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KINGDOM OF SAUDI ARABIA

Emerging Innovative Technologies in Economies of the Future

The Research, Development and
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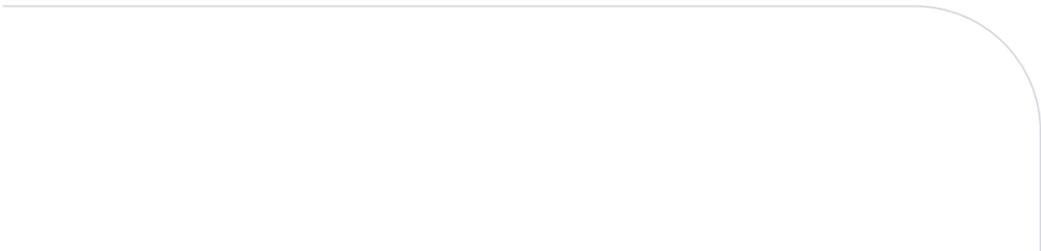
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2025

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INTRODUCTION

The pace of technological advancement continues to redefine industries, economies, and societies, making Technology Foresight a critical tool for shaping future strategies. By anticipating transformative trends and evaluating their potential impacts, foresight enables stakeholders to align innovation with economic and societal needs, ensuring sustainable growth and resilience in an increasingly interconnected world.

This report explores a diverse range of cutting-edge fields that are driving profound changes in how we work, communicate, and live. From the extraordinary computational power of exascale computing to quantum computing, advancements in computing are creating new opportunities for industries worldwide. Meanwhile, the integration of generative artificial intelligence and humanoid robotics is reshaping creativity, automation, and human-machine interaction, offering unprecedented possibilities for innovation.

In parallel, immersive environments such as the industrial metaverse and the deployment of Low-Earth Orbit (LEO) satellites are revolutionizing communication, collaboration, and global connectivity. These are complemented by breakthroughs in Reconfigurable Intelligent Surfaces (RIS), which promise to transform wireless communication infrastructure, and Cybersecurity Mesh Architecture (CSMA), which provides scalable solutions to safeguard increasingly complex digital ecosystems. Emerging technologies like Unmanned Aerial Vehicles (UAVs) and smart city solutions are also reshaping mobility, logistics, and urban planning, paving the way for more efficient, sustainable, and interconnected cities.

Through an in-depth analysis, this report examines the economic drivers behind these innovations, provides insights into their current and projected market impact, and highlights their alignment with Saudi Vision 2030 and the National Missions for Research, Development, and Innovation (RDI). By leveraging both qualitative and quantitative criteria, the report evaluates the significance of these fields through the lens of the Scientific Committee of the National Research, Development, and Innovation Observatory (NRDIO).

As the world stands on the cusp of a new technological era, these advancements represent not only opportunities for growth but also the foundation for building resilient, sustainable, and forward-looking economies. This report provides insights into harnessing the transformative power of these innovations, paving the way for the development of resilient and sustainable economies of the future.

02

METHODOLOGY

The technical foresight methodology at the National Research, Development and Innovation Observatory (NRDIO) consists of four main axes: monitoring, analysis, evaluation, and alignment which are explained as follows:

1. Monitoring

When forecasting emerging technologies, the National Research, Development and Innovation Observatory (NRDIO) incorporates Proactive and Reactive Monitoring to enhance the accuracy and responsiveness of analysis.

A) Proactive Monitoring

Proactive monitoring involves anticipating trends, innovations, and breakthroughs before they gain mainstream attention. This helps in identifying emerging technologies early on, allowing for strategic preparation and planning.

- Horizon scanning: NRDIO regularly reviews scientific literature, patent filings, venture capital funding reports, technology roadmaps, and expert opinions. Tools like artificial intelligence and text mining are utilized to identify trends from large datasets.

- Delphi method: A panel of experts was established to gain foresight into potential technological advances. This iterative consultation helps forecast new developments.

- Trend analysis: NRDIO examines historical data on similar technologies to predict growth curves and tipping points. This includes analyzing adjacent technologies and potential convergences.

- Technology readiness level (TRL): The development stage of technologies is continuously evaluated based on their TRL, helping to understand when they might mature into scalable solutions.

B) Reactive Monitoring

Reactive monitoring focuses on responding to real- world developments as they happen. It involves tracking the real-time progress of technologies that have already been identified as emerging, and adjusting forecasts based on new data. It is performed by the following methods:

- Continuous real-time data collection: Systems are implemented to track real-time developments such as new product launches, regulatory changes, mergers and acquisitions, and shifts in the competitive landscape.

- Signal detection: Key indicators are monitored (e.g., breakthroughs, government policy shifts, industry adoption rates) that suggest when a technology is gaining momentum or encountering barriers.

- **Social media and news analysis:** Sentiment analysis and media monitoring tools are used to capture public and industry reactions to technological developments.

- **Post-launch evaluation:** Once an emerging technology reaches the market, its performance is evaluated through user feedback, financial performance metrics, and industry reviews.

Utilizing the above methods, the next steps follow:

- **Strategic adjustment and reflection:** Based on the real-time insights gathered through reactive monitoring, NRDIO continuously adjusts its strategic forecasts, and priorities to ensures that NRDIO remains adaptable, making course corrections where necessary to capitalize on opportunities or mitigate risks.

- **Interdisciplinary stakeholder engagement:** Engaging Interdisciplinary experts from the industry and academia to gain a holistic view and qualitative feedback that complements quantitative data.

2. Analysis

The analysis activity in the technical foresight methodology followed at NRDIO consists of the following elements:

- **Technical analysis:** This includes providing an overview of the field under which the tech signal falls to place it in a broader context. The technical analysis also includes providing an overview of the tech signal in terms of describing it, explaining its principles and advantages, and its points of superiority over competing and alternative technologies.

- **Economic analysis:** This involves offering an overview of the field in which the technology signal is positioned within a broader context. It also includes describing the technology signal, explaining its principles and advantages, and highlighting its superiority over competing or alternative technologies.

- **Risk analysis:** The risks and challenges associated with emerging technologies are analyzed, whether ethical, legal, environmental, social, or otherwise. This also includes suggesting how to address potential obstacles, which leads to improving the chances of success of the emerging technology and achieving its desired goals.

3. Evaluation

Technological signals are evaluated quantitatively and qualitatively by a scientific committee of experts specialized in various fields, through several main criteria that aim to measure the extent of their impact and feasibility from different aspects, in terms of:

1. **Strategic Impact:** This criterion indicates the role of technology in solving global challenges, and evaluates the importance of technology in dealing with the major challenges facing the world, such as climate change, food security, natural resources, and others.

2. **Long-term impact**: This criterion measures the sustainability of the impact of technology in the long term in different sectors, and determines the extent of the technology's ability to bring about permanent change or a long-term impact on individuals, companies, or industries.

3. **Need within the sector**: This criterion determines the extent to which a technology is considered in demand within the technology sector itself or within related industries. The need for technology is determined based on current gaps in the sector, whether in manufacturing, services, or other technical systems.

4. **Consumers' attitude towards technology:** This criterion measures the extent to which consumers or end users are interested in the new technology, whether at the individual or corporate level.

5. **Economic impact and commercial benefit**: This criterion assesses the expected economic benefit of the technology, including commercial profits and market growth, the potential market size, and the value of commercial returns.

6. **Technology Readiness Level (TRL):** This criterion determines the extent to which the technology has progressed in its development cycle, from research and development to commercialization. The closer the technology is to commercial readiness, the more important it is in terms of investment and adoption.

In order to achieve a broader, more diverse, and more accurate perspective on emerging technologies and their various impacts. A score of (0 - 5) is given to each of the six aforementioned aspects; 5 indicates the 'highest' importance, while 0 indicates the 'lowest' importance. The "Evaluation" activity involves also the engagement of stakeholders (such as academics, companies, regulators, and other parties related to research, development, and innovation) through a questionnaire dedicated to technology foresight.

4. Alignment

The results of technology foresight are aligned to strategic plans and implementation steps that can be taken at the policy or investment level, where the results of monitoring, analysis and evaluation are translated into practical recommendations that can be implemented at the policy and regulatory level or the strategic plans of institutions. The aim is to ensure that technology foresight does not remain within the scope of theory or research only, but is transformed into concrete steps to stimulate innovation and support the knowledge-based economy.

The technology signals highlighted in this report are linked to the goals of Saudi Vision 2030 and aligned with the following National RDI Missions in the Economies of the Future:

1. Going beyond Smart Cities, establish five Cognitive Cities in KSA by 2040.

2. Creating a safe trustworthy Artificial General Intelligence that learns and realizes autonomous work in favor of humans by 2040.

3. Developing programmable fault-tolerant quantum computer by 2040.

4. Demonstrating x10,000 computing performance improvement by 2040.

5. Achieving 50% automation of in-Kingdom logistics shipments by 2040.

6. Future of connectivity: building sustainable 6G technologies by 2035.

7. Developing general purpose robots that assist humans in daily tasks by understanding and adapting to their dynamic environment by 2040.

8. Developing multi-purpose industrial robots that understand and adapt to their changing environment by 2035.

03

STRUCTURE

The current report highlights 10 technology fields shaping the Economies of the Future, categorized into four main themes as outlined below:

Advanced Computing

1. Quantum Computing: Revolutionizing fields like cryptography, optimization, material science, and AI with unparalleled computational power.

2. Exascale Computing: Enabling breakthroughs in climate modeling, drug discovery, and complex simulations by pushing the limits of computational performance.

Artificial Intelligence and Machine Learning

3. Generative Artificial Intelligence (Gen AI): Transforming creativity, content generation, and automation across industries, from healthcare to entertainment.

4. Humanoid Robotics: A significant milestone in robotics, merging human-like interaction capabilities with machine precision, with applications in healthcare, manufacturing, and service industries.

5. Industrial Metaverse: Emerging as a transformative tool for industrial simulations, training, and collaboration.

Communication and Connectivity

6. Low-Earth Orbit (LEO) Satellites: Revolutionizing global connectivity, remote sensing, and disaster management with affordable, high-speed internet and data coverage.

7. Reconfigurable Intelligent Surfaces (RIS): Pioneering the next generation of wireless communications, optimizing 6G networks, and improving spectrum efficiency.

8. Cybersecurity Mesh Architecture (CSMA): Addressing growing security challenges by providing a scalable, modular approach to cybersecurity in distributed systems.

Intelligent Mobility and Urban Optimization

9. Unmanned Aerial Vehicles (UAVs): Making significant impacts in logistics, agriculture, surveillance, and disaster response, with further potential for autonomous advancements.

10. Smart Cities and Traffic Congestion Solutions: Contributing to sustainability and urban living; paving the way to cognitive cities.

For each of the 10 identified fields, this report presents a Technology Signal as a representative showcase. This is followed by a comprehensive Economic Overview, highlighting the key growth drivers of the field alongside estimates of its current and projected market size. Each technology field is then contextualized within the framework of Saudi Vision 2030, demonstrating its alignment with the National Missions for RDI. Finally, the report assesses the significance of each field using a rigorous evaluation process, incorporating multiple quantitative and qualitative criteria (Multi-Dimensional Evaluation) as determined by the Scientific Committee of the National Research, Development, and Innovation Observatory (NRDIO).

Emerging Innovative Technologies in Economies of the Future

01
Quantum Computing

Quantum computing, a revolutionary field at the intersection of physics and computer science, promises to transform the way we process information. Unlike classical computers that rely on bits (0 or 1), quantum computers leverage qubits, which can exist in multiple states simultaneously due to a phenomenon called superposition. This enables quantum computers to perform certain calculations exponentially faster than classical computers.

Qubits, the fundamental units of quantum information, can be entangled, meaning their states become interconnected regardless of distance. This entanglement allows for parallel processing, enabling quantum computers to solve complex problems that would be intractable for classical machines. The potential applications of quantum computing are vast and span various fields:

- Materials Science: Quantum computers can simulate the behavior of molecules and materials at a quantum level, accelerating the discovery of new materials with desired properties.

- Drug Discovery: By simulating the interactions between molecules, quantum computers can help identify potential drug candidates more efficiently, reducing the time and cost of drug development.

- Optimization Problems: Quantum algorithms can solve optimization problems, such as logistics and scheduling, more effectively than classical methods, leading to significant efficiency gains.

- Machine Learning: Quantum machine learning algorithms have the potential to revolutionize artificial intelligence by enabling faster training of models and improving their performance on complex tasks.

- Cryptography: While quantum computers pose a threat to classical cryptographic algorithms, they can also be used to develop new, quantum-resistant encryption methods. Post-quantum cryptography (PQC) refers to cryptographic methods designed to be secure against the potential threats posed by quantum computers.[1]

- Despite its immense potential, quantum computing faces several challenges:

- Qubit Coherence: Maintaining the quantum state of qubits is difficult, as they are highly susceptible to interference from their environment. This limits the duration of quantum computations.

- Error Correction: Quantum errors can occur due to various factors, such as noise and decoherence. Developing effective error correction techniques is crucial for reliable quantum computing.

- Scaling: Building large-scale quantum computers with a sufficient number of qubits to tackle complex problems is a significant engineering challenge.

- Software Development: Creating quantum algorithms and software that can harness the power of quantum hardware is an active area of research.

As researchers continue to address the challenges and limitations in quantum computing, it is expected that quantum computers will play an increasingly important role in various fields. The future of quantum computing holds the promise of groundbreaking discoveries and transformative applications that will shape our world.

