A renewed wave of technological innovation in nuclear energy is under way to address demands for green power options. Generation III reactors are primarily pressurized water-cooled reactors and incorporate accident-tolerant fuels and improved safety systems. In parallel, Generation IV reactors propose alternative cooling fluids, such as molten metals, molten salts or gases like helium. These alternative coolants operate at higher temperatures and lower pressures, simplify reactor designs, improve safety and reduce costs.

There is also a growing trend towards reducing the scale of power plants, with designs allowing key components to be manufactured in a factory and then transported to site. These small modular reactors (SMRs) typically cover about one-third of the generating capacity of traditional nuclear power reactors.[32] Deploying multiple identical SMRs to achieve power outputs eliminates the high costs and long design cycles of a bespoke reactor, making SMRs attractive for distributed power generation.

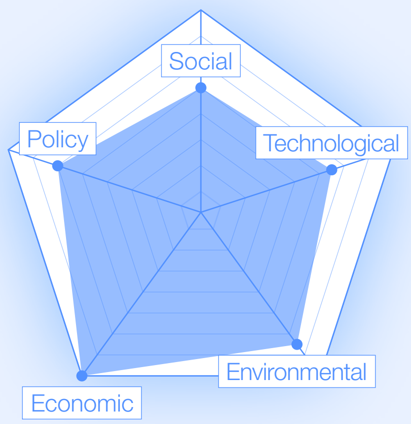
Nations are dedicating substantial public funds to support large-scale SMRs and alternative cooling designs.[33] These investments extend to new fuel fabrication facilities and enrichment plants, making deployment possible by the end of this decade.[34] Currently, only a few countries are heavily investing in large reactors outside of Russia and China. Most notably, South Korea has 26 nuclear reactors, accounting for one-third of the country's electricity,[35] and the United Arab Emirates' Clean Energy Strategy involves investment of $163 billion by 2050 to have half of its electricity come from nuclear and renewables.[36] Two European Pressurised Reactors (EPRs) and two AP1000s in the US[37] have also been brought online in recent years.

In the SMR arena, Russia and China already have operational plants, while Western countries are rapidly advancing in design, construction and regulatory frameworks to establish a competitive industry. In November 2024, in collaboration with Accenture, the World Economic Forum published *A Collaborative Framework for Accelerating Advanced Nuclear and Small Modular Reactor Deployment*, which serves as a tool to align stakeholders on key actions required to achieve the deployment of this key technology.

While the immediate future of nuclear deployment lies in fission reactors, the long-term goal for many is nuclear fusion, or the process of fusing hydrogen atoms to form helium, which releases enormous amounts of energy – the same mechanism that powers the sun. Although no net power gain has yet been achieved, there is high confidence that within one to two decades, this near-limitless source of clean energy will mature.

This shift towards advanced nuclear technologies, combined with enhanced renewable energy strategies and improved energy storage solutions, underscores the global urgency of transitioning away from fossil fuels and securing a sustainable, zero-carbon future.

Ecosystem readiness map



KEY ACTIONS TO ACHIEVE SCALE

Launch community-focused safety demonstrations – Develop educational programmes showcasing the enhanced safety features of new nuclear designs through transparent demonstrations and community engagement.

Accelerate prototype testing – Fund comprehensive testing programmes for next-generation nuclear designs, particularly gas-cooled reactors, to validate safety systems and operational efficiency under various conditions.

↑ Image:
Advanced nuclear technologies support rising clean energy demands and decarbonization goals.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Nuclear reaction creating a swirl of energy."

Read more:
For more expert analysis, visit the advanced nuclear technologies transformation map. Authored by: Sergei Dudarev, Wenxi Tian.

Strategic outlook

Advanced nuclear technologies

By Dubai Future Foundation

Advanced nuclear technologies, particularly SMRs and gas-cooled reactors, offer a promising path to clean, reliable power. These technologies combine flexible siting with enhanced safety compared to traditional nuclear plants, positioning them as key enablers of a sustainable energy future.

By 2030, SMRs could redefine how power is delivered. These factory-built units are capable of serving remote communities or being added to existing industrial sites, expanding access to steady, zero-carbon electricity. This flexibility helps support the integration of variable renewable energy sources, and their modular design boosts grid stability. SMRs extend nuclear technology's reach to areas previously unreachable for traditional large-scale plants.[38]

In parallel with SMRs, gas-cooled reactors could redefine how power is delivered. They represent a significant opportunity to drive industrial decarbonization by providing high-temperature process heat (600-950°C) for challenging applications like hydrogen production and heavy industry. With these sectors contributing approximately 15% of global CO_2 emissions,[39,40] nuclear technology could help address emissions considered among the most difficult to abate.

Looking further ahead, global nuclear capacity could double between 2020 and 2050 to support net-zero emissions goals.[41] While high initial capital costs remain a challenge, the push for standardized reactor designs and economies of scale [42] offers a pathway to more affordable deployment.

For advanced nuclear technologies to scale effectively, addressing supply chain and workforce challenges will be pivotal. Stable, sustainable access to specialized materials like radiation-resistant alloys, combined with overcoming the decline in nuclear engineering talent – highlighted by a 25% decline in nuclear engineering graduates from 2012 to 2022[43] – will be essential for maintaining momentum in reactor development and deployment.

Widespread adoption of advanced nuclear technology will hinge on rebuilding public trust through transparent communication and demonstrating the safety of next-gen reactors. Additionally, as plants become more digitalized, strong cybersecurity will be crucial to protecting infrastructure and ensuring secure, resilient power generation.

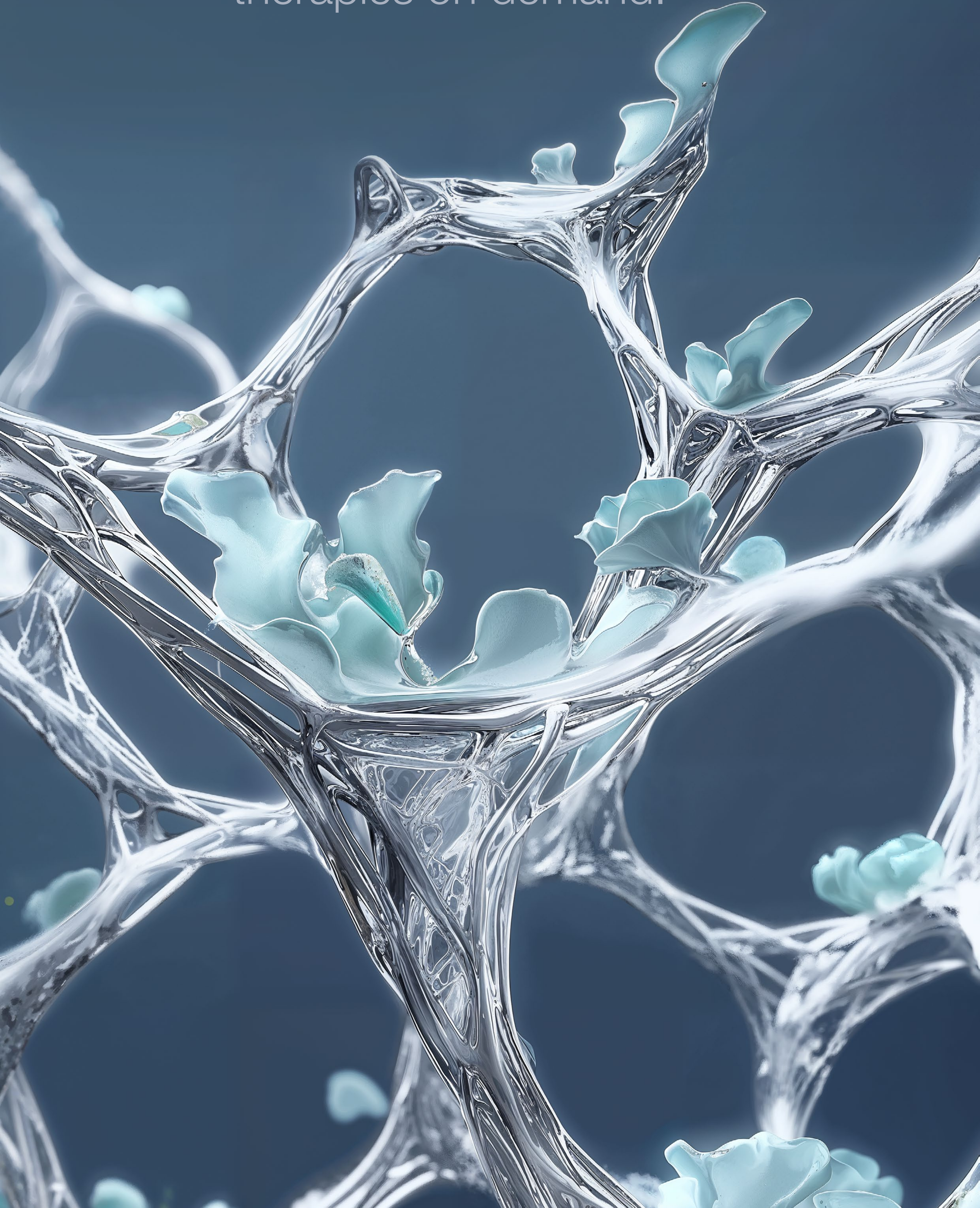
Countries leading in SMR deployment, including China, the UK and the US, are positioning themselves at the forefront of a new technological paradigm.[44] Leadership in nuclear is now a marker of strategic technology capability.

Advanced nuclear technologies will likely follow distinct adoption pathways based on specific use cases rather than a single deployment model. SMRs may first serve remote communities and industrial facilities requiring reliable power independent of grid infrastructure, while advanced reactor designs may integrate into existing power grids as replacements for retiring conventional plants. The greatest value lies where nuclear intersects with renewables, hydrogen and industrial decarbonization.

→ **Related DFF megatrends:** Materials and Energy Boundaries[45]

04 Engineered living therapeutics

Microbes designed to deliver therapies on demand.



Thomas Hartung
Professor, Doerenkamp Zbinden Chair for Evidence-based Toxicology, Johns Hopkins Bloomberg School of Public Health

Wilfried Weber
Scientific Director and Professor for New Materials, Leibniz Institute for New Materials

Sang-Yup Lee
Senior Vice-President, Research; Distinguished Professor, Korea Advanced Institute of Science and Technology (KAIST)

Engineered living therapeutics are advanced probiotic systems – such as microbes, cells and fungi associated with human health – that are being developed to produce therapeutic substances like drugs, enzymes and hormones in a controlled and sustainable manner. To enable this, the genetic code containing instructions for producing therapeutics is introduced into the systems. An important feature of this approach is the ability to include biological control mechanisms that regulate therapeutic production – either through patient-managed triggers or in response to specific, clinically recognized disease signals – ensuring precise and safe activation.[46]

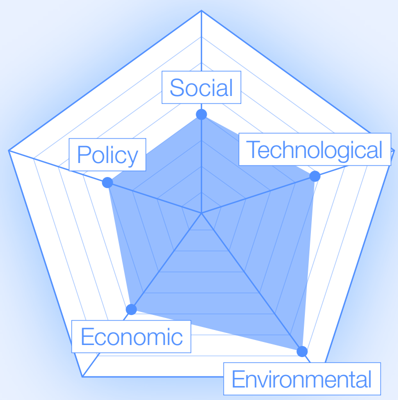
Production within the patient promises to overcome crucial shortcomings of conventional medications, especially for high-cost biopharmaceuticals. These drugs are currently produced in laboratory settings using modified cell lines, followed by extensive purification, processing and formulation. Producing therapeutics directly in the body avoids the need for these downstream steps, which typically account for 70% of production costs.[47] Further, for drugs requiring frequent administration through injections, sustained production within the patient would ensure prolonged and stable drug supply and increased patient adherence to treatment, where crucial, as in the treatment of diabetes.

These developments are made possible by advances in synthetic biology and genetic engineering, with ongoing research receiving attention in the US, Europe and China. Several companies are now developing this technology for commercial use. For example, Chariot Bioscience in the US is exploring microbial platforms that release therapeutics into the bloodstream following a single dose, significantly reducing the need for repeated injections.[48] Finnish company Aurealis Therapeutics is conducting phase II clinical trials using modified probiotic lactic acid bacteria to simultaneously produce three therapeutic proteins in the treatment of diabetic foot ulcers.[49] NEC is conducting clinical phase I/II trials using a weakened strain of *Salmonella* bacteria to facilitate activation of the patient's immune system to fight cancer cells.[50]

Importantly, safety is a central focus. Developers are actively addressing concerns such as unintended genetic transfer, immune responses and environmental release.[51] Promising approaches currently in the research phase are metabolic and genetic programmes that prevent growth or kill bacteria on command, or the safe encapsulation into polymer-based containers.[52]

Beyond scientific and technological advancements, regulatory frameworks – such as the Advanced Therapy Medicinal Products in Europe – need to be developed to enable health authorities to evaluate efficacy and safety and ultimately grant market approval.

Ecosystem readiness map



KEY ACTIONS TO ACHIEVE SCALE

Create regulatory sandboxes – Establish specialized regulatory frameworks that allow for controlled testing of engineered living therapeutics while developing permanent safety guidelines.

Launch patient-centred communication initiatives – Develop clear, accessible information resources that explain the science, benefits and safeguards of genetically modified therapeutics to patients and healthcare providers.

↑ **Image:**
Engineered living therapeutics use programmed microbes to produce drugs inside the body, reducing costs and improving treatment.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Web-like structure, growing fungi and living organisms."

Read more:
For more expert analysis, visit the engineered living therapeutics transformation map. Authored by: Jean Marie François.

Strategic outlook
Engineered living therapeutics

By Dubai Future Foundation

Engineered living therapeutics represent a promising reimagining of medicine, not as a conventional treatment but as a living system inside the body. This approach could shift drug production from pharmaceutical facilities to biological processes within patients, potentially opening new frontiers in how and where healing occurs.

For healthcare systems globally, this represents a potential solution to persistent distribution challenges. As living therapeutics enable localized, capsule-based or food-embedded treatments, traditional manufacturing and distribution models will be redefined, prompting a shift to decentralized production and the repurposing of existing pharmaceutical infrastructure for broader accessibility in areas previously deemed inaccessible.

For patients, the transformation extends beyond convenience to fundamentally alter the experience of managing chronic conditions. The current paradigm could evolve towards treatment approaches that operate seamlessly in the background of daily life. The psychological burden of constant health management could diminish as treatments become more autonomous and adaptive, potentially improving not just clinical outcomes but overall quality of life.

The pharmaceutical landscape could undergo significant transformation. Pharmaceutical corporations, biotechnology firms and research universities are likely to lead the development of living therapeutics, with new players such as dairy and probiotics manufacturers possibly entering the field. Mergers between non-traditional partners may emerge as this field evolves, with some researchers exploring the potential for carefully regulated probiotic-based platforms to support future consumer health applications.