Tech Signal: New Advancements in Quantum Computing

1. Reliable Quantum Computing with Virtualized Qubits

A major breakthrough was achieved through a collaboration between Quantinuum and Microsoft, which introduced a highly efficient qubit-virtualization system. This system dramatically reduced the number of physical qubits required to create a logical qubit, from the previously estimated hundreds or thousands down to just 30 physical qubits. This advancement marks a critical step toward fault-tolerant quantum computing, a necessary condition for making quantum computers truly practical and reliable for various applications. The innovation challenges the prevailing assumptions about the resources needed for error correction in quantum computing and paves the way for more efficient and scalable quantum systems.[2]

2. A Quantum Computing Breakthrough Reducing Errors

In September 2024, Google has made a significant breakthrough in quantum computing error correction, demonstrating that adding more physical qubits to form a single «logical» qubit can reduce errors. Their team created a logical qubit from 105 physical qubits, showing improved error suppression over smaller configurations. While this enhances the potential for reliable quantum computing, it is just a step toward building large-scale quantum systems. Challenges remain, such as scaling up to multiple logical qubits and executing complex algorithms, but the research is promising for the future of error-corrected quantum computing.[3]

In December 2024, Google announced a significant advancement in quantum computing with the introduction of its new quantum processor, Willow. This 105-qubit chip achieved a remarkable computational feat by solving a complex problem in under five minutes—a task that would take the fastest classical supercomputers an estimated 10 septillion years, a duration vastly exceeding the age of the universe.[4]

A key feature of Willow is its enhanced error correction capabilities. Quantum bits, or qubits, are notoriously susceptible to errors due to environmental disturbances. Willow addresses this challenge by reducing error rates exponentially as more qubits are added, marking a critical milestone in the development of scalable and reliable quantum computers.[5]

3. Achieving 99.9% quantum computing accuracy on existing silicon chips

Diraq, an Australian startup, achieved a record 99.9% quantum computing accuracy using existing silicon chips, a milestone essential for full-scale quantum processors. This breakthrough, facilitated by Imec, a nanoelectronics R&D hub, leverages CMOS technology to integrate qubits with standard transistors, potentially allowing millions of qubits per chip. Diraq's advancements involve real-time feedback and advanced analysis tools, and the company plans to scale quantum processors using existing semiconductor foundries. A partnership with GlobalFoundries will support chip design and manufacturing. This development could revolutionize applications like drug discovery and cryptography.[6]

4. A Breakthrough Qubit Technology Paves Way for Practical Quantum Computer

Researchers at the University of Basel have made significant progress in quantum computing by demonstrating controlled interactions between hole spin qubits. This advancement is promising for developing scalable and efficient quantum computers using existing silicon technology. Hole spin qubits offer several advantages, including their ability to be controlled entirely electrically and their potential for fast and high-fidelity two-qubit gates.

Hole spin qubits represent a promising type of qubit based on the spin of holes in semiconductors. Researchers achieved precise control over interactions between two-hole spin qubits. The approach followed is compatible with existing silicon chip fabrication methods, making it potentially scalable. Hole-spin qubits have shown promise for fast and high-fidelity two-qubit gates. These advancements bring us closer to realizing practical quantum computers with the potential to revolutionize various fields, such as materials science, drug discovery, and artificial intelligence.[7]

5. China's Largest Quantum Chip Could Be Key to Building a Quantum Cloud

China has developed a 504-qubit quantum computing chip, Xiaohong, aimed at matching the performance of industry leaders like IBM and enhancing the global scalability of quantum computers.

The chip, the largest built by China to date, was created by scientists at the Center for Excellence in Quantum Information and Quantum Physics, part of the Chinese Academy of Sciences (CAS). It is designed to improve systems that manage the behavior and interaction of qubits in quantum computers. The new chip will be used by Chinese quantum computing company QuantumCTek to test in-house «kilo-qubit» QCMCSs, potentially influencing the overall performance of quantum computers. Despite being China's largest quantum chip, Xiaohong is smaller than Atom Computing's 1,125-qubit quantum computer, currently the world's largest.

2. Quantinuum
3. MIT Review
4. Reuters

5. Nature
6. Interesting Engineering
7. Scitechdaily

Economic Overview

According to McKinsey & Company[8] , several key factors are propelling the quantum computing market forward:

- Technological Advancements: Continuous breakthroughs are enhancing quantum computing capabilities, bringing the technology closer to practical, scalable solutions.

- Increased Investment: There's a significant rise in funding from both private and public sectors, indicating strong confidence in quantum computing's potential.

- Proliferation of Start-ups: The growing number of start-ups in the quantum space is fostering innovation and accelerating development.
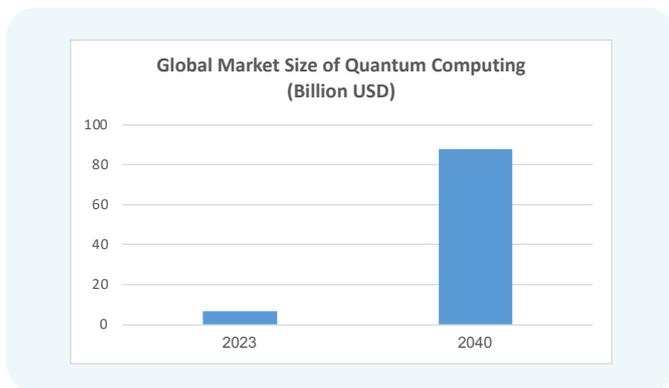
Global Market Size of Quantum Computing (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through the:
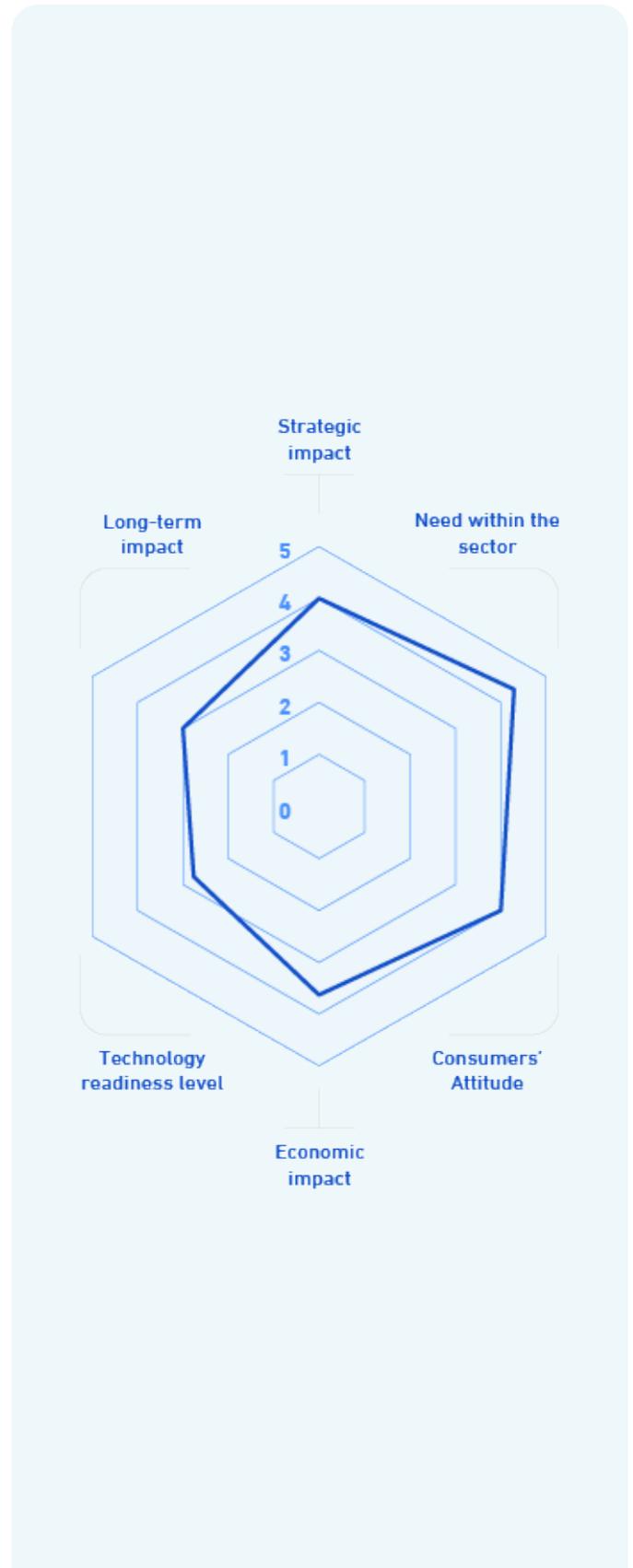
- Development of the digital economy.

- Localization of technologies and knowledge.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

- Developing programmable fault-tolerant quantum computer by 2040.

- Demonstrating x10,000 computing performance improvement by 2040.

Multi-Dimensional Evaluation

8. McKinsey

02
Exascale Computing

Exascale computing represents a significant milestone in the evolution of high-performance computing (HPC). It is defined by the ability of a computer system to perform at least one exaFLOP, or one quintillion (10^{18}) floating-point operations per second. This level of computing power is about a thousand times more powerful than the most advanced petascale computers available today. Exascale computers are expected to revolutionize various fields, including climate modeling, genomics, materials science, and artificial intelligence (AI), by providing unprecedented computational capabilities.

The need for exascale computing arises from the growing complexity and scale of scientific and engineering challenges. Traditional petascale computers, while powerful, often lack the necessary processing speed and data handling capabilities to tackle the vast datasets and highly detailed simulations required in many contemporary scientific endeavors. For instance, modeling the Earth's climate with high accuracy, understanding the molecular structures of proteins for drug discovery, or simulating the physics of nuclear fusion requires immense computational power.

Exascale systems are designed to meet these needs by providing vastly superior speed and efficiency, enabling researchers to run simulations and analyze data at scales previously thought impossible. By achieving exascale performance, these systems can enhance our understanding of complex phenomena, accelerate scientific discovery, and drive innovations that have a direct impact on society, such as more effective treatments for diseases, improved weather forecasting, and enhanced cybersecurity.

The impact of exascale computing extends across a broad range of scientific, industrial, and societal domains. In healthcare, exascale systems could enable the simulation of complex biological processes, accelerating drug discovery and personalized medicine. In energy, they can be used to model and optimize renewable energy systems or explore new materials for more efficient batteries and solar cells. For AI, exascale computers could dramatically enhance machine learning models, enabling breakthroughs in natural language processing, image recognition, and autonomous systems.

Furthermore, exascale computing has the potential to revolutionize climate science by providing the computational power needed to model the Earth's climate at a much higher resolution, leading to more accurate predictions of weather patterns, extreme events, and long-term climate change. This, in turn, can inform better policy decisions and strategies for mitigating and adapting to climate change.

Exascale computing represents the next frontier in high-performance computing, offering immense potential to solve some of the world's most challenging problems. While significant technical and logistical hurdles remain, the global push towards exascale capabilities underscores its critical importance. As the development of exascale systems progresses, they are expected to drive significant advances in science, technology, and innovation, impacting multiple fields and shaping the future of computing.[9]

Achieving exascale computing is a highly complex task that involves overcoming several technical challenges. One of the primary hurdles is energy consumption. Current supercomputers consume massive amounts of power, and scaling them up to exascale levels would require enormous energy, making it unsustainable with existing technologies. To address this, exascale systems must incorporate energy-efficient designs, such as advanced cooling methods, low-power processors, and new memory architectures.
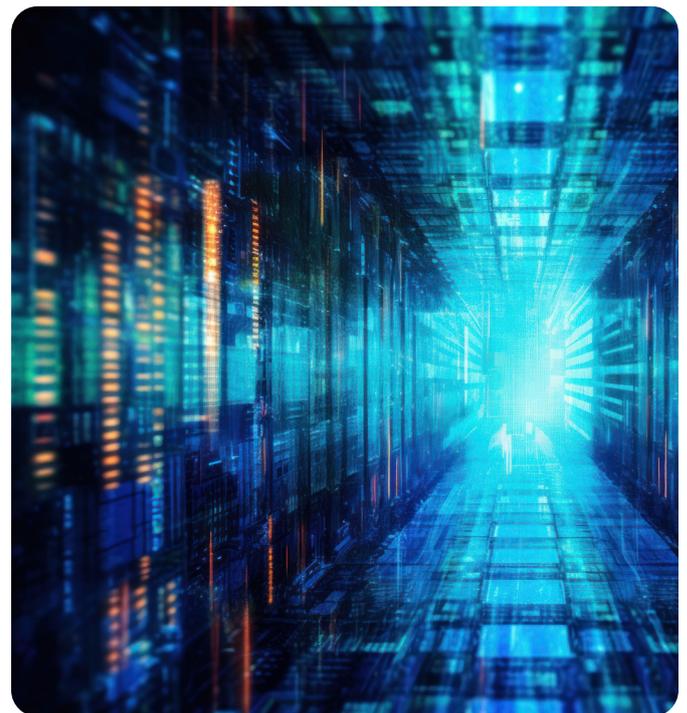
9. sites.uci.edu

Tech Signal: The RED-SEA's Project in Inter-node Interconnect Technologies

The RED-SEA project, funded by the EuroHPC Joint Undertaking (JU), has achieved significant advancements in the development of scalable and efficient interconnect technologies essential for exascale computing. Launched in April 2021 and concluded after three years, the RED-SEA project, alongside its sister projects DEEP-SEA and IO-SEA, focused on developing key technologies based on the Modular Supercomputing Architecture (MSA). These initiatives aim to prepare Europe for the exascale era in supercomputing by creating a blueprint architecture that supports the deployment of highly efficient and scalable systems.

The RED-SEA project brought together 12 partners from six European countries (France, Germany, Greece, Italy, Spain, and Switzerland) combining expertise from academia and key industrial enterprises in interconnection networks. With a budget of €8 million funded by Horizon Europe, the EU's research and innovation program, the project aimed to advance Europe's capabilities in high-performance computing (HPC) and make it a global leader in this field.

The primary goal of the RED-SEA project was to develop the next generation of interconnection networks that are fast, scalable, and reliable for exascale supercomputers. Exascale systems, capable of performing a quintillion (10^{18}) calculations per second, require sophisticated interconnect technologies to ensure seamless communication between hundreds of thousands of nodes and millions of cores. These interconnects act as the backbone of supercomputers, enabling efficient data flow and supporting parallel tasks crucial for AI-related applications and data-intensive computing.

The project's objectives were supported by three pillars:

1. Next-Generation Network Interconnects: The first pillar involved preparing high-performance interconnect technologies through specification and design, leveraging existing European technologies such as the BullSequana eXascale Interconnect (BXI) and intellectual properties from previous EU-funded projects. This effort resulted in significant advancements in the European Interconnect BXI, enhancing the current version (BXIv2) and laying the groundwork for the next generation (BXIv3).

2. Innovative Network Solutions: The second pillar focused on exploring innovative solutions to optimize network performance. The project achieved breakthroughs in network resource management, including enhancing network features like collective operations by offloading tasks from compute resources (CPUs, GPUs) to network components. This innovation reduced congestion and global latencies, improving overall system performance.

3. Ecosystem Development: The third pillar aimed to build a robust ecosystem for interconnect technologies by fostering collaboration between research and industrial teams. This collaboration created a supportive environment for advancing interconnect technologies, promoting greener and more sustainable supercomputing practices.

The RED-SEA project prioritized energy efficiency, recognizing the enormous power requirements of exascale computing. It developed low-power communication protocols and optimized network topologies to minimize energy consumption in supercomputers. Additionally, the project introduced techniques to offload collaborative work from compute resources, allowing them to focus on primary tasks and enabling network components to handle network operations independently. This approach led to significant energy savings and improved overall system efficiency. The RED-SEA project has laid a solid foundation for future innovations in high-performance computing. With 21 exploitable results, including two patents, and several products already integrated into commercial applications, the project has paved the way for the next generation of high-performance network interface cards (BXIv3) designed for advanced computing environments.[10]
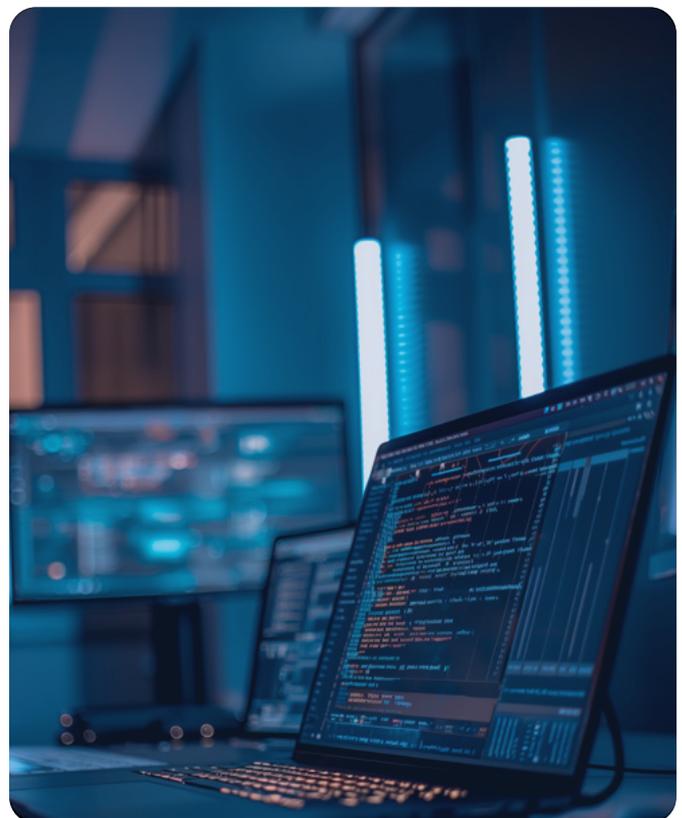

10. EuroHPC

Economic Overview [11]

Several countries are investing heavily in exascale computing to gain a competitive edge in scientific research, economic development, and national security. The United States, China, the European Union, and Japan are leading the race to build the first exascale computers. The U.S. Department of Energy, for example, has initiated the Exascale Computing Project (ECP) to develop an exascale ecosystem that includes hardware, software, and applications. Similarly, China is making significant strides in its exascale ambitions, with multiple projects aiming to reach this milestone.

To further support European HPC users and promote sustainability, the project offered open-source tools, including network simulators and trace collection tools, enabling users and developers to evaluate the performance of interconnect networks in their IT environments. These tools helped drive innovation and optimization in network design, contributing to the broader goals of green computing.
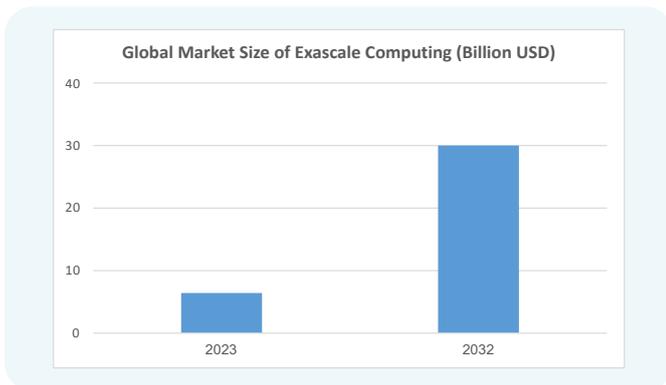
Global Market Size of Exascale Computing (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through the:

• Development of the digital economy.

• Localization of technologies and knowledge.

•

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Mission:

• Demonstrating x10,000 computing performance improvement by 2040.

Multi-Dimensional Evaluation

Exascale Computing
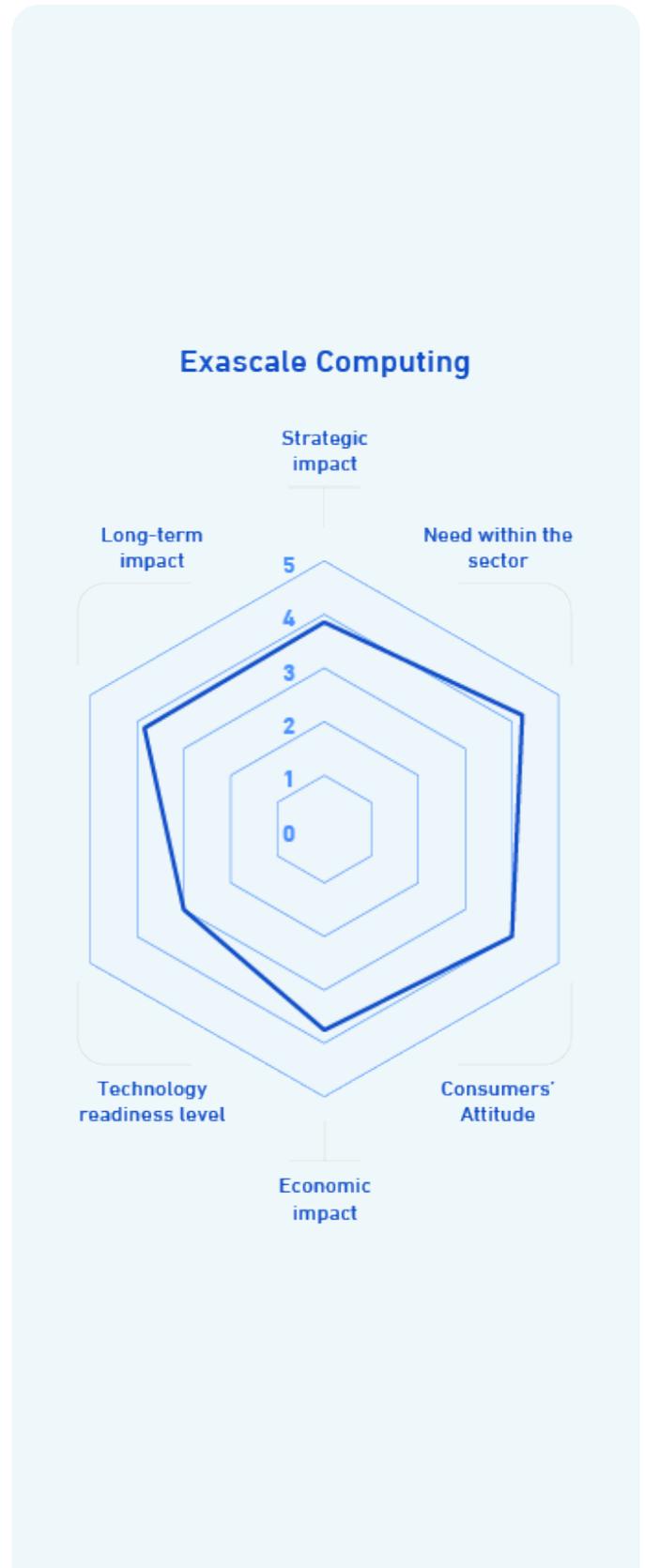
11. MarketResearchFuture

03
Generative Artificial Intelligence (Gen AI)

Generative Artificial Intelligence (Gen AI) represents a transformative area of artificial intelligence focused on creating new content — from text and images to audio and video. Unlike traditional AI, which primarily deals with recognizing patterns and classifying data, Gen AI models are designed to produce original content based on the information they have learned. This ability has far-reaching implications across various fields, including art, literature, design, medicine, and software development. Advances in deep learning, particularly through architectures such as Transformers, have revolutionized how machines understand and generate human-like content, driving a surge of interest and innovation in this domain.

At the core of Gen AI are models like the Transformer, which has enabled the development of highly sophisticated language models. These models can generate coherent and contextually relevant text, mimicking human conversation and writing styles with remarkable accuracy. For example, they are increasingly used in applications like automated content creation, virtual assistants, and chatbots, where the ability to understand and produce natural language is essential. This has opened up new possibilities in various sectors, from customer service to education, where personalized and scalable communication is crucial.

Gen AI extends beyond text to visual content creation. It can produce realistic images, videos, and even animations based on the patterns it has learned. This has vast applications, from creating new artwork and enhancing photo quality to generating virtual environments for video games or simulations.[12] Gen AI has experienced significant advancements recently, leading to more sophisticated and versatile models across various domains. Notable breakthroughs   include:

1. **Transition to Reasoning Models:** OpenAI introduced the o1 series, marking a shift from traditional prediction-based models to those capable of complex reasoning. These models, exemplifying «long thinking,» are designed to process and deliberate over tasks more thoroughly, enhancing performance in areas such as scientific research and complex problem-solving.[13]

2. **Enhanced Multimodal Capabilities:** Google's Gemini 2.0 represents a leap in AI integration, combining text, image, and audio processing to enable more comprehensive understanding and generation across multiple modalities. This development facilitates the creation of AI agents capable of interacting seamlessly with diverse data types, paving the way for more intuitive and human-like AI interactions.[14]

3. **Advanced AI-Generated Video:** Meta's Movie Gen and Runway's Gen-3 Alpha have set new standards in AI-driven video generation. These tools can produce extended video content from simple text prompts, incorporating complex elements like object motion and camera movements, thereby expanding creative possibilities in media production.[15]

4. **Agentic AI:** refers to software systems specifically designed to autonomously make decisions and perform actions to achieve defined objectives. These systems integrate a range of AI techniques alongside capabilities such as memory, planning, environmental awareness, tool utilization, and adherence to safety protocols, enabling them to complete tasks independently in pursuit of their goals. The autonomous or semi-autonomous capabilities of agentic AI have the potential to assist CIOs in achieving their vision of leveraging generative AI to enhance organizational productivity.[16]
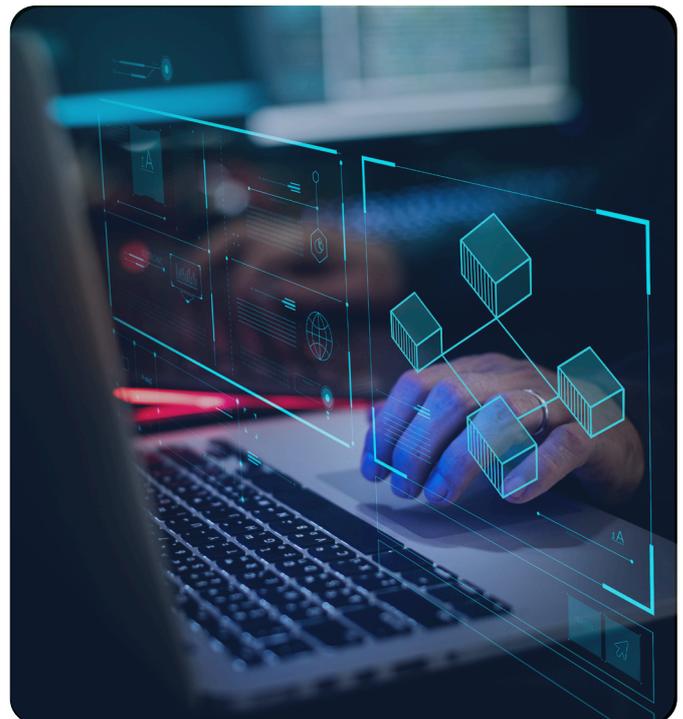
12. Technologyreview
13. The Atlantic
14. Medium

15. Business Insider
16. Gartner

Tech Signal: A New Generation of Reasoning Models for Gen AI

In 2024, several notable advancements in generative AI were achieved by different companies. Examples include:

OpenAI's models: In September 2024, OpenAI has introduced a new series of AI models designed to excel at complex problem-solving. These models are capable of deeper reasoning and can tackle more challenging tasks than previous generations. In December 2024, OpenAI unveiled its latest reasoning model, o3, along with a streamlined version, o3-mini. These models represent a substantial advancement in AI reasoning capabilities, achieving superior performance on complex benchmarks.

xAI's Grok-2: xAI has launched Grok-2 and its streamlined version, Grok-2 mini, as a significant upgrade from Grok-1.5, introducing advanced conversational, coding, and reasoning capabilities. These models outperform competitors like GPT-4-Turbo and Claude 3.5 in key benchmarks, excelling in areas such as visual math reasoning and document-based question answering. Grok-2 is now available to X platform Premium users, offering enhanced text and visual processing. xAI plans to expand Grok-2's functionality with a forthcoming enterprise API and additional features for improving platform search, post insights, and reply mechanisms.[17]

Meta's Movie Gen: Meta unveiled Movie Gen, an AI model capable of generating realistic video and audio clips based on user prompts. This tool can create clips depicting various activities and adds synchronized sound effects and background music. Meta claims that Movie Gen outperforms similar models from competitors like OpenAI and Google in human evaluations.[18]

DeepSeek's AI Models: Chinese startup DeepSeek introduced several AI models, including DeepSeek-R1, an open-source model designed for tasks requiring logical inference, mathematical reasoning, and real-time problem-solving. DeepSeek claimed that this model exceeded the performance of OpenAI's o1 on benchmarks such as the American Invitational Mathematics Examination (AIME) and MATH.[19]

Anthropic's Claude 3.5: Anthropic released the Claude 3.5 series of large language models, including Claude 3.5 Sonnet, which demonstrated improved performance in areas such as coding, multistep workflows, and image analysis. These models showcased significant advancements in AI capabilities, contributing to the competitive landscape of generative AI.[20]

Google's Gemini 2.0: Google introduced Gemini 2.0, an advanced AI model capable of complex task execution across computers and the web. This model exhibits human-like interaction, comprehends the physical world, and boasts enhanced multimodal abilities, including parsing video and audio.