The integration with wearable technologies could create feedback loops between therapeutic organisms and external monitoring systems. Wearable technologies may further enhance this by enabling precise, real-time monitoring of bacterial therapy, ensuring both safety and efficacy. Scaling this technology will require advancements at the intersection of AI, biotechnology and health technology. AI is expected to support the safe and targeted design of bacterial functions, helping optimize their therapeutic performance and compatibility with the human body under tightly controlled clinical conditions. The convergence of biology and technology, both in bacterial production and real-time product monitoring, will be key to living therapeutics.

Strategic preparation requires addressing several critical challenges. The ability to terminate microbial activity on demand will be needed to mitigate risks of uncontrolled replication or unintended genetic transfer. Researchers are exploring innovative safety mechanisms, such as externally activated, light-responsive bacterial systems,[53] that may offer additional layers of control compared to traditional ingestion-based shutdown methods. Regulatory frameworks are a critical part of responsible development, with structured sandbox environments offering a way to test these innovations under defined conditions, while ensuring robust ethical oversight and public accountability.

Decision-makers face a pivotal moment in healthcare's evolution. Organizations that proactively invest in engineered living therapeutics will be positioned to:

- **Transform chronic disease management from episodic treatment to continuous care**
- **Redesign pharmaceutical supply chains for enhanced accessibility and resilience**
- **Create localized production systems that reduce dependence on centralized manufacturing**
- **Develop new treatment modalities that respond dynamically to individual patient physiology**
- **Pioneer regulatory frameworks that balance innovation with appropriate safeguards**

Over the next decade, healthcare organizations, pharmaceutical companies and biotechnology firms that engage with the development of engineered living therapeutics may contribute to a meaningful evolution in how medicine is delivered and experienced.

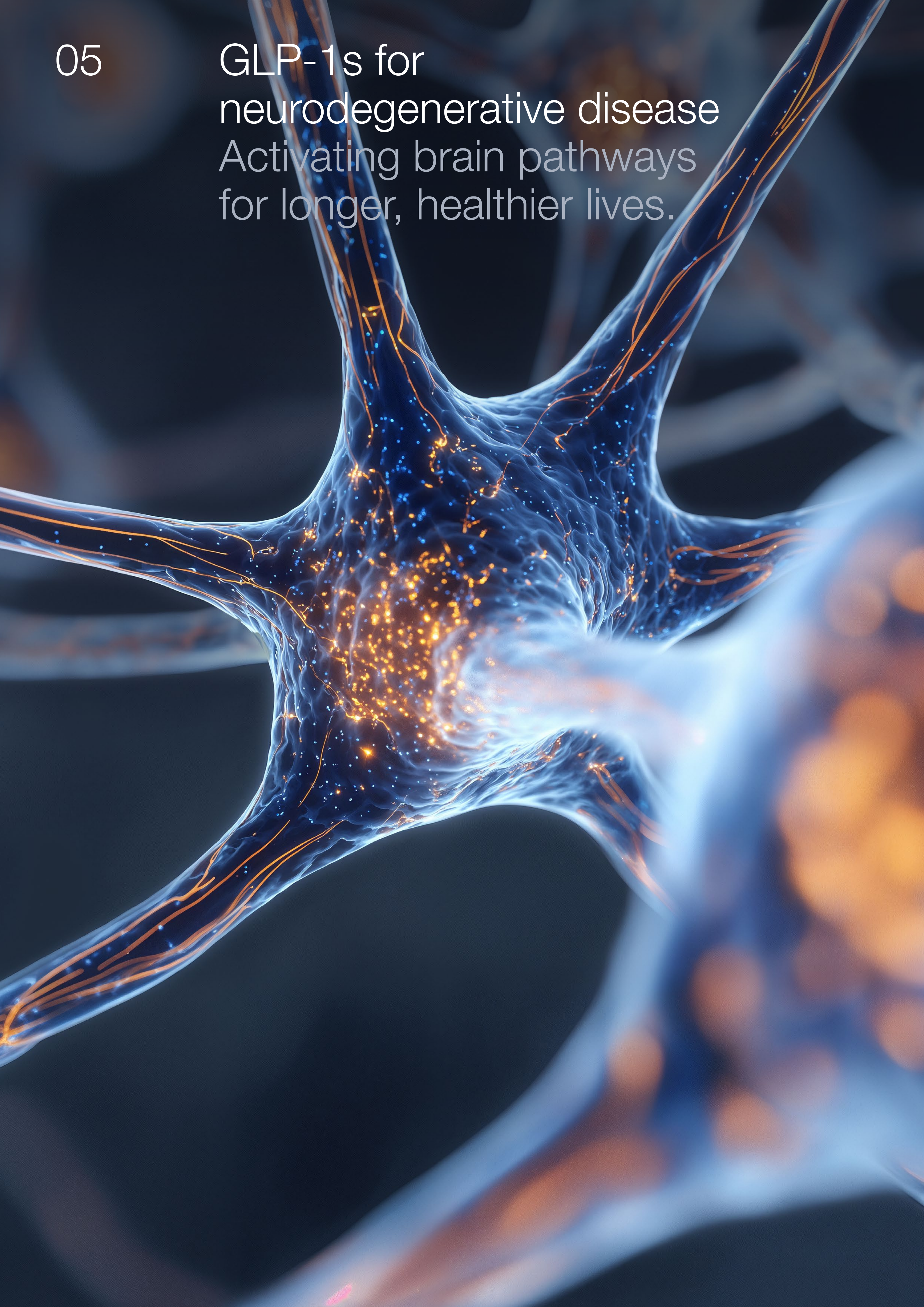
Progress would likely depend on collaboration across synthetic biology, AI, clinical medicine, patient advocacy and regulatory science to explore a future where treatments might adapt to patients rather than patients adapting to treatments.

→ **Related DFF megatrends:** Future Humanity and Advanced Health and Nutrition[54]

05

GLP-1s for neurodegenerative disease

Activating brain pathways for longer, healthier lives.



Thomas Hartung

Professor, Doerenkamp Zbinden Chair for Evidence-based Toxicology, Johns Hopkins Bloomberg School of Public Health

A recent class of drugs originally developed for type 2 diabetes and obesity management – technically known as glucagon-like peptide-1 receptor agonists (GLP-1RAs) – is now being explored for its potential in treating neurodegenerative conditions such as Alzheimer's and Parkinson's disease. Early research suggests that these drugs may have neuroprotective properties, including anti-inflammatory, antioxidant and insulin-sensitizing effects that could slow or modify disease progression.[55]

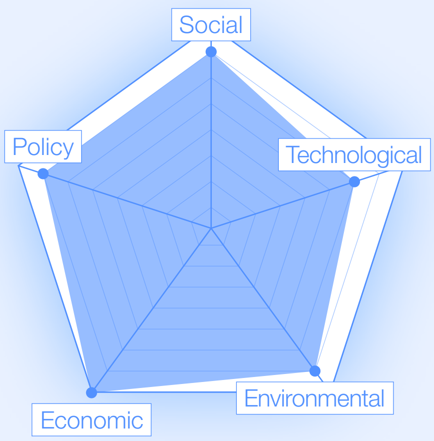
GLP-1RAs, once administered, cross the blood-brain barrier and interact with the brain's neurons and glial cells. They have been shown to reduce inflammation and promote the removal of toxic proteins, both of which, if left untreated, are linked to the development of Alzheimer's and Parkinson's.[56] This class of drugs has also been shown to enhance brain cell longevity and energy regulation, which may improve cognitive and motor function. Newer formulations are being developed to improve delivery to the brain, with the aim of enhancing their potential therapeutic effects.[57]

Preliminary observational data from use in the general population[58] have suggested possible associations with improved outcomes in individuals living with neurodegenerative conditions. Initial clinical studies have shown mixed results, but with promising signals. At present, the long-term potential of GLP-1RAs remains optimistic, but sophisticated, rigorous clinical trials are required, and are now under way, to confirm this and establish optimal protocols for drug use with desired outcomes.

If proven effective in treating Alzheimer's and Parkinson's disease, GLP-1s could have tremendous global economic impact. With over 55 million people living with dementia, the global market for GLP-1 drugs is projected to grow to $55.7 billion by 2031.[59] Similarly, benefitting society, the emotional and monetary costs associated with caring for and treating those living with these diseases would drop dramatically.

Regulatory approval remains a hurdle, as long-term clinical efficacy data are needed. Additionally, high drug costs may limit access, requiring policy interventions for affordability. Careful safety monitoring is essential, particularly regarding weight loss in frail patients. As advanced clinical trials continue, GLP-1RAs are being closely studied for their potential to improve outcomes in neurodegenerative diseases. While early research is encouraging, future impact will depend on the strength of emerging evidence and continued collaboration across the scientific, regulatory and healthcare communities.

Ecosystem readiness map



KEY ACTIONS TO ACHIEVE SCALE

Expand specialized clinical trials – Design and implement phase II/III clinical trials specifically focused on neurodegenerative applications of GLP-1RAs with longer duration to capture disease modification effects.

↑ Image:
GLP-1RAs show promise for treating Alzheimer's and Parkinson's by reducing inflammation and improving brain health.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Close-up of synapses connecting with flowing, orange energy."

Read more:
For more expert analysis, visit the GLP-1s for neurodegenerative disease transformation map. Authored by: Thomas Hartung and Jeff M.P. Holley.

Strategic outlook

GLP-1s for neurodegenerative disease

By Dubai Future Foundation

The repurposing of GLP-1RAs for neurodegenerative diseases could catalyse a significant shift in the approach to conditions that have long defined late-life decline. As early-stage research explores the potential of these medications for Alzheimer's and Parkinson's disease[60,61] – affecting nearly 50 million people globally[62,63] – their future impact, if validated, could extend beyond clinical outcomes to influence approaches to healthcare delivery, eldercare and societal expectations of ageing.

Over the next decade, healthcare delivery systems could begin a meaningful transition towards earlier intervention and disease modification rather than symptom management alone. This evolution could gradually reshape eldercare infrastructure, potentially reducing demand for intensive memory care while creating new care models focused on maintaining function and independence. Healthcare economics could shift as resources reallocate from late-stage care towards prevention and early intervention, potentially improving outcomes while creating new value pathways.

The societal impact could be substantial. For patients in early disease stages, even modest delays in progression could translate to additional years of independence and family engagement. If future treatments prove effective in slowing disease progression, this could ease caregiving demands and potentially support greater workforce participation and financial stability for caregivers – who are often women. This may also help older adults remain active and engaged for longer, potentially supporting social continuity and intergenerational connection within communities.

Supply chains for this emerging class of drugs are under pressure as demand grows.[64,65] Several major pharmaceutical firms have announced large-scale investments aimed at expanding manufacturing capacity – reflecting interest in the potential of GLP-1 therapies and the significant innovation required to meet evolving production needs.

Affordability remains a key challenge. With high costs and limited reimbursement in many settings,[66,67] GLP-1RAs may present immediate cost tensions despite potential long-term savings in care needs.[68] This raises important questions around pricing models that better balance immediate expenses against future benefits, potentially accelerating broader reforms in how healthcare systems value preventive interventions.

Given the promising but mixed results from recent clinical trials,[69] GLP-1RAs are being explored as a potential component of future therapeutic strategies – pending further clinical validation. Complementary approaches like GIP (glucose-dependent insulinotropic polypeptide) receptor agonists[70] are also under investigation, contributing to a potentially more personalized and stage-specific therapeutic landscape as clinical understanding evolves.

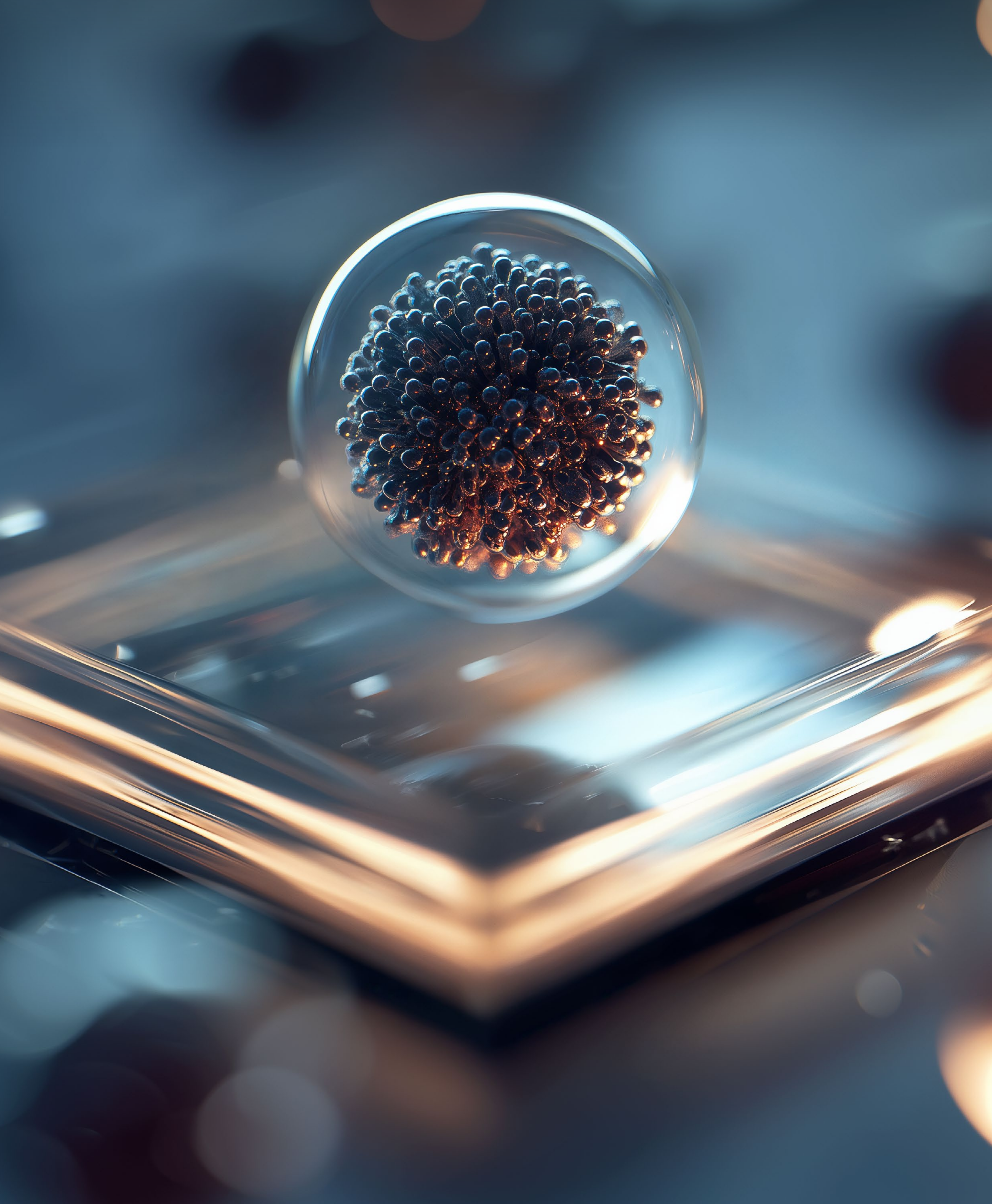
The potential of GLP-1RAs is currently being explored for their role in shifting the treatment approach to neurodegenerative diseases – from symptom management towards possible disease modification. If future research supports this direction, it could influence how healthcare systems and societies approach ageing and cognitive health, with broader implications for care models and community support structures.