NVIDIA's Fugatto: NVIDIA unveiled Fugatto (Foundational Generative Audio Transformer Opus 1), an AI model capable of generating music and audio, modifying voices, and creating novel sounds. Aimed at professionals in music, film, and video game production, Fugatto can transform a piano line into a human voice or alter the accent and mood of spoken words. While its public release is pending due to concerns over potential misuse, Fugatto represents a significant advancement in AI-driven audio generation.[21]
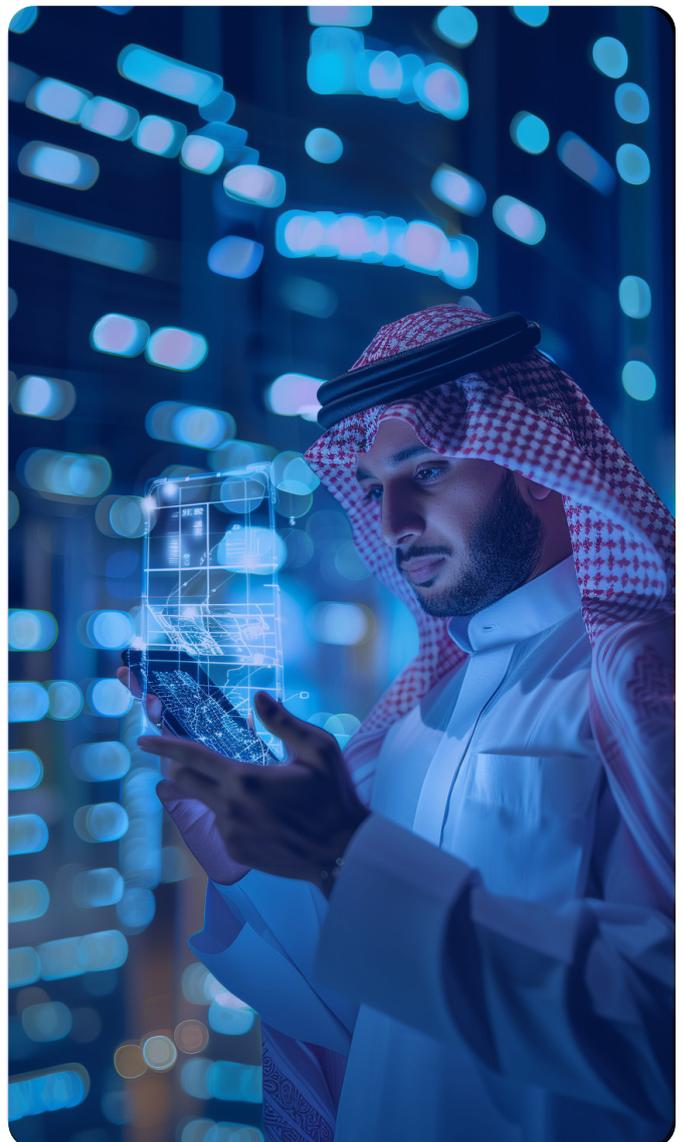
17. communeify
18. Reuters
19. deepseek
20. anthropic
21. Reuters

Economic Overview [22]

The growth of Gen AI market is driven by various aspects and applications. In fields such as fashion, architecture, and advertising, Gen AI can quickly generate design ideas, allowing creators to explore countless variations in a fraction of the time traditionally required. In healthcare, it aids in generating synthetic medical data, which can be used to train other AI models, ultimately advancing research while maintaining patient privacy.

Gen AI is also impacting the marketing industry. AI-generated content is becoming a staple for producing personalized advertisements, social media posts, and even interactive experiences tailored to specific consumer demographics, thus enhancing brand reach and engagement.

Gen AI is also revolutionizing scientific research by expediting complex discoveries. For instance, AI models have been instrumental in protein design and gene editing, enabling breakthroughs that were previously unattainable without advanced computational assistance.[23]
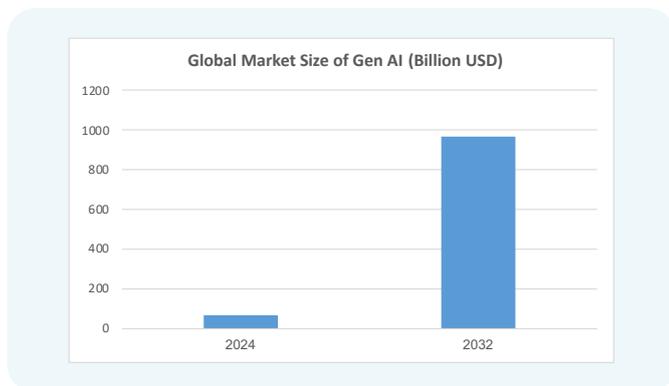
Global Market Size of Gen AI (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through the:

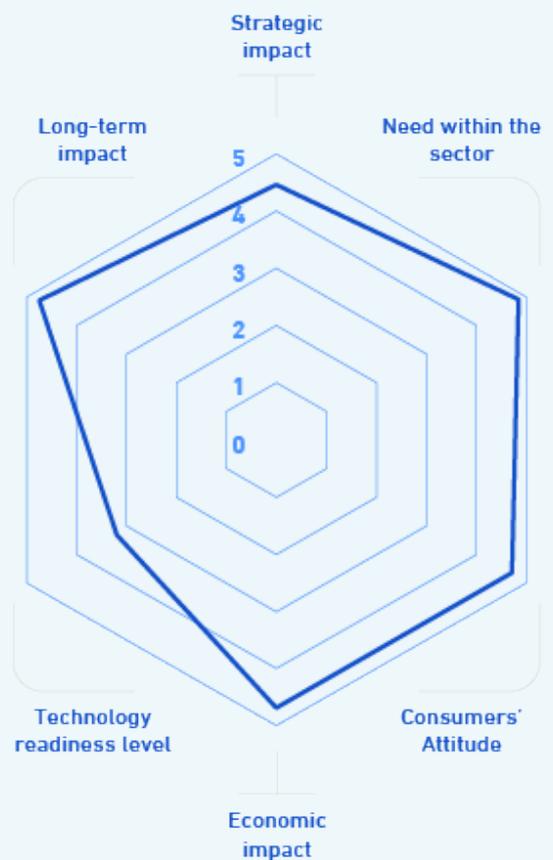• Development of the digital economy.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Mission:

• Creating a safe trustworthy Artificial General Intelligence that learns and realizes autonomous work in favor of humans by 2040.

Multi-Dimensional Evaluation

Generative Artificial Intelligence

22. FottuneBusinessinsights
23. The Atlantic

04
Humanoid Robotics

Humanoid robotics is an interdisciplinary field at the intersection of mechanical engineering, electrical engineering, computer science, and cognitive sciences, dedicated to creating robots that emulate human form and behavior. These robots are designed with human-like structures, including a head, torso, arms, and legs, enabling them to interact seamlessly within environments tailored for humans.

The development of humanoid robots serves multiple purposes:

- Functional Assistance: They are engineered to assist humans in daily tasks, ranging from household chores to complex industrial operations.

- Research and Understanding: Humanoid robots act as platforms for studying human biomechanics and cognition, providing insights into human motion, perception, and interaction.

- Social Interaction: They are utilized in roles that require human-robot interaction, such as receptionists, caregivers, or companions, enhancing user engagement through familiar human-like appearances and behaviors.

Technological advancements have significantly propelled the capabilities of humanoid robots. Modern developments include sophisticated locomotion systems that enable bipedal walking, running, and even complex maneuvers like navigating stairs or uneven terrain. Enhanced sensory systems, incorporating cameras, microphones, and tactile sensors, allow these robots to perceive and interpret their surroundings with increasing accuracy. Furthermore, the integration of artificial intelligence facilitates advanced decision-making, learning, and adaptation, enabling robots to perform tasks with a degree of autonomy and interact more naturally with humans.

The field continues to evolve, with ongoing research focusing on improving the dexterity, adaptability, and cognitive abilities of humanoid robots. Challenges remain in achieving seamless human-robot interaction, ensuring safety, and developing cost-effective solutions for widespread adoption. Nonetheless, the progress in humanoid robotics holds promising potential for transforming various sectors by enhancing efficiency, providing companionship, and contributing to our understanding of human physiology and cognition.

Also, MIT Technology Review highlights significant advancements in robotics, particularly in the rapid training of robots to perform new tasks. Traditionally, programming robots to execute specific functions has been a time-consuming and labor-intensive process, often requiring extensive coding and manual input. Recent developments in artificial intelligence, especially in generative AI, have revolutionized this aspect of robotics.

Generative AI models can now enable robots to learn new tasks almost instantly by analyzing vast amounts of data and generating appropriate responses or actions without explicit programming for each specific task. This capability allows robots to adapt to new environments and requirements with unprecedented speed and efficiency.

Companies such as Agility Robotics, Amazon, Covariant, Robust.AI, and the Toyota Research Institute are at the forefront of integrating these AI advancements into their robotic systems. By leveraging generative AI, these organizations are developing robots capable of performing a wide range of tasks, from warehouse logistics to complex assembly processes, with minimal human intervention.

This progression signifies a paradigm shift in robotics, where machines are no longer limited to predefined actions but can learn and adapt in real-time, enhancing productivity and operational flexibility across various industries.[24]
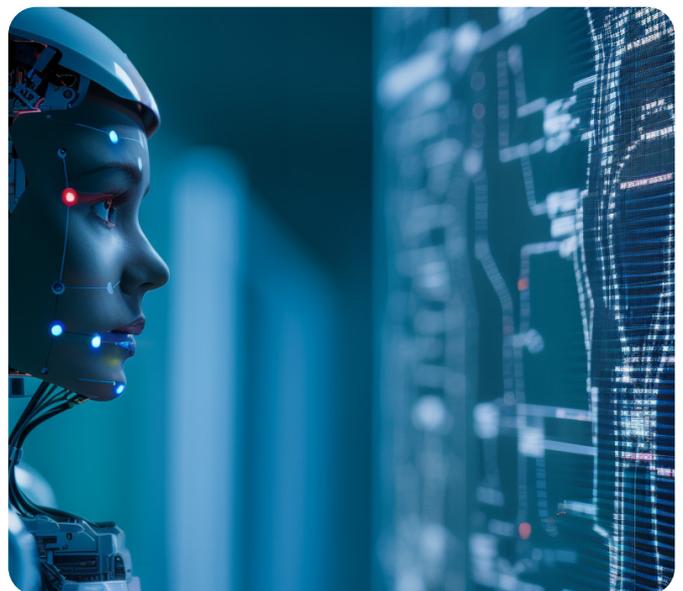
24. MIT Technology Review

Tech Signal: A new humanoid robot with natural speech conversations

 In August 2024, Figure has introduced a new humanoid robot leveraging OpenAI's technology to enable natural speech conversations. This advanced robot, designed to appear and interact in a human-like manner, aims to revolutionize human-robot interaction by making it more intuitive and seamless. The robot is equipped with sophisticated sensors and expressive facial features, allowing it to engage in realistic and meaningful dialogues. This innovation marks a significant step forward in robotics, offering potential applications in various fields, from customer service to companionship. The company has provided teaser videos reminiscent of consumer electronics advertisements, as well as demonstrations of the robot's capabilities. One video highlights the Figure 02's gait and its application in carrying totes, a common use for such robots. [25]

Figure is a pioneering AI robotics company focused on creating the first general-purpose humanoid robot designed to integrate seamlessly into human environments. Their flagship product, Figure 02, is around 168 cm tall, 70 kg humanoid robot capable of carrying 20 kg, running for 5 hours on a single charge, and moving at 1.2 meters per second. Utilizing advanced AI, Figure 02 can perform various tasks in manufacturing, logistics, warehousing, and retail. The robot's human-like form factor allows it to interact with and navigate spaces designed for humans, enhancing productivity and addressing labor shortages. The company's team, with over a century of combined experience in AI and robotics, aims to revolutionize the workforce by placing these versatile robots in roles traditionally held by humans, thus improving safety and efficiency. [26]

The most significant upgrade comes from Figure's collaboration with OpenAI, which contributed to a $675 million Series B funding round, raising the company's valuation to $2.6 billion. The integration of neural networks is particularly appealing for humanoid robots due to their potential to work alongside humans in environments like factory floors. Figure 02 is equipped with speakers and microphones to facilitate natural speech interaction, enhancing safety and functionality.

AI models like ChatGPT and Google Gemini, known for their natural language processing, are essential for instructing robots and ensuring transparency in their operations. This communication is critical for humanoid robots, which, despite their human-like design, are heavy and potentially dangerous. Speech, combined with vision and proximity sensors, enhances the robots' safety measures.

Figure is not the only company in this space; Agility Robotics has also been integrating generative AI to improve human-robot communication. Google's Everyday Robots team had a similar focus before its dissolution. Elon Musk's projects, Grok AI and Optimus, are expected to merge AI and robotics soon. OpenAI has diversified its investments, previously backing the Norwegian firm 1X before focusing on Figure. This shift in attention is reflected in the participation of tech giants like Microsoft, Amazon, Nvidia, and Intel Capital in Figure's Series B round.

The development of Figure 02 involved a comprehensive hardware and software redesign, including enhanced cameras, computing capabilities, and improved hands with 16 degrees of freedom. The debate continues on the best design for robotic hands, with Figure opting for human-like hands for their dexterity. While the timeline for a wider rollout of Figure 02 is unclear, the company envisions applications beyond warehouses and factories, potentially extending to home environments. Figure's robots combine human-like dexterity with advanced AI to perform a wide range of tasks across various commercial applications, with future expansions in sight.

Similarly, companies like Tesla are developing humanoid robots, such as Optimus, aiming to integrate them into mainstream applications, including industrial automation and personal assistance. [27]
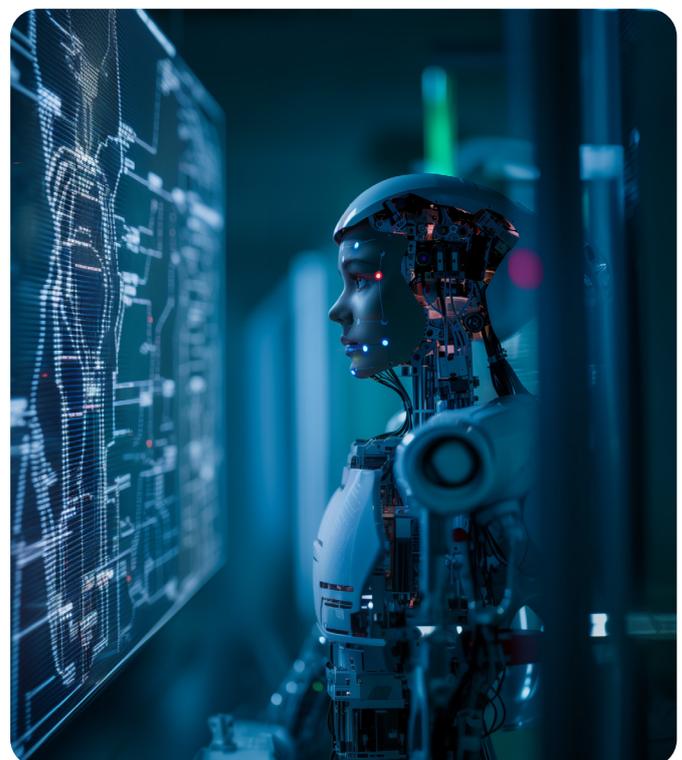
25. techcrunch
26. figure.ai
27. Business Insider

Economic Overview [28]

The humanoid robot market is experiencing significant growth, driven by several key factors:

- **Industrial Automation:** Humanoid robots, with their ability to operate in human-centric environments and perform tasks similar to humans, are becoming integral to modern industrial operations.

- **Healthcare Assistance:** In the medical field, humanoid robots are utilized for patient care, rehabilitation, and surgical assistance. Their precision and ability to operate in sterile environments make them valuable assets in healthcare settings.

- **Public Relations and Hospitality**: Businesses are deploying humanoid robots in customer-facing roles, such as receptionists and concierges, to enhance customer service experiences and streamline operations.
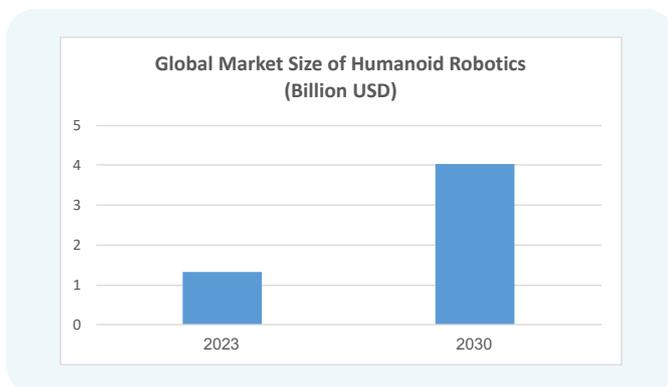
Global Market Size of Humanoid Robotics (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through the:

- Localization of promising industries.

- Localization of technologies and knowledge.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

- Develop general purpose robots that assist humans in daily tasks by understanding and adapting to their dynamic environment by 2040.

- Develop multi-purpose industrial robots that understand and adapt to their changing environment by 2035.

Multi-Dimensional Evaluation

Humanoid Robotics

28. grandviewresearch
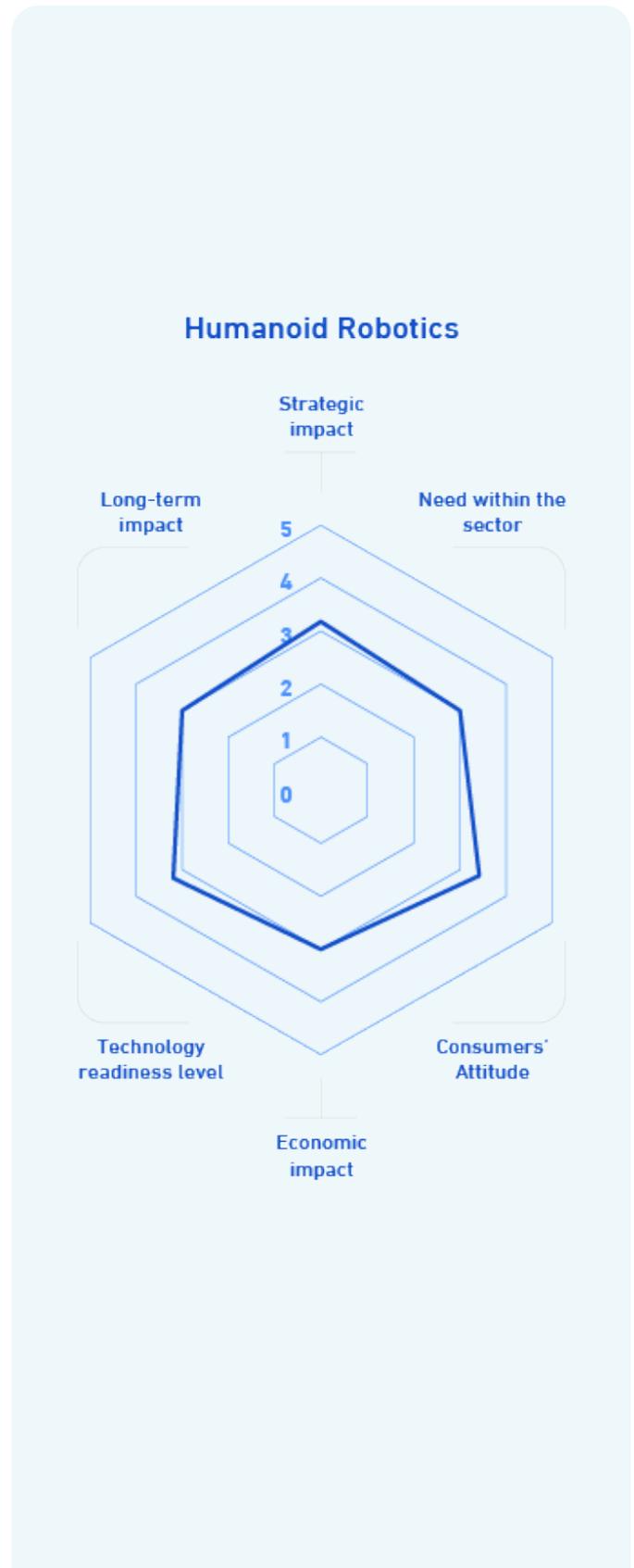
O5
Industrial Metaverse

The industrial metaverse represents a transformative concept that blends the physical and digital worlds, extending beyond traditional metaverse applications to revolutionize entire industries. This immersive, 3D virtual environment replicates industrial processes, logistical networks, and even entire factories or sectors, utilizing advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), and augmented and virtual reality (AR/VR). The industrial metaverse is poised to significantly impact efficiency, productivity, and sustainability in modern workspaces, offering businesses a platform to test, refine, and optimize digital practices before implementing them in the physical world.

Central to the industrial metaverse is the concept of the digital twin—a precise digital replica of physical entities like factories, production lines, or entire industries. These digital twins continuously assimilate real-time data, providing an accurate, dynamic representation of the industrial world. Unlike traditional metaverses focused on gaming or entertainment, the industrial metaverse emulates and interacts with the complex realities of various industries, enabling businesses to optimize operations, make informed decisions, and predict outcomes with greater accuracy.

One of the key advantages of the industrial metaverse is its ability to facilitate global collaboration. Workers from different geographical locations can enter a shared virtual space, interact with digital objects, and collaborate on tasks in real time, breaking down physical barriers and fostering a more interconnected industrial environment. This global collaboration is especially significant in an era where remote work and globalized operations are becoming increasingly common.

Sustainability is another critical aspect of the industrial metaverse. By simulating and predicting the outcomes of resource use, waste management, and environmental impacts, industries can adopt more sustainable practices and reduce their ecological footprint. The industrial metaverse also lowers the costs and risks associated with innovation, allowing new technologies, processes, or products to be tested and refined in a virtual environment before being implemented in the real world.

Applications of the industrial metaverse span various sectors, including manufacturing, logistics, healthcare, education, and smart city planning. In manufacturing, digital twins of production lines or entire factories enable real-time monitoring, identification of bottlenecks, and simulation of responses to different stimuli, thereby enhancing productivity and reliability. The industrial metaverse can also integrate AI-based machine learning algorithms to predict potential breakdowns and suggest proactive maintenance, minimizing downtime. Additionally, it offers a virtual platform for designing, testing, and customizing products, reducing economic and environmental costs.

In logistics, the industrial metaverse provides unprecedented visibility and precision by digitalizing the entire supply chain. Companies can monitor the real-time status and location of goods, simulate optimal transport routes, and predict potential disruptions, leading to a more robust and reliable logistics network. Smart city development is another area where the industrial metaverse shows great promise. Planners can create digital twins of proposed structures, infrastructure, or entire cities, allowing for extensive testing and refinement of aspects like traffic flow, energy efficiency, and waste management. This approach also facilitates public participation in urban planning by enabling residents to explore proposed changes virtually and provide feedback.

The industrial metaverse is also set to redefine the future of work, enabling a «telepresence» where workers can interact with each other and digital objects within the metaverse, regardless of their physical location. This capability promotes a more efficient, flexible, and inclusive workspace that transcends physical limitations.[29]

29. metaversereality

Tech Signal: Deploying Industrial Metaverse in Advanced Manufacturing

The metaverse is poised to revolutionize the internet by creating a new dimension of three-dimensional virtual spaces. Recent advances in artificial intelligence and immersive technologies have made it a popular topic across multiple sectors, including manufacturing. A study published in ICT Express seeks to offer a thorough understanding of the metaverse, its foundational technologies, and current trends. By exploring its potential applications in manufacturing, the study aims to uncover its transformative benefits, highlight practical implications, and address challenges like privacy and security concerns, ultimately encouraging further research and contributing to the ongoing discussion on this emerging concept.[30]

In the same context, the Institute of Electrical and Electronics Engineers (IEEE) introduced its Metaverse Initiative, which includes holding the international symposium on emerging metaverse technologies, held in Seattle, Washington, in October 2024; with the aim of promoting the seamless integration of the digital and physical worlds through the metaverse, opening new opportunities for individuals and industries in academic, personal, professional and social aspects, and discussing economic, ethical and technical challenges.[31]

The World Economic Forum (WEF) has recently published its report: "Navigating the Industrial Metaverse: A Blueprint for Future Innovations". The report highlights the role of the metaverse in driving the next industrial revolution through digital twins, spatial computing, AI, and blockchain. It identifies opportunities for leaders, showcases industry applications, and discusses foundational elements for a collaborative, responsible, and sustainable digital future, while addressing challenges like privacy, security, and the need for cross-industry collaboration. Key insights from report include:

* The metaverse is set to accelerate the next industrial revolution by merging digital and physical worlds, enhancing experiences, engagement, and productivity.

* Embracing innovation helps industries cope with disruptions from technological changes, evolving consumer preferences, and climate challenges, promoting efficiency in processes.

* The industrial metaverse opens new value creation avenues, boosting productivity, generating revenue, and solving real-world problems digitally.

* With competition increasing, major companies are implementing spatial and Web3 initiatives across various industries.

* Companies that adopt these technologies will better navigate changing landscapes and improve their operations.

* Cross-industry collaboration is crucial for building the necessary capabilities and ecosystems to realize the metaverse's full potential.