→ **Related DFF megatrends:** Future Humanity and Advanced Health and Nutrition[71]

06

Autonomous biochemical sensing

Wiring biological sensors for real-time insight.



Katherine Daniell

Director and Professor, School of Cybernetics, Australian National University

Wilfried Weber

Scientific Director and Professor for New Materials, Leibniz Institute for New Materials

Autonomous biochemical sensors are analytical devices that autonomously and continuously detect and quantify specific biochemical parameters, such as disease markers for patient-individualized health management or chemical changes in soil or water for environmental management.

They detect the chemical of interest using tailored physicochemical transducers or bio-based sensors employing enzymes, antibodies or even engineered living cells. These sensors are designed to operate and report findings independently, without the need for human intervention. They employ wireless communication and energy harvesting, through self-sustaining power sources such as biofuel cells,[72] to enable real-time continuous monitoring. As data from these sensors can be retrieved remotely, they are suitable for applications in difficult-to-reach areas or remote locations. This enables the continuous monitoring of human health as well as environmental conditions.

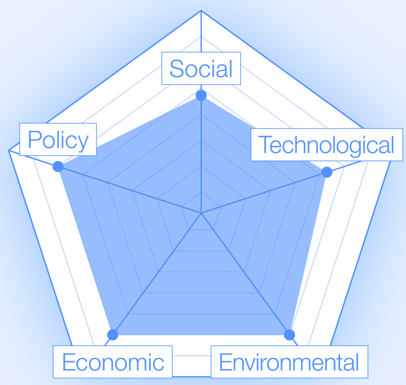
While typical sensors, such as well-known COVID-19 tests, are single-use, the challenge in autonomous biochemical sensing is to achieve continuous monitoring and electronic data capture. Such technical limitations have restricted autonomous biochemical sensors to very specific applications. The most successful to date is the wearable glucose sensor, which measures glucose concentration in real time and communicates with a smartphone[73] that controls an insulin pump to stabilize glucose levels. Some of the biggest companies investing in the development and manufacturing of such technologies include Abbott Laboratories, Roche and DuPont.

Due to simultaneous advancements in materials science, nanotechnologies, bio-mimetics and wireless technologies, autonomous biochemical sensing is emerging to address other targets and applications. An example is the inclusion of an active-reset function in a wearable sensor for inflammation markers, enabling continuous monitoring instead of a single use.[74] US-based Persperity Health is developing wearables for continuous monitoring of female hormones for ovulation tracking, fertility treatments and menopause care. In ongoing development are microbial whole-cell biosensors, employing microbes that produce or deplete an enzyme when they encounter what they are targeted to detect, that enzyme being their means of signalling "detection".

These emerging forms of this technology have the potential to transform the lives of many people requiring continuous monitoring of specific health conditions. Processes for food safety and environmental monitoring, particularly for early detection of contamination, could also lead to significant social and environmental benefits.

Many sensors still have short lifespans, requiring regular replacement. However, new generations of sensors are likely to see improvements that reduce costs. Microbial whole-cell biosensors face additional regulatory hurdles and ethical challenges compared to conventional medical or environmental sensing devices, as they are genetically engineered biological organisms with the potential for environmental release.

Ecosystem readiness map



KEY ACTIONS TO ACHIEVE SCALE

Establish ethical guidelines for biological sensors – Develop clear industry standards for privacy, data ownership and biological safety in partnership with bioethics organizations and regulatory bodies.

Conduct public demonstrations of non-invasive applications – Showcase environmental and agricultural applications of biochemical sensing to build public comfort with the technology before expanding to healthcare use.

↑ **Image:** Autonomous biochemical sensors enable continuous, remote health and environmental monitoring using self-powered, wireless, bio-based technologies.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Microbe floating above a micro piece of technology."

Read more: For more expert analysis, visit the autonomous biochemical sensing transformation map. Authored by: Dermont Diamond.

Strategic outlook
Autonomous biochemical sensing

By Dubai Future Foundation

Autonomous biochemical sensing could enhance the ability to safeguard health across multiple scales – from individual well-being to ecosystem vitality. These systems – evolving from operator-dependent instruments into self-sufficient, predictive networks[75] – offer the potential to monitor and respond to biological and chemical signals without human intervention, creating more robust protection for communities, food systems and natural environments.

Self-operating sensing networks could fundamentally reshape early warning systems across critical infrastructure. Environmental protection agencies could transition from periodic sampling to continuous, real-time detection networks that identify pollutants, pathogens and toxins without human intervention.[76] This shift from reactive to proactive monitoring could enable response systems that address contamination events hours or days earlier, potentially preventing widespread exposure rather than merely documenting it.

Food safety systems stand to undergo a similar transformation. With sensors capable of detecting food toxins 1,000 times more sensitively in under 60 seconds,[77] supply chains could implement continuous verification rather than batch testing. This evolution would alter both regulatory frameworks and production economics, potentially reducing the scale and frequency of food recalls[78] while enabling more precise traceability throughout global distribution networks.

Healthcare delivery models could experience significant reconfiguration as biochemical sensing advances. The decentralization of diagnostics through wearable and point-of-care biosensors would extend testing capabilities beyond traditional healthcare facilities into homes and remote communities.[79] This distribution of diagnostic intelligence could fundamentally alter care pathways, enabling earlier intervention while generating vast streams of population-level health data.

The technological challenges, while substantial, are addressable. Balancing molecular-level sensitivity with long-term stability remains difficult in natural environments where competing microbiomes affect sensor performance.[80,81] For example, engineered bacterial sensors for TNT (trinitrotoluene) detection maintain effectiveness for several weeks before declining significantly.[82] These biological constraints necessitate innovations in sensor design that draw inspiration from natural systems through biomimicry.[83]

Beyond physical sensor design, data integration represents another critical area of advancement. As autonomous sensing networks generate continuous molecular information across multiple domains, the resulting data streams will require new analytical frameworks and governance models. The privacy and security implications, particularly for health-related sensing, demand regulatory approaches that balance innovation with the protection of sensitive information.[84]

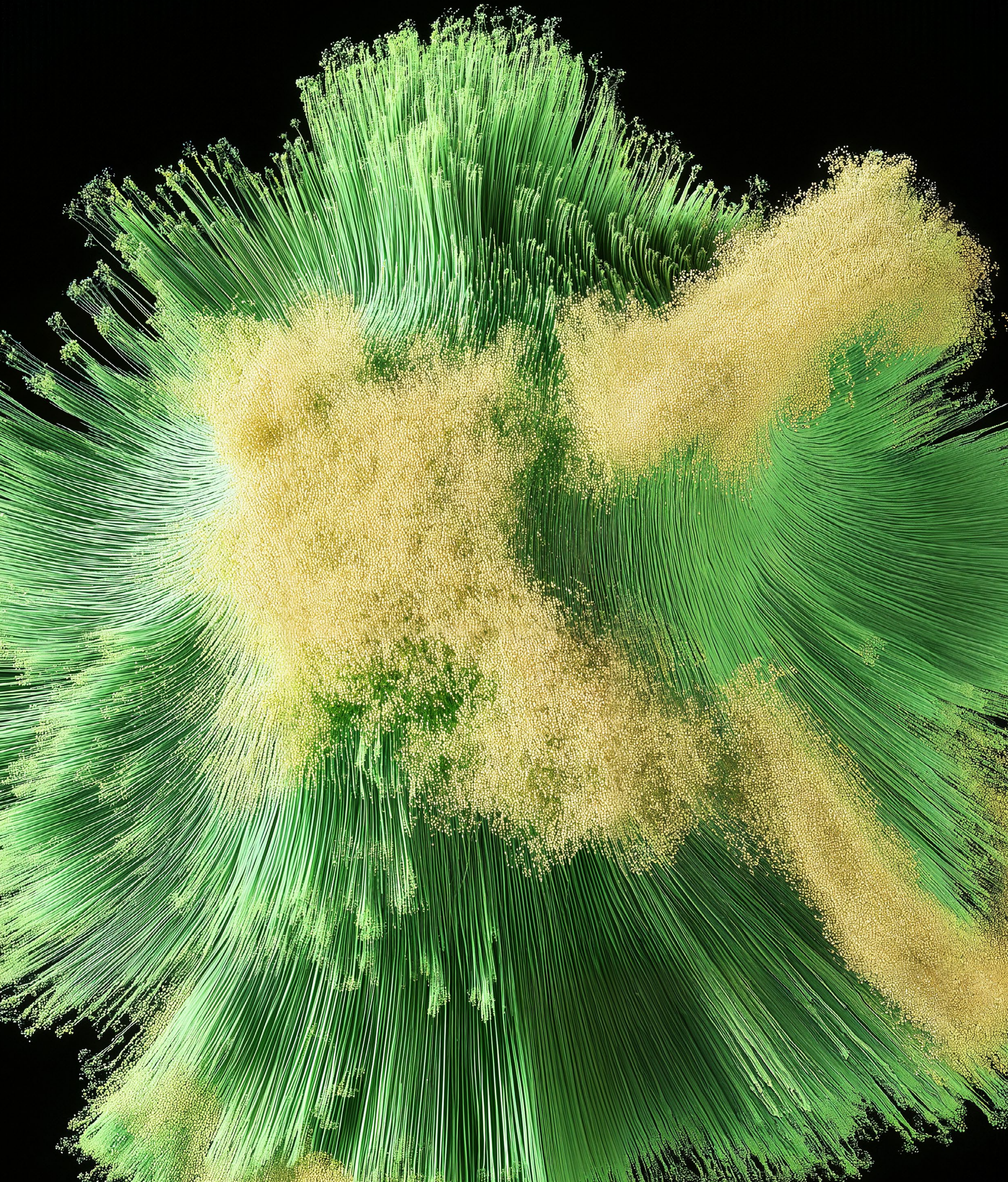
The convergence of continuous monitoring capabilities across environmental, food safety and healthcare domains suggests a future where molecular detection becomes an integrated layer of everyday infrastructure rather than a specialized function. Organizations that successfully implement autonomous biochemical sensing will likely move beyond applying these technologies to isolated problems and instead develop interconnected monitoring networks that share data across traditional boundaries. This integration would create new capabilities: environmental contaminants could be traced to their source and linked to potential health impacts in real-time; foodborne pathogens might be detected and contained before reaching consumers; and early disease indicators could trigger preventive interventions before symptoms appear.

The organizations that will lead in this space will be those that address not just the technical challenges of sensor design but also the complex data governance and cross-domain collaboration requirements that enable these technologies to function as a cohesive system rather than isolated tools.

→ **Related DFF megatrends:** Future Humanity and Advanced Health and Nutrition[85]

07 Green nitrogen fixation

Reimagining ammonia production for a net-zero future.



Javier Garcia-Martinez
Professor, Director of the Molecular Nanotechnology Lab, University of Alicante

Krishna Kumar
Chief Executive Officer, Cropin Sage

Sang-Yup Lee
Senior Vice-President, Research; Distinguished Professor, Korea Advanced Institute of Science and Technology (KAIST)

Wilfried Weber
Scientific Director and Professor for New Materials, Leibniz Institute for New Materials

Nitrogen fixation, a $200 billion market in the US alone, converts atmospheric nitrogen into ammonia at a scale of more than 150 million tonnes per year, which is needed to produce fertilizer supporting 50% of the world's food production.[86] Green nitrogen fixation now aims to reduce the significant carbon footprint of conventional nitrogen production, which currently accounts for 2% of global energy consumption.[87]

In nitrogen fixation, microorganisms convert nitrogen in the atmosphere into forms that plants and other organisms can use for nutrients, primarily ammonia. The key challenge in nitrogen fixation is breaking the extremely stable triple bond that holds together the two nitrogen atoms that make up atmospheric nitrogen (N_2). In the state-of-the-art Haber-Bosch process, this step requires temperatures of 400-500°C, pressures 130 to 150 times greater than that found in the Earth's atmosphere, and hydrogen primarily sourced from natural gas[88] in a CO_2-generating reaction.

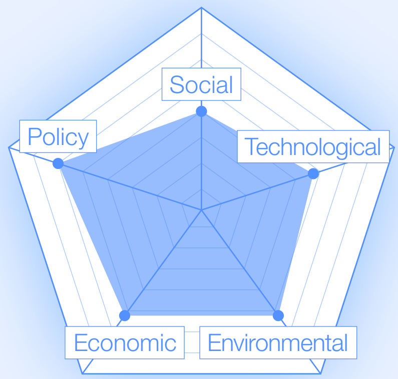
While the principle of alternative nitrogen fixation was discovered in the 1930s, only recently has there been considerable progress towards large-scale commercialization. For example, bio-based approaches use engineered bacteria and enzymes to fix nitrogen[89] and sunlight, or green electricity can provide energy and reduction equivalents. Bio-inspired systems also show promising results, replicating enzyme function by inorganic polyoxometalates or anionic metal-oxide clusters.[90] Further, electrochemical technologies relying on lithium as mediators are at the brink of commercial application.[91]

Green nitrogen fixation technologies are currently being explored by both established and start-up companies. Australian Jupiter Ionics is spearheading lithium-based nitrogen fixation technology, whereas California-based Ammobia is focusing on new, more efficient catalysts. Such alternative technologies would also allow decentralized production plants, enabling ammonia to be generated using locally abundant renewable energy, such as wind and solar. The ammonia produced locally could then be efficiently stored and/or processed into fertilizer on-site,[92] saving transport energy and costs.

Progress in creating localized green ammonia production would not only reduce ammonia production's carbon footprint but also would reduce related CO_2 sources, such as in required transport.[93] Means of transport will also benefit, as commercial vessels are already employing ammonia as diesel fuel and estimates project that more than 30% of global marine fuel could be carbon-free ammonia by 2050.[94]

Next-gen technologies employing lithium chemistry or biology-based approaches to nitrogen fixation are being explored, but their commercial viability has yet to be established.[95] In contrast, ammonia production plants using green hydrogen instead of natural gas have proven viable and are currently being scaled globally.[96] The ammonia industry is in a transition,[97] where increasing R&D efforts in green ammonia fixation technology paired with an increasing demand (as, for example, from the transport sector) will spark additional innovation and investment towards net-zero carbon ammonia production.

Ecosystem readiness map



KEY ACTIONS TO ACHIEVE SCALE

Build industry-agriculture partnerships – Create focused collaborations between green nitrogen technology developers and major agricultural stakeholders to establish pilot programmes demonstrating cost and environmental benefits.

Accelerate alternative process technologies – Invest in targeted research to improve lithium-mediated and biological nitrogen fixation methods to provide viable alternatives to traditional processes.

↑ **Image:**
Green nitrogen fixation uses renewable energy and biology to produce ammonia sustainably, reducing emissions and enabling local production.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Highly detailed green bio fibres interweaving and connecting."

Read more:
For more expert analysis, visit the green nitrogen fixation transformation map. Authored by: Hailong Li and Zequn Yang.