By demystifying technologies and addressing potential challenges, the report aims to guide stakeholders in effectively adopting the industrial metaverse over the next decade.[32]

Also, "The Emergent Industrial Metaverse" is an MIT Technology Review Insights report sponsored by Siemens. The report was produced through interviews with technologists, industry analysts, and academics worldwide. It examines the emergence of the industrial metaverse, its use cases and future challenges and opportunities, and the impacts it will have on both businesses and everyday life.[33]

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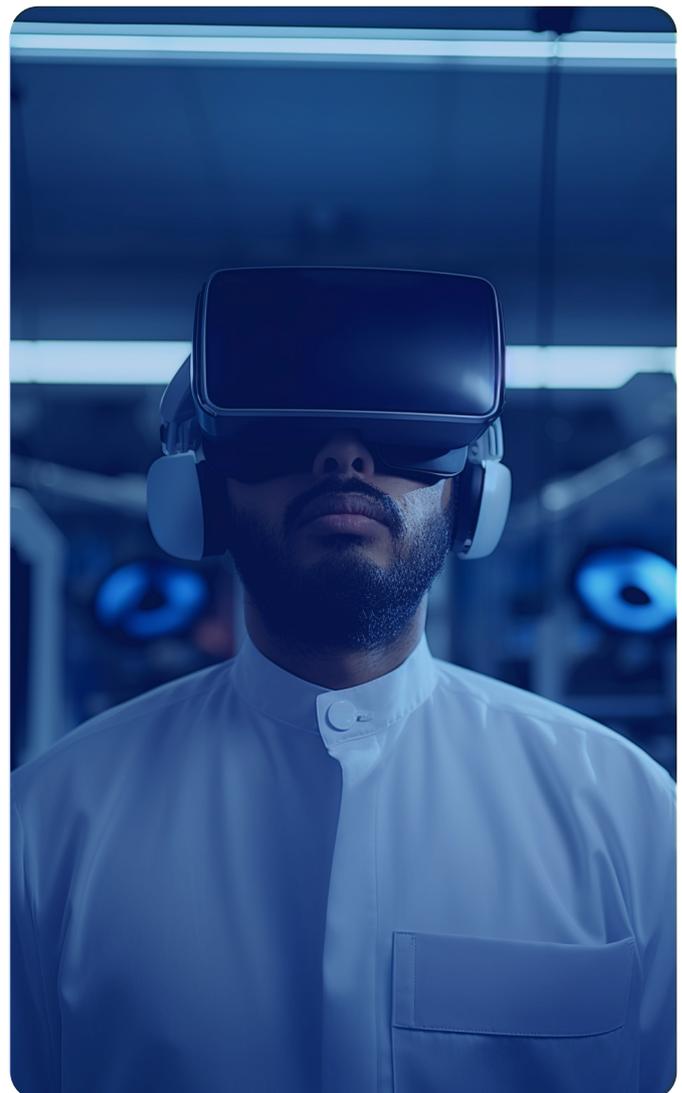
30. sciencedirect
31. IEEE
32. weforum.org

33. MIT

Economic Overview [34]

- The industrial metaverse represents a powerful convergence of the physical and digital worlds, offering unparalleled benefits to industries and economies worldwide. As it continues to evolve, the industrial metaverse is poised to reshape how industries operate, drive digital transformation, and create a more efficient, sustainable, and interconnected global economy.

- As industries increasingly embrace digitization, the industrial metaverse is set to play a crucial role in driving economic growth, fostering innovation, and creating new job opportunities. However, this future also presents challenges related to privacy, data security, and digital disparity. Governments and institutions must prepare for a future where the industrial metaverse becomes ubiquitous, with comprehensive legislation, digital inclusivity initiatives, and workforce development efforts to ensure a smooth transition to this new digital era. [35]
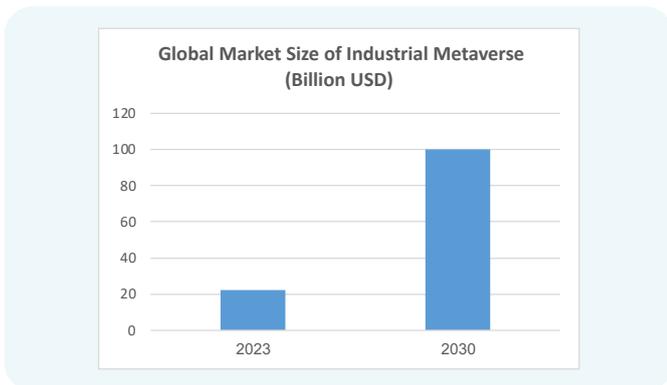
Global Market Size of Industrial Metaverse (Billion USD)

Year	Value
2023	~22
2030	~100

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through:
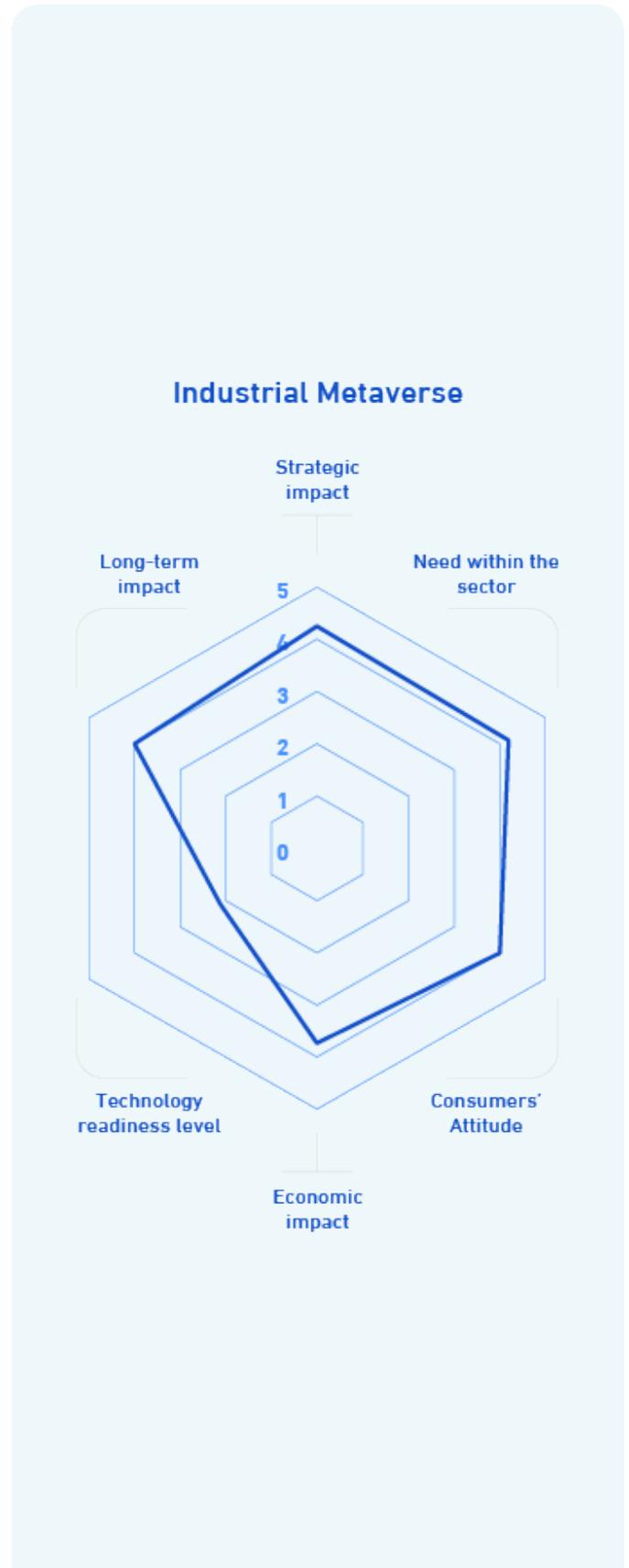
- Localizing promising industries.

- Expanding vocational training.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Mission:

- Develop multi-purpose industrial robots that understand and adapt to their changing environment by 2035.

Multi-Dimensional Evaluation

Industrial Metaverse

Radar chart axes: Strategic impact, Need within the sector, Consumers' Attitude, Economic impact, Technology readiness level, Long-term impact (scale 0–5)

34. weforum.org
35. metaversereality

06
Low-Earth Orbit (LEO) Satellites

Low-Earth Orbit (LEO) satellites are positioned between 180 and 2,000 kilometers above Earth's surface. Unlike geostationary satellites that remain in a fixed position relative to the Earth, LEO satellites move quickly around the planet, typically completing an orbit in 90 to 120 minutes. Their proximity to Earth offers several advantages, including reduced signal latency and higher bandwidth, making them ideal for services like high-speed internet, Earth observation, and defense applications.

One of the key benefits of LEO satellites is their ability to provide more reliable, faster communication services, especially in remote areas where traditional infrastructure is unavailable. Companies like SpaceX (with its Starlink project) are deploying large constellations of LEO satellites to offer global high-speed internet coverage. Starlink, for example, is revolutionizing connectivity in rural and underserved regions by using thousands of satellites to create a global web of coverage, minimizing the digital divide between urban and rural areas.[36]

These satellites are also vital for scientific research. They are used for monitoring climate change, tracking weather patterns, and providing crucial data for natural disaster responses. For instance, LEO satellites play a key role in Earth observation, capturing high-resolution imagery that can be used to study deforestation, monitor ice caps, or respond to forest fires.

LEO satellite constellations, like those from OneWeb and Amazon's Project Kuiper, also focus on expanding the global reach of the internet. These companies are creating constellations of small satellites that work in tandem to provide widespread, seamless coverage. Unlike traditional communication satellites, which can be costly to deploy and maintain, LEO satellites are smaller, cheaper, and launched in clusters, allowing for more rapid scaling and replacement when needed.[37]

However, the rapid growth of LEO satellites brings challenges. Increased satellite traffic raises concern about space debris and collision risks. With thousands of new satellites being launched each year, regulators and companies must work together to ensure responsible deployment and management of space assets. Organizations like the International Telecommunication Union (ITU) and national space agencies are playing a pivotal role in developing policies and technologies to manage space traffic and mitigate the risks posed by space debris.

Direct-to-cell (D-C) satellites provide connectivity for phones and IoT devices in areas where terrestrial infrastructure is unavailable or impractical, such as rural regions, oceans, and airplanes. Unlike terrestrial cellular networks, which require extensive, costly radio access networks (RANs) and are profitable mainly in urban areas, D-C satellites extend broad coverage to underserved regions. This approach can reduce the capital and operational costs for mobile network operators (MNOs) by complementing traditional networks and bridging the connectivity gap for approximately 2.7 billion unconnected users worldwide.[38]

Direct-to-cell satellites can also dramatically enhance the air passengers' experience by allowing internet use from gate to gate, removing the need for pre-downloaded content. Moreover, this service provides an array of services such as live support through a specified app and the ability to connect multiple devices simultaneously. This move sets a new standard for onboard entertainment and connectivity, which has become an important differentiator for travelers.

36. SpaceX's Starlink Project
37. OneWeb
38. usenix

Tech Signal: Launching Direct-to-Cell Service via Low-Earth Orbit Satellites

In 2024, Starlink and T-Mobile introduced Direct-to-Cell (D2C) technology—a groundbreaking advancement designed to deliver mobile phone connectivity directly via satellite, eliminating the need for specialized satellite phones. This breakthrough will allow ordinary smartphones to communicate through Starlink's satellite network, even in areas where there are no terrestrial cell towers, effectively eliminating dead zones in the U.S. and other regions.

The technology works by utilizing Starlink's Low-Earth Orbit (LEO) satellites equipped with custom silicon and advanced phased arrays, which enable communication with consumer-grade smartphones despite their low-gain antennas. Initially, this service will provide text messaging, with voice and data expected to roll out in future phases. The satellites orbit at approximately 340 miles above Earth, and Starlink has overcome the technical challenge of maintaining consistent connections with rapidly moving satellites (orbiting at 17,000 miles per hour).

The collaboration was first announced in 2022, but 2024 marked the successful launch and early testing of this service, making it a major milestone. Field testing began in early 2024, and the service will be expanded globally, with operators from countries like Japan, Australia, and Canada already joining the initiative.[39] This innovation is aimed at improving safety and convenience, especially in remote or disaster-affected regions where terrestrial infrastructure may be lacking or disrupted.[40]

Also, Starlink achieved another breakthrough in 2024 in inflight connectivity through its partnership with United Airlines. This collaboration will provide free, high-speed Wi-Fi to passengers across United's fleet, marking a significant shift in inflight internet services. What sets this development apart is that Starlink's satellite internet will be accessible even in traditionally hard-to-reach areas, such as over oceans, polar regions, and remote locations where traditional Wi-Fi or cell signals often fail.

Using Starlink's constellation of LEO satellites, United will be the first major airline to commit to such a large-scale deployment of satellite-based inflight internet. The service is designed to offer speeds and performance comparable to ground-based broadband, allowing passengers to live stream, use real-time apps, work, or even play video games without buffering or lag.[41]

SpaceX's Starlink achieved a new milestone in mobile gateway technology by reaching download speeds of up to 8 Gbps and upload speeds of 2.8 Gbps in a recent test. This innovation targets high-speed internet services for ships, airplanes, and remote sectors, offering significant potential for large commercial and governmental applications. This development further solidifies Starlink's role in expanding reliable global connectivity across challenging environments.[42]

SpaceX's new direct-to-cell (DTC) Starlink satellites, designed to provide smartphone connectivity, are significantly brighter than their predecessors. Recent research indicates that these DTC satellites shine nearly five times brighter in the sky compared to traditional Starlink satellites. This increased luminosity is partly due to their lower orbital altitude of approximately 217 miles, whereas traditional Starlink satellites orbit at about 340 miles (550 kilometers). The heightened brightness has raised concerns among astronomers about potential interference with astronomical observations. SpaceX has acknowledged this issue and plans to collaborate with the astronomical community to assess the impact and implement hardware adjustments to reduce the satellites' brightness.[43]

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39. starlinkinsider.com
40. Business Wire
41. United - Newsroom

42. techspot
43. Space

Economic Overview [44]

The market for Direct-to-Cell (D2C) services via Low-Earth Orbit (LEO) satellites is expanding rapidly, driven by several key factors:

- **Global Connectivity Demand:** There's an increasing need to provide seamless communication services in remote and underserved regions where traditional terrestrial infrastructure is lacking. LEO satellites enable direct communication with standard mobile devices, bridging these connectivity gaps.

- **Strategic Partnerships:** Collaborations between satellite operators and mobile network providers are facilitating the integration of D2C services, expanding coverage areas, and improving service reliability.

- **Regulatory Approvals:** Recent authorizations from regulatory bodies, such as the FCC's approval for SpaceX's direct-to-cell services, are paving the way for broader implementation and commercialization of these services.
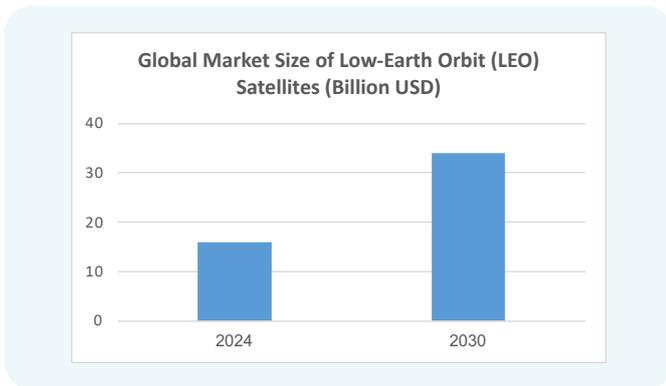
Global Market Size of Low-Earth Orbit (LEO) Satellites (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through the:

- Development of the digital economy.

- Localization of technologies and knowledge.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

- Future of connectivity: building sustainable 6G technologies by 2035.

- Going beyond Smart Cities, establish five Cognitive Cities in KSA by 2040.

Multi-Dimensional Evaluation

Low-Earth Orbit (LEO) Satellites
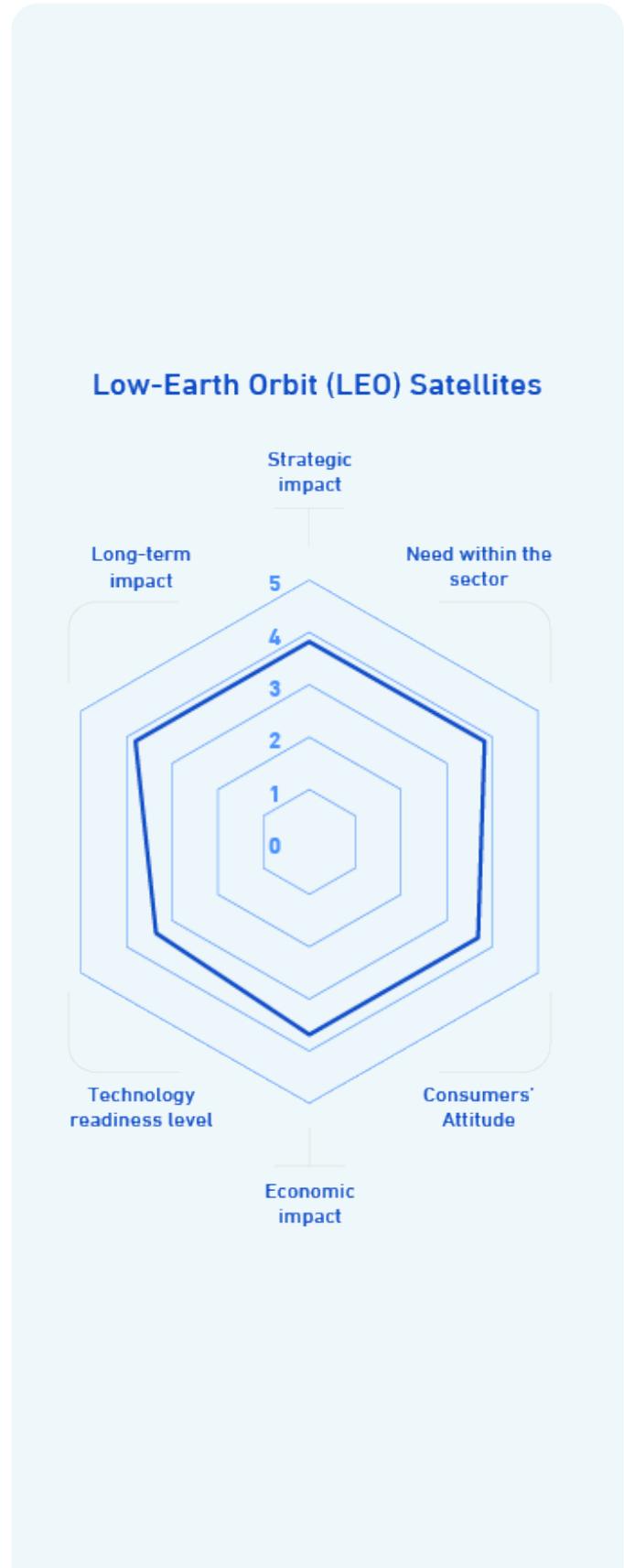
44. satellitemarkets

07
Reconfigurable Intelligent Surfaces (RIS)

Reconfigurable Intelligent Surfaces (RIS) is an emerging technology revolutionizing wireless communication by manipulating electromagnetic waves. RIS are programmable surfaces capable of manipulating electromagnetic waves, offering significant advantages in terms of signal optimization in wireless communication. RIS can dynamically adjust wireless environments, enabling more efficient and faster communication by reducing interference and improving data rates. By integrating metamaterials and intelligent algorithms, these surfaces can be used in diverse environments like smart cities, factories, and next-gen networks, including 6G.

One key application of RIS is in smart cities and factories, where the need for seamless, low-latency communication is critical. In these settings, RIS could improve wireless connectivity for a range of devices, from sensors and cameras to autonomous vehicles. The technology is also expected to be vital in improving the performance of 6G networks, which will rely on ultra-reliable and low-latency communication (URLLC). RIS could significantly boost energy efficiency in communication networks, reducing power consumption by reflecting signals in desired directions without the need for additional active transmission power.

The implementation of RIS will likely have far-reaching effects across several industries. In transportation, for example, RIS could enhance vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) communications, improving the safety and efficiency of autonomous driving systems. In industrial settings, RIS could optimize the wireless connectivity of machines and devices in smart factories, contributing to the overall efficiency of Industry 4.0 technologies. As a result, RIS is poised to be a foundational technology in the future of telecommunications.

RIS is a game-changing innovation with significant implications for the future of wireless communication. As the technology continues to evolve, it will likely play a key role in enabling the next generation of mobile networks, as well as supporting advancements in smart cities, autonomous vehicles, and the Internet of Things (IoT). With continued investment and research, RIS could become a cornerstone of digital infrastructure, addressing some of the biggest challenges in wireless communication, such as data congestion, signal interference, and energy efficiency.[45]

The potential for RIS extends beyond just the telecommunications industry. Its ability to control electromagnetic waves could have applications in various other fields, such as healthcare, where precise control of radiation could be used for medical imaging or targeted treatments. In defense, RIS could be used to improve the stealth capabilities of military vehicles by controlling how radar signals are reflected.

While the road to widespread RIS adoption will not be without obstacles, the promise of more efficient, faster, and smarter wireless communication is driving significant interest and investment in this technology. If the current pace of innovation continues, RIS could become an integral part of our future digital landscape, enhancing the way we interact with the digital and physical worlds alike.[46]
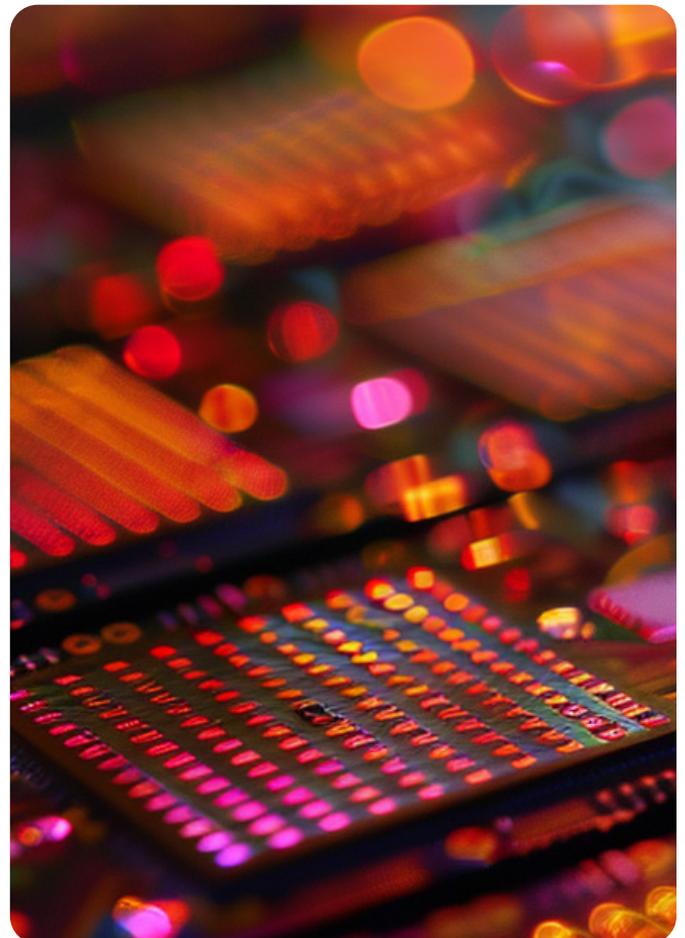
45. weforum
46. rohde-schwarz

Tech Signal: Launching Direct-to-Cell Service via Low-Earth Orbit Satellites

A research team from University of Glasgow and other institutes has published a paper in Nature Communications Engineering that is titled «Coded Environments: Data-driven Indoor Localisation with Reconfigurable Intelligent Surfaces». It investigates the potential of Reconfigurable Intelligent Surfaces (RIS) to enhance the accuracy of indoor localization systems.[47]

Indoor localization remains a challenge due to environmental factors like reflections, signal absorption, and multipath propagation that degrade the accuracy of current positioning systems. Technologies such as Wi-Fi, Bluetooth, and UWB are commonly used for indoor localization; however, they often struggle with precise positioning, especially in complex or large indoor environments where signals can be scattered and obstructed. The research focuses on integrating RIS with data-driven, machine learning algorithms to overcome these limitations. By dynamically controlling the propagation of wireless signals in an indoor environment, RIS can create a «coded» environment. This allows the system to better understand and interpret the position of devices or objects within a space, thus improving localization accuracy. The Nature's paper emphasizes several key areas:

- **RIS Architecture:** RIS panels are composed of sub-wavelength elements that can be electronically adjusted to reflect wireless signals in a controlled manner. This creates a tunable, programmable radio environment that improves the direction and strength of signals, enhancing how localization systems process spatial information.

- **Machine Learning Integration:** The system incorporates machine learning techniques to process the data collected by RIS. This involves using large datasets of signal patterns to train models that can predict the position of a device within the coded environment. The authors demonstrate that these algorithms can significantly improve the accuracy of indoor localization systems by better analyzing and interpreting the modified signal paths created by RIS.

- **Experimental Setup and Results:** By evaluating different test scenarios, the researchers show that the use of RIS can lead to a substantial improvement in localization accuracy compared to traditional methods. Specifically, the RIS system achieved a localization success rate of 82.4%, demonstrating its effectiveness in various settings, including environments with significant interference or complex physical layouts.[48]

Reconfigurable Intelligent Surfaces offer several benefits and opportunities:

- **Diversity of Applications:** They include smart buildings, where precise indoor localization is crucial for navigation and automation, as well as in industries like healthcare, manufacturing, and logistics. Accurate positioning can enable better asset tracking and enhance robotic systems by providing precise information about the location of people and objects within a space.

- **Energy Efficiency:** RIS technology is highly promising for improving network capacity and energy efficiency. One of its core features is its ability to transform ordinary surfaces into active components of communication networks. The underlying metamaterials are artificially structured to control and reflect electromagnetic waves.

- **Utilization of Machine Learning:** RIS, combined with machine learning, offers a promising solution to the challenges of indoor localization. By creating a programmable environment that manipulates signal propagation, RIS can significantly improve the accuracy of positioning systems, paving the way for more advanced and reliable indoor localization technologies in the future.[49]
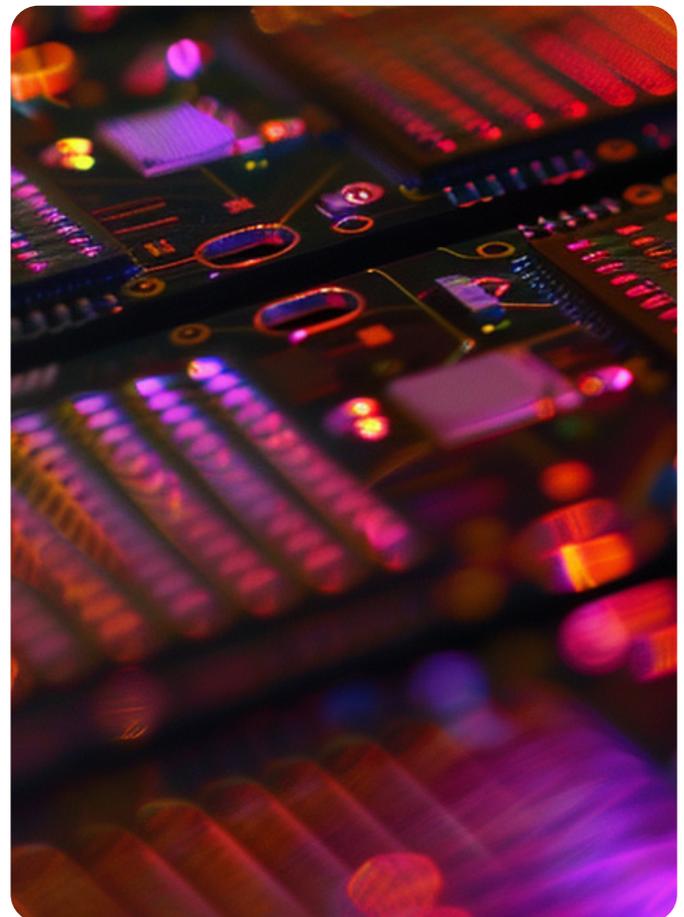
47. gla.ac.uk
48. nature
49. KAUST

Economic Overview [50]

The market drivers for Reconfigurable Intelligent Surfaces (RIS) technology include:

- Advancements in Wireless Communication: With the rollout of 5G networks, RIS enhances signal quality, coverage, and capacity, making it valuable for telecom operators.