Strategic outlook
Green nitrogen fixation

By Dubai Future Foundation

The Haber-Bosch process, developed over a century ago, fundamentally altered humanity's relationship with food production by enabling industrial-scale nitrogen fixation. Now, lithium-mediated electrochemical processes could present another significant advancement: the potential ability to produce ammonia using only air, water and renewable electricity. This technological shift might transform global ammonia production from a centralized, carbon-intensive industry into a more distributed, carbon-neutral network.

The strategic significance extends far beyond decarbonization. The current Haber-Bosch process consumes 1-2% of global energy[98] and emits 2.4 tons of CO_2 per ton of ammonia produced – nearly twice that of steel production and four times that of cement manufacturing.[99] Green ammonia production represents a critical opportunity to transform this carbon-intensive foundation of global agriculture while simultaneously enabling new energy applications.

Agriculture stands to undergo the most profound transformation. With nearly 80% of industrially produced ammonia consumed in fertilizers,[100] green nitrogen fixation could catalyse a shift towards distributed, smaller-scale production facilities that reduce transport vulnerabilities, stabilize fertilizer prices[101] and enhance food system resilience. This distributed model could fundamentally reshape agricultural supply chains and empower regions currently dependent on imported fertilizers.

Beyond agriculture, green ammonia emerges as a versatile energy carrier with strategic advantages over liquid hydrogen. With storage requirements up to 30 times lower in cost than liquid hydrogen,[102] ammonia presents a more practical medium for hydrogen energy storage and transport. The shipping industry has recognized this potential, with maritime regulations evolving to accommodate ammonia-fuelled vessels, suggesting a pathway towards decarbonizing global shipping networks.

While offering advantages over hydrogen in the Haber-Bosch process, technical and resource challenges remain significant but navigable. Recent advances have demonstrated electrochemical conversion rates approaching the efficiency of the Haber-Bosch process (60-75%),[103,104,105] indicating technical viability. The dependence on lithium – a critical mineral with demand expected to more than double by 2030[106] – presents a resource constraint that will require strategic supply chain development. Environmental considerations must also address ammonia's toxicity[107] and potential PM2.5 (particulate matter) emissions impacts.[108]

Strategically, the geopolitical landscape of ammonia production currently stands at a pivotal moment. With China currently accounting for 30% of global production and India and Middle Eastern countries poised to expand capacity,[109] green nitrogen fixation could reshape regional dependencies and create new centres of agricultural and energy influence. Those who develop scalable green ammonia production capabilities may gain significant strategic advantages in both food security and clean energy transitions.

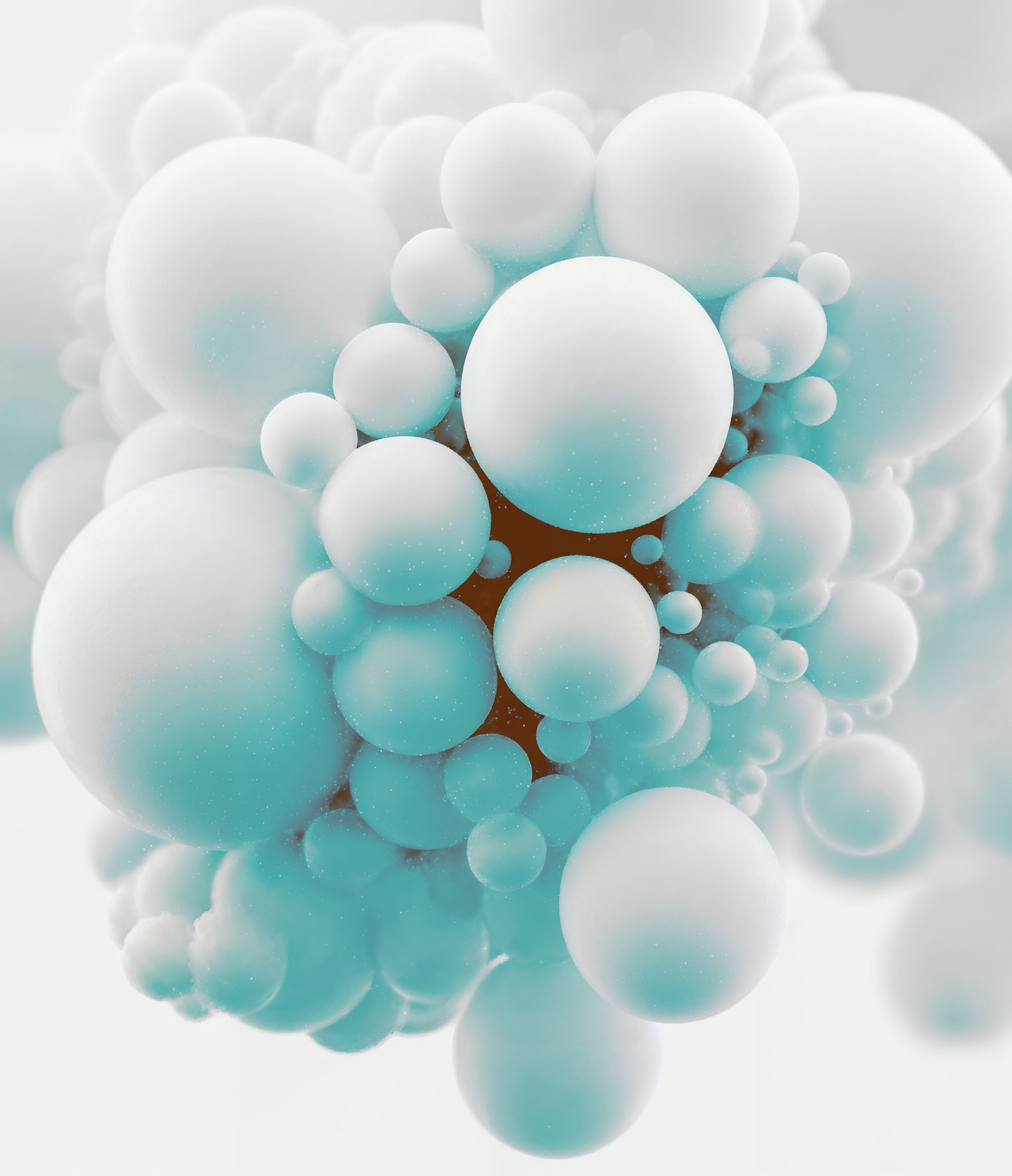
Over the next decade, leadership in green nitrogen fixation would likely emerge from those who can integrate three distinct strategic capabilities: advanced electrochemical manufacturing, renewable energy infrastructure and agricultural innovation ecosystems. The technology represents a potential convergence where food security, energy innovation and climate action might intersect in a single transformative platform.

→ **Related DFF megatrends:** Evolving Ecosystems and Advanced Health and Nutrition[110]

08

Nanozymes

Replicating nature’s catalysts for health and environmental breakthroughs.



Javier Garcia-Martinez

Professor, Director of the Molecular Nanotechnology Lab, University of Alicante

Andrew Maynard

Professor, School for the Future of Innovation in Society, Arizona State University

Nanozymes are laboratory-produced and manufactured nanomaterials with enzyme-like properties. Nanozymes, unlike enzymes, which are produced by living organisms or chemically synthesized at significant cost and complexity, offer increased stability, lower production costs and simpler synthesis processes.[111] Composed of nanoparticles of metals, metal oxides, carbon and other materials, nanozymes act like catalysts and promote the same chemical reactions enzymes support.[112] Their robust nature allows them to function in far more diverse environments, expanding their potential applications in biomedical, environmental and industrial fields. Using advanced nanoscale design and production techniques, it is also possible to engineer multifunctional nanozymes.

Rapid advancements in nanozyme technology in the last two decades have garnered significant attention from major pharmaceutical companies, resulting in a surge of investment in nanozyme research and development. This increased funding has accelerated the pace of innovation and expanded the potential applications of nanozymes across various medical fields. Therefore, numerous clinical trials for nanozyme-based therapies are currently in progress, with particularly promising results emerging in the areas of cancer and neurodegenerative disease treatment.[113] In cancer treatment, nanozymes have shown potential for targeted drug delivery, enhancing the efficacy of chemotherapy while reducing side effects. For neurodegenerative diseases such as Alzheimer's and Parkinson's, nanozymes are being explored for their ability to mitigate oxidative stress and reduce inflammation in the brain, potentially slowing disease progression. The versatility of nanozymes has also led to investigations in other medical areas, including cardiovascular diseases, infectious diseases and wound healing.

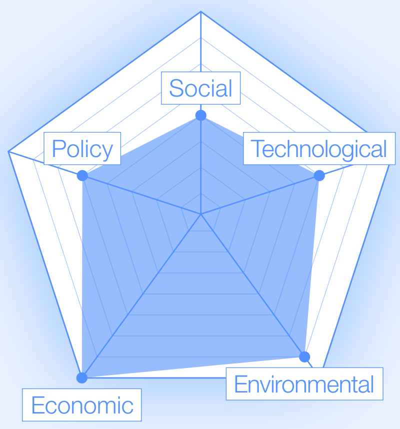
Several companies and start-ups are actively working towards the commercialization of nanozymes. Level Nine is developing nanozymes for use in industrial biomanufacturing.[114] Nanozyme, Inc., a University of Florida spin-out, is developing synthetic nanomachines programmed to enter only targeted diseased cells, with the goal of enabling targeted disease treatment with fewer side effects.[115] Though a work in progress, barring unanticipated challenges, such programmes are hoped to mature into commercial applications in the coming years.

The impact of nanozymes extends well beyond healthcare to environmental applications, including water purification, potentially offering sustainable solutions to a critical global challenge. In the food industry, they could enhance food safety through the rapid detection of contaminants in on-shelf packaged meats and other consumables.[116] In industrial catalysis, nanozymes may offer more efficient and environmentally friendly alternatives to traditional catalysts, potentially reducing energy consumption and waste materials.[117]

The global nanozyme market, valued at $5.13 billion in 2024, is projected to grow at a compound annual growth rate (CAGR) of 27.4% to reach $57.95 billion by 2034.[118] Key applications include biosensing, environmental remediation and targeted drug delivery. Nanozymes promise to revolutionize diagnostics and therapeutics, particularly in areas such as early disease detection and targeted drug delivery. This convergence of nanotechnology and enzyme mimicry has the potential to drive innovation across multiple sectors, ultimately contributing to improved quality of life.

As with all emergent technologies, nanozymes face several challenges. Technical hurdles include improving their selectivity and catalytic efficiency to match or exceed natural enzymes. Ethical considerations arise from their potential use in biological systems, requiring thorough safety evaluations. Finally, the regulatory framework for nanozyme-based products is still evolving, which could impact their commercialization and widespread adoption.

Ecosystem readiness map



KEY ACTIONS TO ACHIEVE SCALE

Establish biocompatibility testing frameworks – Create standardized protocols for assessing the safety and biological interaction of nanozymes across different application environments to address ethical concerns.

↑ Image: Nanozymes are synthetic enzyme-like nanomaterials offering stable, low-cost and versatile solutions across medicine and industry.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Clusters of matte circles, varying in sizes."

Read more: For more expert analysis, visit the nanozymes transformation map. Authored by: Sanjay Singh.

Strategic outlook
Nanozymes

By Dubai Future Foundation

Nanozymes offer engineered alternatives to natural enzymes with distinct practical advantages: they can operate in extreme pH (potential of hydrogen) conditions, withstand high temperatures and maintain stability for extended periods while costing significantly less to produce. With demonstrated capabilities like detecting antioxidants at parts-per-billion concentrations and achieving up to 21 times the catalytic efficiency of natural enzymes,[119] these materials can enable chemical reactions in environments where biological enzymes would rapidly degrade. This combination of performance and stability opens possibilities across scientific and industrial applications that have previously been limited by the fragility of natural enzyme systems.

Healthcare and environmental applications demonstrate the technology's transformative potential. Smartphone-integrated diagnostic tools could expand medical capabilities in resource-constrained regions,[120] enabling more sensitive biosensors for early disease detection.[121] Wound care technologies offer targeted treatments against drug-resistant bacteria, killing 99.99% of challenging infections without triggering resistance mechanisms.[122]

Beyond direct applications, secondary impact emerges in the global research ecosystem. Nanozymes require integrating AI, computational design and domain-specific expertise,[123] potentially dissolving traditional disciplinary boundaries. International research networks might develop collaborative models that transcend geographical and institutional limitations, creating more adaptive approaches to addressing complex global challenges.

This collaborative potential could fundamentally alter how countries approach technological innovation. Shared research platforms might emerge, addressing critical global issues through integrated, multidisciplinary strategies. The technology's capacity to reduce harmful chemical use[124] suggests a new paradigm of environmentally conscious scientific development, where research simultaneously advances technological capabilities and environmental sustainability.

Significant challenges remain. Biocompatibility concerns and the need for robust safety standards create critical implementation hurdles.[125,126] Developing comprehensive regulatory frameworks will require coordinated global efforts and a systematic approach to research and implementation. To address these challenges, the International Organization for Standardization's (ISO) existing nanotechnology standards provide a foundation for this collaborative approach.[127]

The development of nanozymes points towards a more precise approach to catalysis where reaction specificity, stability in diverse environments and recyclability become standard features rather than compromises. Initial applications in diagnostics, environmental remediation and targeted therapeutics will likely provide the proving grounds for these technologies, establishing performance benchmarks and regulatory precedents.

The organizations best positioned for success will develop specialized nanozyme designs optimized for specific reaction environments – whether in industrial processes, biomedical applications or environmental contexts. Rather than competing with natural enzymes across all applications, successful nanozyme development will focus on addressing the specific limitations of biological catalysts: their instability in harsh conditions, high production costs and limited tunability. This targeted approach will create practical value while navigating the biocompatibility challenges and regulatory requirements that currently limit broader deployment.

→ **Related DFF megatrends:** Materials and Advanced Health and Nutrition[128]

09

Collaborative sensing

Empowering connected systems to make context-aware decisions.

Daniel Dossenbach
Scientific Advisor in Innovation, State Secretariat for Education, Research and Innovation Switzerland

David Parekh
Chief Executive Officer, SRI International

Karen Hallberg
Principal Researcher, Bariloche Atomic Center (CONICET)

Sensing devices are now ubiquitous in people's homes, vehicles and workplaces. Already useful in isolation, these distributed sensors are increasingly being connected to each other and integrated with AI-infused systems, paving the way for rapid advances in collaborative sensing that can generate insights to improve the capabilities of individual sensors. Beyond autonomous urban mobility, promising applications for collaborative sensing are diverse, including perceptive mobile networks that combine communications and sensing on the same network. Collaborative sensing will reshape how cities operate and how organizations use information to make decisions.

Promising applications for collaborative sensing are diverse, including improving urban mobility. For example, connected traffic lights can dynamically adjust themselves based on traffic cameras and environmental sensors to manage urban congestion and emission levels. Other examples for collaborative sensing include large-scale autonomous mapping in mines,[129] analysing storm systems,[130] drone swarms,[131] internet-of-things-based structural health monitoring,[132] environmental monitoring and bringing more precision to agriculture and natural resource management.[133]

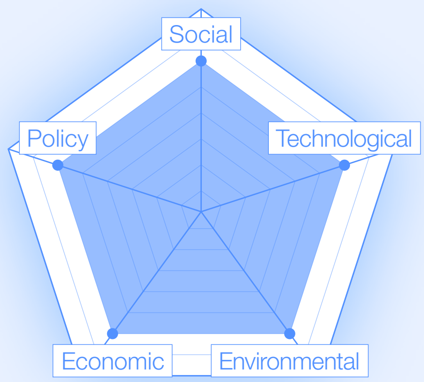
Collaborative sensing pairs distributed sensors, including those on satellites and underwater and subterranean platforms, with reliable connectivity and algorithmic processing at the network's edge to reduce transmitted data volumes. Autonomous agents, such as robots, drones, intelligent vehicles and IT systems, with semantic reasoning and dynamic planning capabilities, will be equipped to navigate unfamiliar environments and make collective decisions.

Research in sensor fusion, collaborative sensing and collaborative autonomy has often been driven by the defence industries' need for real-time decisions and actions. Increasingly, the civilian benefits of these linked capabilities are becoming apparent. Imagine an autonomous vehicle that drives appropriately in the context of its own sensors, and that also knows (thanks to connected sensors on a traffic light hundreds of yards away) that a speeding vehicle is approaching on a collision course. The US Federal Communications Commission's (FCC) recent decision[134] to adopt the 5.9 gigahertz (GHz) band for cellular-vehicle-to-everything technology is a critical step towards enabling such advances and will create new opportunities to explore how collaborative sensing might address infrastructure costs, reduce traffic congestion and accidents and lower carbon emissions. The European Commission and China's Ministry of Industry and Information Technology have similarly enacted enabling legislation.

Challenges remain. Most platforms on which sensors are deployed have strict power and connectivity constraints, requiring engineering approaches such as compressing 3D scene classification methods,[135] improved navigation[136] in the absence of GPS and improved low-power processing at the network edge. Data-sharing security and privacy policies will also need to evolve.

The key to unlocking the benefits of collaborative sensing at scale and achieving true collaborative autonomy, will be multi-modal algorithms[137] that can process numerous varieties of sensor data, from LiDAR (light detection and ranging) to EO/IR (electro-optical/infra-red) cameras to radar and beyond. Much of this work is currently focused on balancing a shared information landscape and operational picture with distributed processing, while also minimizing bandwidth and power requirements. Generative AI may play a role here. Recent research demonstrates that large language models (LLMs) may optimize simple collaborative navigation tasks much more efficiently than traditional deep reinforcement learning (DRL) approaches.[138]

Ecosystem readiness map



KEY ACTIONS TO ACHIEVE SCALE

Develop cross-industry data standards – Establish common protocols for sensor data sharing, security and interoperability across industries to enable seamless integration of distributed sensing networks.

Modernize critical infrastructure – Upgrade telecommunications and connectivity infrastructure in key urban environments to support the bandwidth and reliability requirements of collaborative sensing systems.

↑ **Image:**
Collaborative sensing networks combine distributed sensors with AI to improve decision-making, urban systems and autonomous technologies.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "LiDAR scan of buildings, cars, people and scenery."

Read more:
For more expert analysis, visit the collaborative sensing transformation map. Authored by: Mehrdad Dianati.

Strategic outlook
Collaborative sensing

By Dubai Future Foundation

Collaborative sensing could significantly reshape urban systems, mobility and societal infrastructure. Powered by vehicle-to-everything (V2X) technologies, 5G, AI and edge computing, this approach may create intelligent urban environments that perceive, respond and adapt to complex environmental dynamics with greater precision than current systems.

The potential impact of collaborative sensing extends beyond traditional traffic management, reshaping urban resilience, supply chains and emergency response capabilities. Cities could develop adaptive infrastructures that respond in real time to changing conditions, enabling more dynamic resource allocation during crises, optimized delivery routes for critical supplies and coordinated emergency vehicle deployment. With intelligent mobility systems forming the foundation of these capabilities, urban environments could serve citizens through seamlessly integrated technological systems.[139]

Among the most immediate and measurable outcomes and initial use case is improved safety. In transport, V2X technologies have demonstrated remarkable potential for accident prevention. Automated emergency braking systems showed 59% crash avoidance when only turning vehicles were equipped, increasing to 77% with full technology integration.[140] Insurance research indicates up to 78% decrease in collisions for vehicles with intelligent sensing capabilities,[141] signalling a potential shift in risk assessment and urban mobility.

Strategic benefits would also ripple across multiple industries. Transport and logistics could gain significantly, with truck platooning demonstrating a 5-10% fuel consumption reduction.[142] Telecommunications infrastructure may undergo fundamental upgrades, with 5G improving location accuracy from over 1 metre to 0.1 metres with 99.9% reliability,[143,144] enabling potentially unprecedented levels of collective vehicle operation.

Yet, the transformative potential of collaborative sensing at scale is matched by complex challenges. With only 55% of the global population currently having 5G access,[145] expanding telecommunications infrastructure represents a critical prerequisite. Additional barriers include developing common data standards, establishing robust cybersecurity frameworks, creating comprehensive liability models and building public trust in collaborative technologies.

The most strategic organizations would view collaborative sensing as a potential platform for reimagining urban systems. Success will depend on collaboration across government, private sector and technological domains. The core challenge lies in moving beyond mere technological connection to creating adaptive urban environments that can learn, respond and evolve.

The next decade presents a critical window for developing collaborative sensing ecosystems. Nations and organizations that lead in establishing integrated data standards, investing in robust telecommunications infrastructure and designing interoperable sensing networks might shape a future where cities become more resilient, responsive and human-centred. As collaborative sensing shifts from isolated, single-use applications towards interconnected sensing networks, the potential for transforming urban systems extends beyond efficiency gains to a fundamental reimagining of how cities could function, adapt and evolve.

→ **Related DFF megatrends:** Technological Vulnerabilities and Digital Realities[146]

10

Generative watermarking

Enhancing trust with invisible, immutable markers.

Katherine Daniell

Director and Professor, School of Cybernetics, Australian National University

Andrew Maynard

Professor, School for the Future of Innovation in Society, Arizona State University

Generative AI watermarking technologies embed invisible markers in AI-generated content – including text, images, audio and video – to verify authenticity and help trace content origins. As AI-generated content becomes increasingly hard to differentiate from that created without AI, there has been a surge in innovative watermarking technologies[147] designed to help combat misinformation, protect intellectual property, counter academic dishonesty and promote trust in digital content.

Watermarking techniques aim to subtly alter generative AI outputs without noticeably impacting their quality. Text-based watermark technologies, such as Google DeepMind's SynthID technology,[148] take advantage of the fact that there are thousands of words in a given language that can be randomly substituted by others. They work by including a narrow and specific subset of such words throughout AI-generated text that seems natural but is distinct from the more random word choices a human writer might make. This results in an AI-specific textual "fingerprint". Image and video watermark technologies include introducing imperceptible changes at the pixel level that can survive edits like resizing and compression – for instance by subtly altering the values of individual pixels so that a machine can see the changes, but the human eye cannot, or embedding hidden patterns[149] in generated output that only a machine can extract.

Watermarking AI-generated content gained traction in 2022, as models like ChatGPT and Stable Diffusion gained popularity and widespread use. By 2023, major AI companies, including OpenAI, Google and Meta, committed to watermarking under regulatory pressure.[150] A breakthrough came in 2024 when Google DeepMind open-sourced SynthID. Simultaneously, Meta introduced VideoSeal,[151] a watermarking system for AI-generated videos.

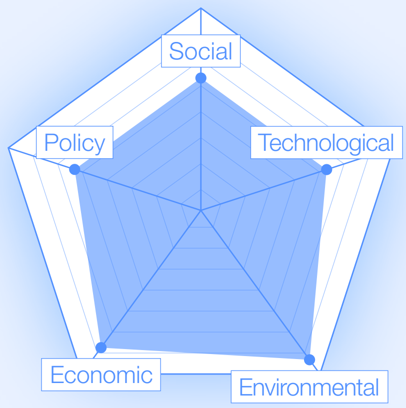
Leading AI companies are now increasingly integrating watermarking into their platforms. Google, for instance, is embedding SynthID into AI-generated images, text and videos across its services. Meta is applying invisible watermarks and metadata tags[152] to AI-generated content on Facebook, Instagram and Threads. AI companies are partnering with organizations like Partnership on AI[153] to ensure "synthetic media transparency".

Despite progress, though, widespread use of AI watermarking faces challenges.[154] Simple modifications to AI-generated outputs can still disrupt detection. Users can attempt to remove or forge watermarks, either by cropping images and video where watermarks are embedded in a specific location, or by adjusting text (and even using AI-based watermark removers). Uneven adoption also presents risks where, without universal industry standards, inconsistent implementation may weaken effectiveness. There are also substantial ethical concerns around misuse, such as falsely labelling real content as AI-generated or false positives, where erroneous accusations of covertly using AI can have unintended consequences, especially in cases related to academic integrity.

To be successful, these technologies will need to be accompanied by equally sophisticated governance and use guidelines. China has acted to regulate generated content to require watermarking,[155] and other regions, such as the EU,[156] are also developing responses to manage the security and authenticity of digital content. The Coalition for Content Provenance and Authenticity (C2PA), a coalition of leading media generators in the AI space, is also leading the development of technical standards for certifying the source of media content; an approach that regulators would struggle to meaningfully produce. Watermarking has proven a fertile area for start-ups globally with different technological approaches.

Emerging generative AI watermarking technologies are becoming a cornerstone of responsible AI deployment as they help balance innovation with accountability. While no single method is foolproof, industry-wide adoption and regulatory alignment will help determine the technology's long-term utility and success of AI-generated content.

Ecosystem readiness map



KEY ACTIONS TO ACHIEVE SCALE

Develop tamper-resistant watermarking standards – Invest in advanced watermarking technologies that can withstand removal attempts and establish industry-wide standards for their implementation.

Create cross-platform verification systems – Build independent verification systems that can detect and authenticate watermarks across different platforms and content types.

↑ **Image:** Generative AI watermarking embeds invisible markers in content to verify authenticity, trace origins and promote accountability.

Credit: Midjourney and Studio Miko.

Prompt (abbreviated): "Digital fingerprint constructed from glowing binary code."

Read more: For more expert analysis, visit the generative watermarking transformation map. Authored by: Sri Krishnan.

Strategic outlook
Generative watermarking

By Dubai Future Foundation

Over the next decade, generative watermarking technologies could evolve from optional technical safeguards to important components of digital trust infrastructure. As synthetic content becomes increasingly prevalent, embedded watermarks might form the foundation of a global verification ecosystem that helps distinguish between human and machine-created digital assets.

The media and creative industries may experience significant transformation. The converging regulatory frameworks across California,[157] China[158] and the European Union[159] – with penalties reaching up to $38 million or 7% of annual turnover[160] – suggest an emerging global interest in content provenance systems. Major platforms have already begun positioning themselves in this space, with Adobe's content credentials,[161] TikTok's AI labelling standards[162] and Google's SynthID representing early attempts to establish market-defining protocols.

This signals something more than a compliance challenge. It marks the early stages of a comprehensive governance system for digital content that will create distinct competitive advantages for early adopters while potentially marginalizing non-compliant creators and platforms. Nations and organizations that take the lead in setting watermarking standards will shape the rules of the emerging synthetic media economy.

The implications could extend beyond creative sectors to potentially reshape legal and financial systems. Courts might eventually accept watermarked content as evidence in intellectual property (IP) disputes and defamation cases, while insurance companies could consider developing tiered coverage models based on content authentication levels. For creators, the ability to verify their work – whether human-made or AI-assisted – may position them to command premium prices in markets increasingly populated with synthetic alternatives.

Technical challenges remain significant but potentially addressable. Currently, watermarking systems are being implemented, but techniques to remove generative watermarks remain, highlighting the gap between existing capabilities and the need for tamper-resistant, cross-format watermarks that accurately identify 100% of AI-generated content.[163] The integration with blockchain systems to create verifiable watermarks[164] represents a promising frontier that could establish better content identity regardless of modification or distribution.

Organizations might prepare strategically by investing in interoperable standards rather than proprietary systems. Those developing more sophisticated watermarking techniques, particularly those resistant to removal and compatible with emerging content formats, could establish leadership in the evolving digital authentication ecosystem. Nations and organizations that take the lead in setting watermarking standards may influence the development of the emerging synthetic media economy.

Looking ahead, generative watermarking represents not just another tool for content verification, but a potential reimagining of how trust is established in an increasingly synthetic digital landscape. Progress would depend on collaboration across technology, policy and creative sectors to create systems that balance innovation with appropriate safeguards.

→ **Related DFF megatrends:** Technological Vulnerabilities and Future Humanity[165]

From weak signals to societal transformation

For over a decade, the World Economic Forum's Top 10 Emerging Technologies report has served as a unique lens for understanding technological transformation – tracking how early-stage technologies evolve from tentative signals to transformative solutions. Consider CRISPR-Cas9, first highlighted in the 2015 report as a promising gene-editing technique. What seemed then like a theoretical breakthrough has since revolutionized multiple domains, from enabling precise vaccine development during the COVID-19 pandemic to facilitating groundbreaking xenotransplantation in 2024.

This trajectory illustrates the core methodology: identifying technologies not for their immediate application, but for their potential to create systemic change. The most profound innovations emerge not in isolation, but through intricate convergences – where synthetic biology meets AI, materials science intersects with energy systems and biotechnology converges with digital technologies.

Each technology tracked represents more than a standalone solution; they are signals of broader transformations, capable of redesigning entire systems. Green nitrogen fixation reimagines agricultural supply chains, structural battery composites transform understanding of material functionality and autonomous biochemical sensing creates entirely new paradigms for health monitoring.

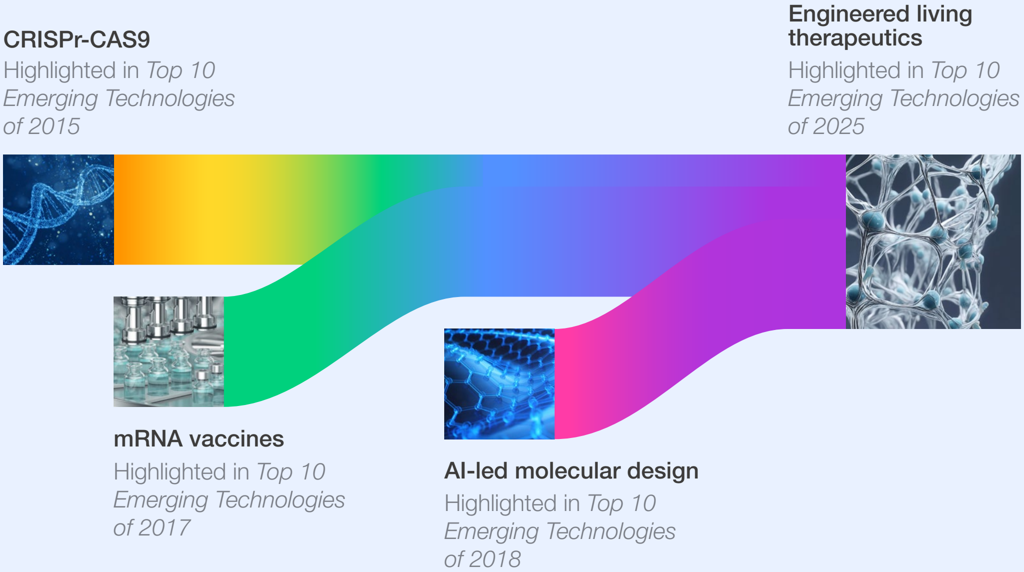
This annual review reveals consistent patterns in technological maturation. Breakthrough innovations require more than technical brilliance – they demand comprehensive ecosystem development. This means navigating complex interactions between social acceptance, technological capability, environmental sustainability, economic viability and regulatory frameworks.

Looking back, the report has consistently demonstrated its predictive power: identifying CRISPR in 2015, anticipating mRNA vaccine platforms in 2017, exploring AI in drug discovery in 2020 and now examining engineered living therapeutics. These are not mere technological snapshots, but waypoints in an ongoing journey of innovation.

As the report continues to track emerging technologies, the goal remains unchanged: to provide a forward-looking perspective that bridges scientific potential with practical implementation. The most profound innovations are rarely obvious at first glance. They emerge through persistent observation, interdisciplinary collaboration and a fundamental willingness to reimagine what's possible.

FIGURE 3 **Scaling innovation: how emerging technologies become tomorrow's foundations**

Technologies featured in the Top 10 Emerging Technologies reports, demonstrate how breakthrough technologies build upon foundational innovations, creating disruptions and redesigns of entire societal ecosystems.



Contributors

World Economic Forum

Kimmy Bettinger
Lead, Expert and Knowledge Communities
Centre for the Fourth Industrial Revolution

Sebastian Buckup
Managing Director, Centre for Nature and Climate

Jeremy Jurgens
Managing Director, Centre for the Fourth Industrial Revolution

Meredith McCleary
Specialist, Strategic Impact, Centre for the Fourth Industrial Revolution

Strategic Intelligence Platform

Bryonie Guthrie
Lead, Foresight and Organizational Transformation

Stephan Mergenthaler
Chief Technology Officer

Minji Sung
Specialist, Content and Partnerships

Astrid Wang
Specialist, Foresight and Organizational Transformation

Frontiers

Susan Debad
Consultant

Toby Dore
Manager, Advanced Analytics

Frederick Fenter
Chief Executive Editor

Anna Ondicova
Specialist, Public Affairs

George Thomas
Lead, Strategic Partnerships

Participating journals:
Frontiers in Biotechnology and Bioengineering
Frontiers in Chemical Engineering
Frontiers in Chemistry
Frontiers in Endocrinology
Frontiers in Energy Research
Frontiers in Future Transportation
Frontiers in Manufacturing Technology
Frontiers in Nuclear Engineering
Frontiers in Sensors
Frontiers in Signal Processing

Dubai Future Foundation

Fatma Abulhoul
Head, Centre for the Fourth Industrial Revolution United Arab Emirates

Khalfan Belhoul
Chief Executive Officer

Heba Chehade
Head, Foresight Research

Saeed Al Falasi
Director, Dubai Centre of Artificial Intelligence

Abdulaziz Al Jaziri
Deputy Chief Executive Officer and Chief Operations Officer

Aruba Khalid
Associate Project Manager, Research

Dhari Al Mawad
Director, Strategy

Yahya Mohammed
Robotics Research Engineer, Dubai Future Labs

Patrick Noack
Executive Director, Dubai Future Institute

Mohamed Qasem
Dean, Dubai Future Academy

Tarek Taha
Director, Robotics Labs, Dubai Future Labs

Biying Zhang
Senior Strategy and Policy Manager, Sandbox Dubai

Production

Rose Chilvers
Designer, Studio Miko

Laurence Denmark
Creative Director, Studio Miko

Martha Howlett
Lead Editor, Studio Miko

Oliver Turner
Designer, Studio Miko

Acknowledgements

Steering Committee

Co-Chairs

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

Barnard S. Meyerson
Chief Innovation Officer Emeritus, IBM

Members

Doug Arent
Executive Director, National Renewable Energy Laboratory Foundation

Katherine Daniell
Director and Professor, School of Cybernetics, Australian National University

Daniel Dossenbach
Scientific Advisor in Innovation, State Secretariat for Education, Research and Innovation (SERI) of Switzerland

Frederick Fenter
Chief Executive Editor, Frontiers

Olga Fink
Professor, Intelligent Maintenance and Operations Systems, EPFL (École Polytechnique Fédérale de Lausanne)

Javier Garcia-Martinez
Professor, Director of the Molecular Nanotechnology Lab, University of Alicante

Karen Hallberg
Principal Researcher, Bariloche Atomic Center (CONICET)

Thomas Hartung
Professor, Doerenkamp Zbinden Chair for Evidence-based Toxicology, Johns Hopkins Bloomberg School of Public Health

Krishna Kumar
Chief Executive Officer, Cropin Sage

Sang-Yup Lee
Senior Vice-President, Research; Distinguished Professor, Korea Advanced Institute of Science and Technology (KAIST)

Alison Lewis
Dean of the Faculty of Engineering and the Built Environment, University of Cape Town

Andrew Maynard
Professor, School for the Future of Innovation in Society, Arizona State University

David Parekh
Chief Executive Officer, SRI International

Nayat Sanchez-Pi
Chief Executive Officer, Inria Chile

Wilfried Weber
Scientific Director and Professor for New Materials, Leibniz Institute for New Materials

World Economic Forum

Maria Alonso
Lead, Autonomous Systems, Centre for the Fourth Industrial Revolution

Rachel Dooley
Lead, Strategic Communications, Centre for the Fourth Industrial Revolution

Manju George
Head, Strategic Impact and Integration, Centre for the Fourth Industrial Revolution

Alfredo Giron
Head, Ocean and Nature Positive, Centre for Nature and Climate

Sarah Kanwar
Project Fellow (Accenture), Centre for Energy and Materials

Jitka Kolarova
Lead, Health and Healthcare Innovation, Centre for Health and Healthcare

Benjamin Larsen
Lead, Artificial Intelligence and Machine Learning, Centre for AI Excellence

Michelle Mormont
Lead, Innovator Communities, Centre for the Fourth Industrial Revolution

Kristen Panerali
Head, Clean Power and Electrification, Centre for Energy and Materials

Arunima Sarkar
Head, Frontier Technologies, Centre for the Fourth Industrial Revolution

Brynne Stanton
Lead, Bioeconomy, Centre for the Fourth Industrial Revolution

Other acknowledgements

Leif Erik Asp
Professor, Chalmers University of Technology

Odne Burheim
Professor, Norwegian University of Science and Technology

Alfredo Caro
Research Professor, George Washington University

Shirley Dent
Head, Public Relations, Frontiers

Dermont Diamond
Professor Emeritus, Dublin City University

Mehrdad Dianati
Professor, University of Warwick

Sergei Dudarev
Senior Fellow, United Kingdom Atomic Energy Authority

Jean Marie François
Professor, Institut Biotechnologique de Toulouse (INSA)

Jeff M.P. Holley
Professor, University of Bristol

Sri Krishnan
Professor, Toronto Metropolitan University

Stephan Kuster
Director, External Affairs, Frontiers

Björn Johansson
Professor, Chalmers University of Technology

Hailong Li
Professor, Central South University

Kaitlyn Schmidt
Senior Public Relations Specialist, Frontiers

Sanjay Singh
Scientist, National Institute of Animal Biotechnology

Wenxi Tian
Professor, Xi'an Jiaotong University

Johanna Xu
Assistant Professor, Chalmers University of Technology

Zequn Yang
Associate Professor, Central South University

Endnotes

1. Imperial College London. (n.d.). *Structural batteries*. https://www.imperial.ac.uk/structural-power-composites/structural-batteries/.
2. Hopkins, B. J., Long, J. W., Rolison, D. R., & Parker, J. F. (2020). High-performance structural batteries. *Joule*, 4(11), pp. 2240-2243. https://doi.org/10.1016/j.joule.2020.07.027.
3. Physics World. (n.d.). *Structural Battery is world's strongest, say researchers – physics world*. https://physicsworld.com/a/structural-battery-is-worlds-strongest-say-researchers/.
4. Credence Research. (2024, 28 September). *Structural Battery Market Size, growth and forecast 2032*. https://www.credenceresearch.com/report/structural-battery-market.
5. Jin, T., Singer, G., Liang, K., & Yang, Y. (2023). Structural batteries: Advances, challenges and perspectives. *Materials Today*, 62, pp. 151-167. https://doi.org/10.1016/j.mattod.2022.12.001.
6. International Energy Agency (IEA). (2024). *Global Critical Minerals Outlook 2024*. https://www.iea.org/reports/global-critical-minerals-outlook-2024.
7. Energy.gov. (n.d.). *Materials technologies*. https://www.energy.gov/eere/vehicles/materials-technologies.
8. Nie, B., Lim, J., Liu, T., Kovalenko, I., et al. (2023). Multifunctional composite designs for structural energy storage. *Battery Energy*, 2(6). https://doi.org/10.1002/bte2.20230023.
9. Karadotcheva, E., Nguyen, S.N., Greenhalgh, E.S., Shaffer, M.S., et al. (2021). Structural Power Performance Targets for future electric aircraft. *Energies*, 14(19), 6006. https://doi.org/10.3390/en14196006.
10. Fairs, M. (n.d.). *Could carbon fibres soon become free of fossil fuels?*. World Economic Forum. https://www.weforum.org/stories/2021/07/scientists-bio-based-carbon-fibres/.
11. Ziemińska-Stolarska, A., Sobulska, M., Pietrzak, M., & Zbiciński, I. (2024). A review of end-of-life scenarios for fibre-reinforced polymer materials. *Energies*, 17(15), 3713. https://doi.org/10.3390/en17153713.
12. Ibid.
13. Dubai Future Foundation (DFF). (2024, 11 February). *Navigating 10 megatrends shaping our future in 2024.* https://www.dubaifuture.ae/navigating-10-megatrends-shaping-our-future-in-2024.
14. Loeb S. & Norman R.S. (1975). Osmotic power plants. *Science*, 189(4203), pp.654-5.
15. Aghapour Aktij S., Dadashi Firouzjaei M., Pilevar M., Asad A., et al. (2025). Enhancing sustainable energy production through co-polyamide membranes for improved pressure-retarded osmosis performance and environmental impact: synthesis and life cycle analysis. *Green Chemistry*, 27(3), pp. 586-606.
16. Ibid.
17. Paşaoğlu M.E., Koyuncu İ. (2021). Tubular PAN/CNC Thin Film Nanocomposite (TFN) Pressure Retarded Osmosis (PRO) Membrane: Fabrication and Preliminary Evaluation in Desalination Process. *Cellulose*, 28(13), pp. 8653-70.
18. Kim C., Lee J., Schmucker D., Fortner J.D. (2020). Highly Stable Superparamagnetic Iron Oxide Nanoparticles as Functional Draw Solutes for Osmotically Driven Water Transport. *NPJ Clean Water*, 3(1).
19. Gül T.F., Akalın M., Dönmezler E.N., Bolat A., et al. (2024). Review on reverse electrodialysis process-a pioneering technology for energy generation by salinity gradient. *Frontiers in Membrane Science and Technology*, 3.
20. SaltPower. (2025). *What is SaltPower*. https://saltpower.net/what-is-saltpower/.
21. Kurihara M., Hanakawa M. (2013). Mega-ton Water System: Japanese national research and development project on seawater desalination and wastewater reclamation. *Desalination*, 308, pp. 131-7.
22. Hitachi News Release. (2015). *Hitachi and Toray to Test "Mega-ton Water System," a Large-scale, High Efficiency Seawater Desalination System, in Saudi Arabia* [Press release]. https://www.hitachi.com/New/cnews/month/2015/05/150520a.html.
23. Cagney, D., & Gruet, R. (2019). *Powering Homes Today, Powering Nations Tomorrow*. Ocean Energy Europe. https://www.oceanenergy-europe.eu/wp-content/uploads/2019/04/ETIP-Ocean-Integrated-Strategy-2019-LR.pdf.
24. International Energy Agency (IEA). (2025). *Supply – Electricity 2025 – Analysis*. https://www.iea.org/reports/electricity-2025/supply.
25. Hassan, Q., Algburi, S., Sameen, A.Z., Salman, H.M., & Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. *Results in Engineering*, 20, 101621. https://doi.org/10.1016/j.rineng.2023.101621.
26. International Renewable Energy Agency (IRENA). (2020). *Innovation outlook: Ocean energy technologies.*
27. SCISPACE. (n.d.). *Osmotic Power: Papers published on a yearly basis*. https://typeset.io/topics/osmotic-power-2esx4hak/2023.
28. Sweetch Energy. (2023, 18 December). *Sweetch Energy secures €25M to accelerate the global deployment of osmotic energy*. https://cdn.prod.website-files.com/6527b5a78159fe64a0eb7cdf/658048131232d2d65a376e14_121823%20PR%20SWEETCH%20ENERGY.pdf.
29. Hedin, J.T.L., Meli, F., & Narasimhan, K. (2023, 6 April). *Method of using nanofiltration and reverse osmosis to remove chemical contaminants*. Google Patents. https://patents.google.com/patent/US20230109082A1/en.

30. Feria-Díaz, J.J., Correa-Mahecha, F., López-Méndez, M.C., Rodríguez-Miranda, J.P., & Barrera-Rojas, J. (2021). Recent desalination technologies by hybridization and integration with reverse osmosis: A Review. *Water*, 13(10), 1369. https://doi.org/10.3390/w13101369.

31. Dubai Future Foundation (DFF). (2024, 11 February). *Navigating 10 megatrends shaping our future in 2024.* https://www.dubaifuture.ae/navigating-10-megatrends-shaping-our-future-in-2024.

32. Liou, J. (2023, 14 September). *What are small modular reactors (SMRs)?*. International Atomic Energy Agency (IAEA). https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs.

33. Energy.gov. (2022, 23 August). *X-energy completes $40 million project to further develop high-temperature gas reactor*. https://www.energy.gov/ne/articles/x-energy-completes-40-million-project-further-develop-high-temperature-gas-reactor#:~:text=X-energy%20received%20the%20Advanced,%20and%20TRISO-X%20particle%20fuel%20.

34. Martucci, B. (2024, 13 May). *Small modular reactor startups Oklo and Nano Nuclear Energy Make Us Stock Market debut*. Utility Dive. https://www.utilitydive.com/news/small-modular-reactor-startups-oklo-nano-nuclear-energy-haleu-fuel/715911/.

35. World Nuclear Association. (2024, 3 May). *Nuclear Power in South Korea.* https://world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.

36. World Nuclear Association. (2024, 5 September). *Nuclear Power in the United Arab Emirates.* https://world-nuclear.org/information-library/country-profiles/countries-t-z/united-arab-emirates.

37. Westinghouse Nuclear. (n.d.). *Westinghouse celebrates Milestone Achievement as AP1000® Technology powers plant vogtle unit 4 into Commercial Operation*. https://info.westinghousenuclear.com/news/westinghouse-celebrates-milestone-achievement-as-ap1000-technology-powers-plant-vogtle-unit-4-into-commercial-operation.

38. Paul, S., Klimenka, M., Duarte, F., Crawford, C., et al. (2024). When Cities Go Nuclear: Exploring the applications of nuclear batteries toward Energy Transformation. *Urban Science*, 8(4), 226. https://doi.org/10.3390/urbansci8040226.

39. Platonova, M. (2024, 14 February). *Decarbonizing steel production with nuclear hydrogen*. International Atomic Energy Agency (IAEA). https://www.iaea.org/bulletin/decarbonizing-steel-production-with-nuclear-hydrogen.

40. Apel, F., Hoyt, J., Marques, F., Reiter, S. & Schulze, P. (2023, 6 October). *Cementing your lead: The cement industry in the net-zero transition*. McKinsey & Company. https://www.mckinsey.com/industries/engineering-construction-and-buildingmaterials/our-insights/cementing-your-lead-the-cement-industry-in-the-net-zero-transition.

41. Fraser, P., Wanner, B., Everhart, K. & Herzog, A. (2022). *Nuclear Power and Secure Energy Transitions: From today's challenges to tomorrow's clean energy systems*. International Energy Agency (IEA).

42. Hanna, B.N., Abou-Jaoude, A., Guaita, N., Talbot, P. & Lohse, C. (2024). Navigating economies of scale and multiples for nuclear-powered data centers and other applications with high service availability needs. *Energies*, 17(20), 5073. https://doi.org/10.3390/en17205073.

43. Fisher, M. (2024, 13 December). *Accelerating advanced nuclear deployment: Meeting the Supply Chain Challenge*. International Atomic Energy Agency (IAEA). https://www.iaea.org/newscenter/news/accelerating-advanced-nuclear-deployment-meeting-the-supply-chain-challenge.

44. International Atomic Energy Agency (IAEA). (2024). *Small Modular Reactors: Advances in SMR Developments 2024*. https://doi.org/10.61092/iaea.3o4h-svum.

45. Dubai Future Foundation (DFF). (2024, 11 February). *Navigating 10 megatrends shaping our future in 2024.* https://www.dubaifuture.ae/navigating-10-megatrends-shaping-our-future-in-2024.

46. Cubillos-Ruiz, A., Guo, T., Sokolovska, A., Miller, P. F., et al. (2021). Engineering living therapeutics with synthetic biology. *Nature Reviews Drug Discovery*, 20, pp. 941-960. https://doi.org/https://doi.org/10.1038/s41573-021-00285-3.

47. Khazem, A., Schmachtenberg, R., Weiand, A., Sankaran, S., & Weber, W. (2025). Engineered microbial living matter for diagnostics, prevention, and therapy. *Current Opinion in Biotechnology*, 92, 103269. https://doi.org/10.1016/j.copbio.2025.103269.

48. Chariot Biosciences. (n.d.). *Innovative Therapeutics Pipeline*. https://www.chariot-bio.com/pipeline/.

49. Aurealis Therapeutics. (2024, 25 November). *Pipeline and science*. https://aurealistherapeutics.com/pipeline-and-science/#pipeline.

50. NEC. (2024, 12 December). *NEC Announces Interim Results from Phase 1 Clinical Trial of NECVAX-NEO1, an AI-Driven Personalized Oral Cancer Vaccine, at ESMO Immuno-Oncology Congress 2024* [Press release]. https://www.nec.com/en/press/202412/global_20241212_01.html.

51. Zalatan, J.G., Petrini, L., & Geiger, R. (2024). Engineering bacteria for cancer immunotherapy. *Current Opinion in Biotechnology*, 85, 103061. https://doi.org/https://doi.org/10.1016/j.copbio.2023.103061.

52. Dey, S., & Sankaran, S. (2024). Engineered bacterial therapeutics with material solutions. *Trends in Biotechnology*, 42(12), pp. 1663-1676. https://doi.org/10.1016/j.tibtech.2024.06.011.

53. Zou, Z.-P., Zhang, X.-P., Zhang, Q., Yin, B.-C., et al. (2024). Genetically engineered bacteria as inflammatory bowel disease therapeutics. *Engineering Microbiology*, 4(4), 100167. https://doi.org/10.1016/j.engmic.2024.100167.

54. Dubai Future Foundation (DFF). (2024, 11 February). *Navigating 10 megatrends shaping our future in 2024.* https://www.dubaifuture.ae/navigating-10-megatrends-shaping-our-future-in-2024.

55. Kalinderi, K., Papaliagkas, V., & Fidani, L. (2024). GLP-1 receptor agonists: A new treatment in parkinson's disease. *International Journal of Molecular Sciences*, 25(7), 3812. https://doi.org/10.3390/ijms25073812.

56. Fessel, J. (2024). All GLP-1 agonists should, theoretically, cure alzheimer's dementia but dulaglutide might be more effective than the others. *Journal of Clinical Medicine*, 13(13), 3729. https://doi.org/10.3390/jcm13133729.

57. Monti, G., Gomes Moreira, D., Richner, M., Mutsaers, H.A.M. (2022). GLP-1 Receptor Agonists in Neurodegeneration: Neurovascular Unit in the Spotlight. *Cells*, 11(13):2023. doi: 10.3390/cells11132023.

58. Novo Nordisk. (2024). *Semaglutide in early Alzheimer's: EVOKE and EVOKE+ clinical trials*. https://clinicaltrials.gov/study/NCT04777396.

59. BioSpace. (2024, 20 November). *GLP-1 Receptor Agonist Market worth $55.70 Billion by 2031, Coherent Market Insights* [Press release].https://www.biospace.com/press-releases/glp-1-receptor-agonist-market-worth-55-70-billion-by-2031-coherent-market-insights.

60. Kopp, K.O., Glotfelty, E.J., Li, Y., & Greig, N.H. (2022). Glucagon-like peptide-1 (GLP-1) receptor agonists and neuroinflammation: Implications for neurodegenerative disease treatment. *Pharmacological Research*, 186, 106550. https://doi.org/10.1016/j.phrs.2022.106550.

61. Pyka, P., Garbo, S., Fioravanti, R., Jacob, C., et al. (2024). Selenium-containing compounds: A new hope for innovative treatments in alzheimer's disease and parkinson's disease. *Drug Discovery Today*, 29(8), 104062. https://doi.org/10.1016/j.drudis.2024.104062.

62. Lobo, A. (2024, 17 September). *In parkinson's disease, healthcare expenses among largest part of cost*. Parkinson's News Today. https://parkinsonsnewstoday.com/news/parkinsons-disease-healthcare-expenses-largest-part-cost/.

63. Mayo Foundation for Medical Education and Research. (2024, 8 November). *Alzheimer's disease*. https://www.mayoclinic.org/diseases-conditions/alzheimers-disease/symptoms-causes/syc-20350447.

64. U.S. Food and Drug Administration (FDA). (2025, 5 March). *FDA clarifies policies for compounders as national GLP-1 supply begins to stabailize* [Press release]. https://www.fda.gov/drugs/drug-safety-and-availability/fda-clarifies-policies-compounders-national-glp-1-supply-begins-stabilize.

65. Don Tracy, A.E. (2024, 25 June). *Novo Nordisk to invest $4.1 billion in expanding manufacturing capabilities in the United States*. PharmExec. https://www.pharmexec.com/view/novo-nordisk-invest-4-1-billion-expanding-manufacturing-capabilities-united-states.

66. Klein, H.E. (2024, 16 May). *Most insured adults still have to pay at least part of the cost of GLP-1 drugs*. AJMC. https://www.ajmc.com/view/most-insured-adults-still-have-to-pay-at-least-part-of-the-cost-of-glp-1-drugs.

67. National Conference of State Legislature. (n.d.). *Growth, volume, price: The skinny on GLP-1 medications - national conference of state legislatures*. https://www.ncsl.org/state-legislatures-news/details/growth-volume-price-the-skinny-on-glp-1-medications.

68. Azam, S., Haque, Md. E., Balakrishnan, R., Kim, I.-S., & Choi, D.-K. (2021). The ageing brain: Molecular and cellular basis of neurodegeneration. *Frontiers in Cell and Developmental Biology*, 9. https://doi.org/10.3389/fcell.2021.683459.

69. Meissner, W.G., Remy, P., Giordana, C., Maltête, et al. (2024). Trial of lixisenatide in early parkinson's disease. *New England Journal of Medicine*, 390(13), pp. 1176-1185. https://doi.org/10.1056/nejmoa2312323.

70. BioSpace. (2024, 9 December). *Evidence mounts for potential of glp-1s in alzheimer's disease*. https://www.biospace.com/drug-development/evidence-mounts-for-potential-of-glp-1s-in-alzheimers-disease.

71. Dubai Future Foundation (DFF). (2024, 11 February) *Navigating 10 megatrends shaping our future in 2024.* https://www.dubaifuture.ae/navigating-10-megatrends-shaping-our-future-in-2024.

72. Maity, D., Guha Ray, P., Buchmann, P., Mansouri, M., & Fussenegger, M. (2023). Blood-glucose-powered metabolic fuel cell for self-sufficient bioelectronics. *Advanced Materials*, 35(21). https://doi.org/10.1002/adma.202300890.

73. National Institute of Diabetes and Digestive and Kidney Diseases (NIDDK). (2024, 28 December). *Continuous glucose monitoring*. https://www.niddk.nih.gov/health-information/diabetes/overview/managing-diabetes/continuous-glucose-monitoring.

74. Zargartalebi, H., Mirzaie, S., GhavamiNejad, A., Ahmed, S. U., et al. (2024). Active-reset protein sensors enable continuous in vivo monitoring of inflammation. *Science*, 386(6726), pp. 1146-1153. https://doi.org/10.1126/science.adn2600.

75. Florea, L., & Diamond, D. (2022). Sensors and "The internet of biochemical things". *Frontiers in Sensors*, 3. https://doi.org/10.3389/fsens.2022.1010212.

76. Huang, C.-W., Lin, C., Nguyen, M.K., Hussain, A., et al. (2023). A review of Biosensor for environmental monitoring: Principle, application, and corresponding achievement of Sustainable Development Goals. *Bioengineered*, 14(1), pp. 58-80. https://doi.org/10.1080/21655979.2022.2095089.

77. Albu, C., Chira, A., Radu, G.-L., & Eremia, S.A. (2025). Advances in cost-effective chemosensors for sustainable monitoring in food safety and processing. *Chemosensors*, 13(3), 113. https://doi.org/10.3390/chemosensors13030113.

78. Institute of Medicine and National Research Council Committee to Ensure Safe Food from Production to Consumption. (1998). The Changing Nature of Food Hazards: Cause for Increasing Concern in *Ensuring Safe Food: From Production to Consumption*. https://www.ncbi.nlm.nih.gov/books/NBK209107/.

79. Lino, C., Barrias, S., Chaves, R., Adega, F. et al. (2022). Biosensors as diagnostic tools in clinical applications. *Biochimica et Biophysica Acta (BBA) - Reviews on Cancer*, 1877(3), 188726. https://doi.org/10.1016/j.bbcan.2022.188726.

80. Florea, L., & Diamond, D. (2022). Sensors and "The internet of biochemical things". *Frontiers in Sensors*, 3. https://doi.org/10.3389/fsens.2022.1010212.

81. Essington, E. A., Vezeau, G. E., Cetnar, D. P., Grandinette, E. (2024). An autonomous microbial sensor enables long-term detection of TNT explosive in natural soil. *Nature Communications*, 15, 10471. https://doi.org/10.1101/2024.10.08.617249.

82. Ibid.

83. Florea, L., & Diamond, D. (2022). Sensors and "The internet of biochemical things". *Frontiers in Sensors*, 3. https://doi.org/10.3389/fsens.2022.1010212.

84. Ibid.

85. Dubai Future Foundation (DFF). (2024, 11 February). *Navigating 10 megatrends shaping our future in 2024.* https://www.dubaifuture.ae/navigating-10-megatrends-shaping-our-future-in-2024.

86. Krietsch Boerner, L. (2019, 15 November). *Industrial Ammonia production emits more CO_2 than any other chemical-making reaction. chemists want to change that*. Chemical & Engineering News. https://cen.acs.org/environment/green-chemistry/Industrial-ammonia-production-emits-CO_2/97/i24.

87. Lehigh University. (2018, 9 July). *Electrochemically-produced ammonia could revolutionize food production*. Phys.org. https://phys.org/news/2018-07-electrochemically-produced-ammonia-revolutionize-food-production.html.

88. Ahmed, M. I., Assafiri, A., Hibbert, D. B., & Zhao, C. (2023). Li-mediated electrochemical nitrogen fixation: Key advances and future perspectives. *Small*, 19(52). https://doi.org/10.1002/smll.202305616.

89. Koh, S., Choi, Y., Lee, I., Kim, G.-M. et al. (2022). Light-driven ammonia production by azotobacter vinelandii cultured in medium containing colloidal quantum dots. *Journal of the American Chemical Society*, 144(24), pp. 10798-10808. https://doi.org/10.1021/jacs.2c01886.

90. Jiang, Y., Chen, C.-J., Li, K., Cui, L.-P., & Chen, J.-J. (2025). Polyoxometalates for the catalytic reduction of nitrogen oxide and its derivatives: From novel structures to functional applications. *Chemical Communications*, 61(26), pp. 4881-4896. https://doi.org/10.1039/d5cc00632e.

91. Ahmed, M. I., Assafiri, A., Hibbert, D. B., & Zhao, C. (2023). Li-mediated electrochemical nitrogen fixation: Key advances and future perspectives. *Small*, 19(52). https://doi.org/10.1002/smll.202305616.

92. Tonelli, D., Rosa, L., Gabrielli, P., Parente, A., & Contino, F. (2024). Cost-competitive decentralized ammonia fertilizer production can increase food security. *Nature Food*, 5(6), pp. 469-479. https://doi.org/10.1038/s43016-024-00979-y.

93. Gallucci, M. (2021). The ammonia solution: Ammonia engines and fuel cells in cargo ships could slash their carbon emissions. *IEEE Spectrum*, 58(3), pp. 44-50. https://doi.org/10.1109/mspec.2021.9370109.

94. Ibid.

95. Izelaar, B., Ramdin, M., Vlierboom, A., Perez-Fortes, M. et al. (2024). Techno-economic assessment of different smallscale electrochemical NH3 production plants. *Energy & Environmental Science*, 17, 7983. https://doi.org/https://doi.org/10.1039/d4ee03299c.

96. Blain, L. (2022, 30 November). *World's largest green ammonia projects could clean up half the market*. New Atlas. https://newatlas.com/energy/largest-green-ammonia-projects/.

97. World Economic Forum. (2023). Ammonia Industry. In *Net-Zero Industry Tracker 2023*. https://www.weforum.org/publications/net-zero-industry-tracker-2023/ammonia-industry-eaee0d0381/.

98. Lehigh University. (2018, July 9). *Electrochemically-produced ammonia could revolutionize food production*. Phys.org. https://phys.org/news/2018-07-electrochemically-produced-ammonia-revolutionize-food-production.html.

99. International Energy Agency (IEA). (2021). Executive summary. In *Ammonia Technology Roadmap*. https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary.

100. Hussain, J., Mubarak, M., Boopathi, D., & Jayabal, R. (2025). A comprehensive review of production and utilisation of ammonia as potential fuel for compression ignition engines. *Next Sustainability*, 5, 100116. https://doi.org/10.1016/j.nxsust.2025.100116.

101. Adeniyi, A., Bello, I., Mukaila, T., Sarker, N., & Hammed, A. (2023). Trends in biological ammonia production. *Trends in Biological Ammonia Production*, 12(2), 41. https://doi.org/10.20944/preprints202304.0543.v1.

102. Ibid.

103. Spry, M., Westhead, O., Tort, R., Moss, B., et al. (2023). Water increases the faradaic selectivity of Li-mediated nitrogen reduction. *ACS Energy Letters*, 8(2), pp. 1230-1235. https://doi.org/10.1021/acsenergylett.2c02792.

104. Fu, X. (2023). Lithium-mediated nitrogen reduction for electrochemical ammonia synthesis: From batch to flow reactor. *Materials Today Catalysis*, 3, 100031. https://doi.org/10.1016/j.mtcata.2023.100031.

105. Zhou, Y., Fu, X., Chorkendorff, I., & Nørskov, J. K. (2024). Electrochemical Ammonia Synthesis: The energy efficiency challenge. *ACS Energy Letters*, 10(1), pp. 128-132. https://doi.org/10.1021/acsenergylett.4c02954.

106. International Energy Agency (IEA). (n.d.). *Critical Minerals*. https://www.iea.org/topics/critical-minerals.

107. Masia, B., Yang, M., & Cozzani, V. (2024). Risk assessment of ammonia fueled ships: Consequences on human health of ammonia releases from damaged fuel storage tanks. *ACS Chemical Health & Safety*, 31(6), pp. 503-520. https://doi.org/10.1021/acs.chas.4c00044.

108. Wyer, K. E., Kelleghan, D. B., Blanes-Vidal, V., Schauberger, G., & Curran, T. P. (2022). Ammonia emissions from agriculture and their contribution to fine particulate matter: A review of implications for human health. *Journal of Environmental Management*, 323, 116285. https://doi.org/10.1016/j.jenvman.2022.116285.

109. International Energy Agency (IEA). (n.d.) *Ammonia Technology Roadmap: Towards more sustainable nitrogen fertilizer production*. https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf.

110. Dubai Future Foundation (DFF). (2024, 11 February). *Navigating 10 megatrends shaping our future in 2024.* https://www.dubaifuture.ae/navigating-10-megatrends-shaping-our-future-in-2024.

111. Sen, A., Oswalia, J., Yadav, S., Vachher, M., & Nigam, A. (2024). Recent trends in nanozyme research and their potential therapeutic applications. *Current Research in Biotechnology*, 7, 100205. https://doi.org/10.1016/j.crbiot.2024.100205.

112. Bilal, M., Khaliq, N., Ashraf, M., Hussain, N., (2023). Enzyme mimic nanomaterials as nanozymes with catalytic attributes. *Colloids and Surfaces B: Biointerfaces*, 221, 112950. https://doi.org/10.1016/j.colsurfb.2022.112950.

113. Sen, A., Oswalia, J., Yadav, S., Vachher, M., & Nigam, A. (2024). Recent trends in nanozyme research and their potential therapeutic applications. *Current Research in Biotechnology*, 7, 100205. https://doi.org/10.1016/j.crbiot.2024.100205.

114. Level Nine. (n.d.). *Next-generationcatalysts, inspired by nature.* https://www.levelninelabs.com/.

115. Gust. (n.d.). *Nanozyme, Inc.* https://gust.com/companies/nanozyme.

116. Wang, T., Lai, L., Huang, Y., & Su, E. (2024). Nanozyme: An emerging tool for food packaging. *Food Control*, 155, 110104. https://doi.org/10.1016/j.foodcont.2023.110104.

117. Sen, A., Oswalia, J., Yadav, S., Vachher, M., & Nigam, A. (2024). Recent trends in nanozyme research and their potential therapeutic applications. *Current Research in Biotechnology*, 7, 100205. https://doi.org/10.1016/j.crbiot.2024.100205.

118. Market Research Future. (n.d.). *Nanozyme market size, share, outlook insights 2034*. https://www.marketresearchfuture.com/reports/nanozyme-market-30279.

119. Cao, X., Liu, T., Wang, X., Yu, Y., et al. (2024). Recent advances in nanozyme-based sensing technology for antioxidant detection. *Sensors*, 24(20), 6616. https://doi.org/10.3390/s24206616.

120. Ibid.

121. Tagaras, N., Song, H., Sahar, S., Tong, W., et al. (2024). Safety landscape of therapeutic nanozymes and future research directions. *Advanced Science*, 11(46). https://doi.org/10.1002/advs.202407816.

122. Zhang, Y., Hu, X., Shang, J., Shao, W., et al. (2022). Emerging nanozyme-based multimodal synergistic therapies in combating bacterial infections. *Theranostics*, 12(13), pp. 5995-6020. https://doi.org/10.7150/thno.73681.

123. Cao, X., Liu, T., Wang, X., Yu, Y., et al. (2024). Recent advances in nanozyme-based sensing technology for antioxidant detection. *Sensors*, 24(20), 6616. https://doi.org/10.3390/s24206616.

124. Ibid.

125. Ibid.

126. Wang, P., Wang, T., Hong, J., Yan, X., & Liang, M. (2020). Nanozymes: A new disease imaging strategy. *Frontiers in Bioengineering and Biotechnology*, 8. https://doi.org/10.3389/fbioe.2020.00015.

127. American National Standards Institute. (2021, 8 October). *With standards, the potential of nanotechnology keeps growing*. https://www.ansi.org/standards-news/all-news/2021/10/10-8-21-with-standards-the-potential-for-nanotechnology-keeps-growing.

128. Dubai Future Foundation (DFF). (2024, 11 February). *Navigating 10 megatrends shaping our future in 2024.* https://www.dubaifuture.ae/navigating-10-megatrends-shaping-our-future-in-2024.

129. Ebadi, K., Chang, Y., Palieri, M., Stephens, A., et al. (2020). Lamp: Large-scale autonomous mapping and positioning for exploration of perceptually-degraded subterranean environments. *IEEE International Conference on Robotics and Automation (ICRA)*, pp. 80-86. https://doi.org/10.1109/icra40945.2020.9197082.

130. Williams, L.C. (2024, 9 April). Drones, maps, and storm-tracking in the Pacific. *Defense One*. https://www.defenseone.com/defense-systems/2024/04/drones-maps-and-storm-tracking-pacific/395574/?oref=d1-category-lander-river.

131. Naratek. (2019, 22 November). *Researchers develop robotic ants with Swarm Intelligence*. https://www.naratek.com/en/2019/researchers-develop-robotic-ants-swarm-intelligence.

132. Yi, L., Deng, X., Yang, L. T., Wu, H., et al. (2021). Reinforcement-learning-enabled partial confident information coverage for IOT-based Bridge Structural Health Monitoring. *IEEE Internet of Things Journal*, 8(5), pp. 3108-3119. https://doi.org/10.1109/jiot.2020.3028325.

133. Delheimer, S. (n.d.). *Using drones in agriculture and Natural Resources*. National Institute of Food and Agriculture. https://www.nifa.usda.gov/about-nifa/impacts/using-drones-agriculture-natural-resources.

134. Federal Communications Commission. (2024, 21 November). FCC ADOPTS 'C-V2X' AUTO SAFETY SPECTRUM RULES. https://docs.fcc.gov/public/attachments/DOC-407683A1.pdf.

135. Armeni, I., He, Z.-Y., Zamir, A., Gwak, J., (2019). 3D scene graph: A structure for unified semantics, 3D space, and camera. *IEEE/CVF International Conference on Computer Vision (ICCV)*. https://doi.org/10.1109/iccv.2019.00576.

136. Cadena, C. et al. (2016). Past, Present, and Future of Simultaneous Localization and Mapping: Toward the Robust-Perception Age. *IEEE Transactions on Robotics*, vol. 32, no. 6, pp. 1309-1332. https://ieeexplore.ieee.org/document/7747236.

137. Feng, D., et al. (2021). Deep Multi-Modal Object Detection and Semantic Segmentation for Autonomous Driving: Datasets, Methods, and Challenges. *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 3, pp. 1341-1360. https://ieeexplore.ieee.org/document/9000872.

138. Rajvanshi, A., et al. (2023). SayNav: Grounding Large Language Models for Dynamic Planning to Navigation in New Environments. *Cornell University*. https://arxiv.org/abs/2309.04077.

139. Pawar, V., Zade, N., Vora, D., Khairnar, V., et al. (2024). Intelligent Transportation System with 5G vehicle-to-everything (V2X): Architectures, vehicular use cases, emergency vehicles, current challenges, and Future Directions. *IEEE Access*, 12, 183937-183960. https://doi.org/10.1109/access.2024.3506815.

140. Adnan Yusuf, S., Khan, A., & Souissi, R. (2024). Vehicle-to-everything (V2X) in the Autonomous Vehicles Domain – A Technical Review of Communication, sensor, and AI Technologies for Road User Safety. *Transportation Research Interdisciplinary Perspectives*, 23, 100980. https://doi.org/10.1016/j.trip.2023.100980.

141. Stone, T. (2020, 19 November). *White Paper: Australian research reveals V2x could reduce crashes by 78%*. Traffic Technology Today. https://www.traffictechnologytoday.com/news/connected-vehicles-infrastructure/white-paper-australian-research-reveals-connected-talking-cars-could-save-lives.html.

142. National Renewable Energy Laboratory (NREL). (n.d.). *Connected and automated trucks: Transportation and Mobility Research*. https://www.nrel.gov/transportation/connected-automated-trucks.html.

143. Adnan Yusuf, S., Khan, A., & Souissi, R. (2024). Vehicle-to-everything (V2X) in the Autonomous Vehicles Domain – A Technical Review of Communication, sensor, and AI Technologies for Road User Safety. *Transportation Research Interdisciplinary Perspectives*, 23, 100980. https://doi.org/10.1016/j.trip.2023.100980.

144. Pawar, V., Zade, N., Vora, D., Khairnar, V., et al. (2024). Intelligent Transportation System with 5G vehicle-to-everything (V2X): Architectures, vehicular use cases, emergency vehicles, current challenges, and Future Directions. *IEEE Access*, 12, 183937-183960. https://doi.org/10.1109/access.2024.3506815.

145. Ericsson. (n.d.). *5G network coverage outlook*. https://www.ericsson.com/en/reports-and-papers/mobility-report/dataforecasts/network-coverage.

146. Dubai Future Foundation (DFF). (2024, 11 February). *Navigating 10 megatrends shaping our future in 2024.* https://www.dubaifuture.ae/navigating-10-megatrends-shaping-our-future-in-2024.

147. Zhao, X., Gunn, S., Christ, M., Fairoze, J., et al. (n.d.). SoK: Watermarking for AI-Generated Content. *arxiv*. https://arxiv.org/html/2411.18479v2.

148. Google DeepMind. (n.d.). *SynthID*. https://deepmind.google/technologies/synthid/.

149. Fernandez, P., Elsahar, H., Yalniz, I. Z., & Mourachko, A. (n.d.). Video Seal: Open and Efficient Video Watermarking. *arvix*. https://doi.org/https://doi.org/10.48550/arXiv.2412.09492.

150. Bartz, D., & Hu, K. (2023, 21 July). *OpenAI, Google, others pledge to watermark AI content for safety, White House says*. Reuters. https://www.reuters.com/technology/openai-google-others-pledge-watermark-ai-content-safety-white-house-2023-07-21/.

151. Fernandez, P. et al. (2024, 11 December). *Video Seal: Open and Efficient Video Watermarking*. Meta. https://ai.meta.com/research/publications/video-seal-open-and-efficient-video-watermarking/.

152. Clegg, N. (2024, 6 February). *Labeling AI-generated images on Facebook, Instagram and threads*. Meta. https://about.fb.com/news/2024/02/labeling-ai-generated-images-on-facebook-instagram-and-threads/.

153. Partnership on AI. (2024, 19 November). *Partnership on AI Unveils New Case Studies from Supporters of Synthetic Media Framework: Meta, Microsoft, Thorn, and Truepic*. https://partnershiponai.org/nov-2024-synthetic-media-case-studies-announcement/.

154. Heitzenrater, C. (2024, 17 January). *The case for and against AI Watermarking*. Rand. https://www.rand.org/pubs/commentary/2024/01/the-case-for-and-against-ai-watermarking.html.

155. Cyberspace Administration of China. (2022). *Provisions on the Management of Deep Synthesis of Internet Information Services*. https://www.cac.gov.cn/2022-12/11/c_1672221949354811.htm.

156. European Parliament. (2023, 13 December). *Generative AI and watermarking*. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2023)757583.

157. California Legislative Information. (2024). *SB-942 California AI Transparency Act. (2023-2024)*. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202320240SB942.

158. Wu, D. (2025, 14 March). *China announces generative ai labeling to cull disinformation.* Bloomberg. https://www.bloomberg.com/news/articles/2025-03-14/china-announces-generative-ai-labeling-to-cull-disinformation.

159. EU Artificial Intelligence Act. (n.d.). *The EU Artificial Intelligence Act*. https://artificialintelligenceact.eu/.

160. EU Artificial Intelligence Act. (2025). *Article 99: Penalties*. https://artificialintelligenceact.eu/article/99/.

161. Adobe. *Content Credentials overview*. (2025, 22 January). https://helpx.adobe.com/creative-cloud/help/content-credentials.html.

162. DiBenedetto, C. (2024, 9 May). *TikTok's ai-generated content is getting watermarked*. Mashable. https://mashable.com/article/tiktok-watermarking-ai-generated-content.

163. Ai watermarking must be watertight to be effective. (2024). *Nature*, *634*(8035), 753–753. https://doi.org/10.1038/d41586-024-03418-x

164. Evsutin, O., & Meshcheryakov, Y. (2020). The use of the blockchain technology and digital watermarking to provide data authenticity on a mining enterprise. *Sensors*, 20(12), 3443. https://doi.org/10.3390/s20123443.

165. Dubai Future Foundation (DFF). (2024, 11 February). *Navigating 10 megatrends shaping our future in 2024.* https://www.dubaifuture.ae/navigating-10-megatrends-shaping-our-future-in-2024.

COMMITTED TO IMPROVING THE STATE OF THE WORLD

The World Economic Forum, committed to improving the state of the world, is the International Organization for Public-Private Cooperation.

The Forum engages the foremost political, business and other leaders of society to shape global, regional and industry agendas.

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