- Energy Efficiency and Sustainability: RIS improves energy efficiency by optimizing signal propagation, aligning with the global focus on sustainable technologies and energy conservation.

- Rising Need for Connectivity in Remote Areas: RIS can improve connectivity in rural and underserved regions by optimizing signal transmission and extending coverage.
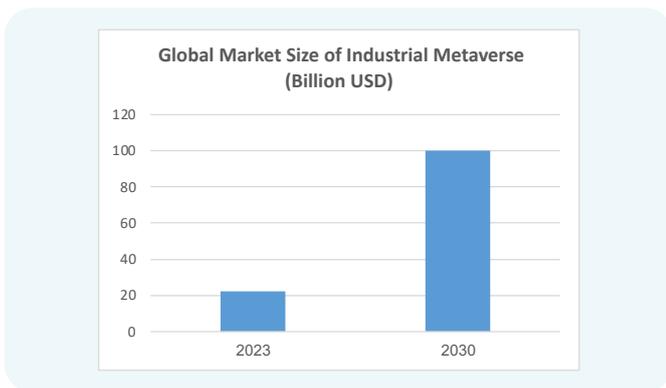
Global Market Size of Industrial Metaverse (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through the:

- Development of the digital economy

- Localization of promising industries

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Mission:

- Future of connectivity: building sustainable 6G technologies by 2035.

Multi-Dimensional Evaluation

Reconfigurable Intelligent Surfaces
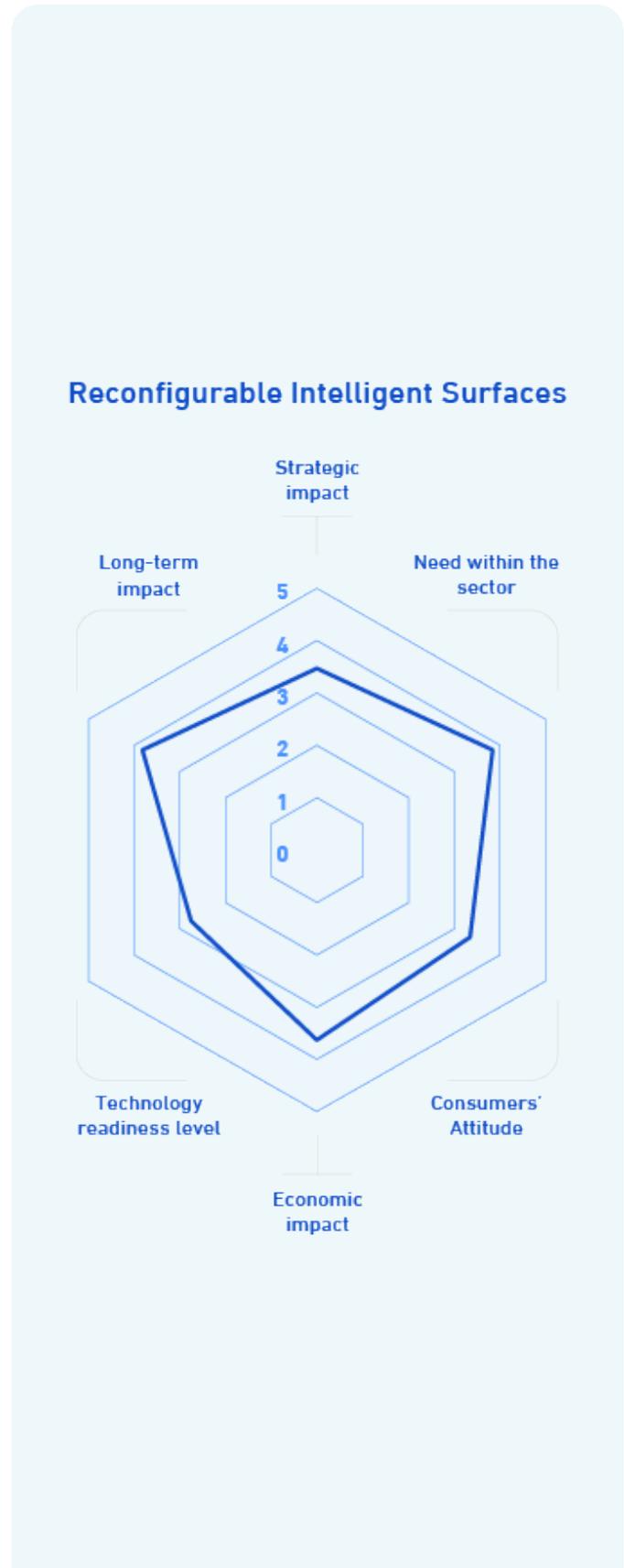
50. verifiedmarketreports

08
Cybersecurity Mesh Architecture (CSMA)

The Cybersecurity Mesh Architecture (CSMA) is a framework designed to create a coordinated ecosystem of security tools and controls to protect modern, distributed enterprises. It focuses on integrating flexible and distributed security tools by centralizing the data and control layers to foster more effective collaboration among these tools. This approach enhances capabilities for threat detection, streamlines response processes, ensures consistent management of security policies, and improves access control. All of these elements contribute to strengthening an organization's overall security posture.[51]

By 2024, the adoption of CSMA is expected to drive significant changes in cloud security. CSMA enables the integration of cloud environments with edge computing and IT/OT (Information Technology/Operational Technology) infrastructures, supporting the predicted growth in interoperability by approximately 45%. Acting as a central security layer, CSMA connects and secures a wide range of security solutions across an organization. The key elements of this architecture include context-aware security measures, identity-focused boundaries, and proactive defense capabilities in real time.

CSMA is expected to transform fragmented security systems across IT/OT and cloud environments into a more integrated cybersecurity framework, enhancing interoperability and connectivity from cloud platforms to edge devices and IT/OT systems. This integration optimizes existing security investments, making security more efficient and maximizing the return on previous expenditures.

Additionally, CSMA enables organizations to evaluate their cloud security posture from a business risk perspective, including regulatory compliance. The architecture supports effective risk management and prioritization, ensuring that security measures are aligned with business objectives and regulations.[52]

CSMA offers several key benefits:

- **Enhanced Security for Distributed Environments:** By decentralizing security perimeters, CSMA provides robust protection for assets regardless of their location, which is crucial in today's hybrid work environments.

- **Scalability and Flexibility:** Its modular approach allows organizations to efficiently scale their security measures, seamlessly integrating new components as the business grows or evolves.

- **Real-Time Threat Detection and Response:** The distributed nature of CSMA enables more effective real-time threat detection and response, placing security controls closer to assets and users.[53]

Implementing CSMA involves integrating composable, distributed security tools by centralizing the data and control plane to achieve more effective collaboration between tools.[54]

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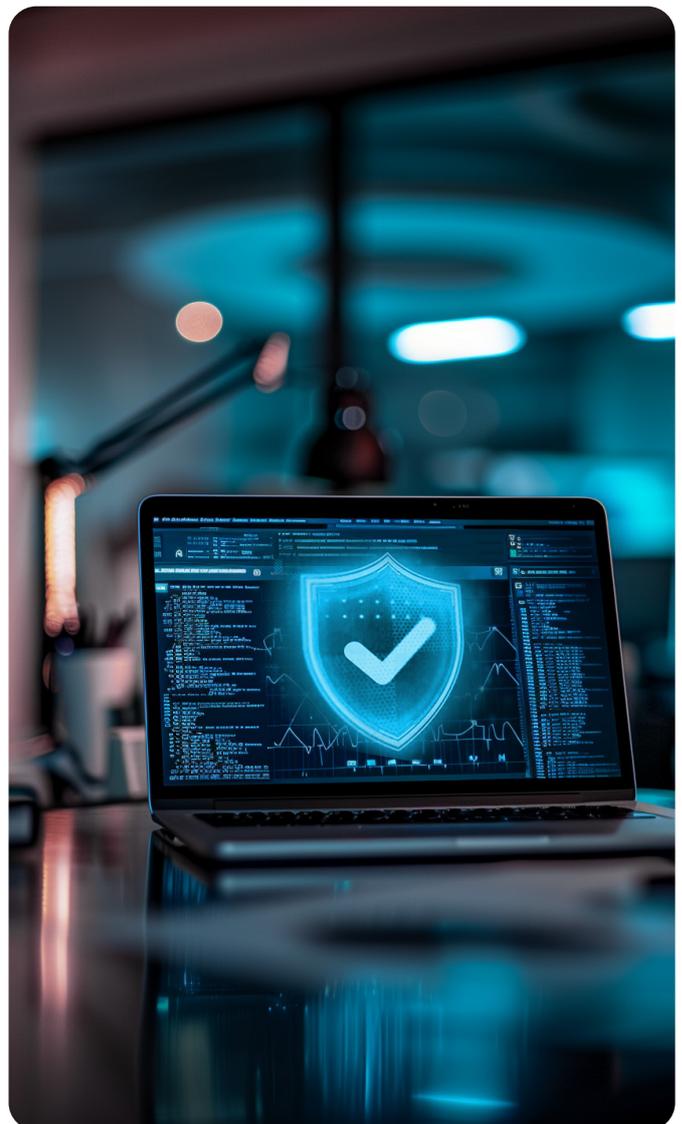
51. gartner
52. eviden
53. Training Camp

54. The Quest Blog

Tech Signal: Cybersecurity Mesh Architecture (CSMA): A Major Advancement in Cybersecurity
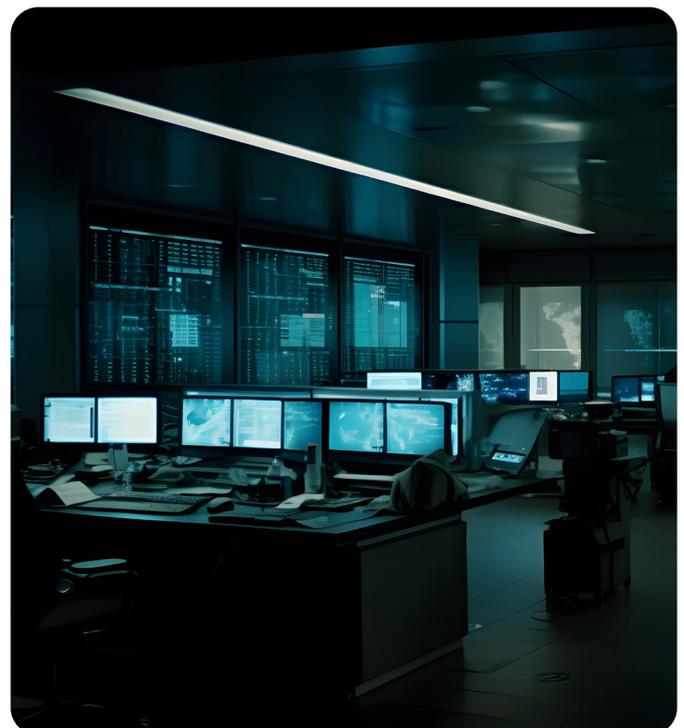
Cybersecurity Mesh Architecture (CSMA) is an advanced cybersecurity framework designed to protect modern, distributed enterprises by creating an ecosystem of interoperable tools and controls. First introduced by Gartner in 2020, CSMA is built on the principle of integrating distributed security tools into a composable architecture that centralizes data and control planes, enabling enhanced collaboration between various security solutions. This centralized approach aims to achieve consistent policy management, improved threat detection, efficient response, and more adaptive and granular access control, ultimately resulting in a stronger overall security posture for organizations.[55]

By 2024, CSMA has evolved significantly, becoming a critical strategy for organizations that need to navigate increasingly complex and distributed IT environments. The architecture's ability to provide a unified security framework across different environments, such as cloud, edge computing, and IT/OT (Information Technology/Operational Technology) infrastructure, is one of its most important advancements as described below:

- **Consolidation of Preventive and Detective Measures:** CSMA now supports the consolidation of both preventive and detective measures across hybrid cloud environments. This includes the integration of security operations (SecOps) workflows with Cloud-Native Application Protection Platforms (CNAPP), providing a comprehensive approach to securing cloud applications and infrastructure. Such consolidation helps prevent misconfigurations, enforce best practices, and enhance real-time detection and response capabilities, which are essential in today's dynamic threat landscape.

- **Focus on Business Risk Management:** CSMA's advancements have made it easier for organizations to align their security strategies with business objectives. The architecture now incorporates tools and processes that help organizations understand their security posture from a business risk perspective, facilitating effective risk management and prioritization. This allows security teams to focus on the most critical vulnerabilities and threats that could impact business operations.

- **Enhanced Support for Zero Trust Security Models:**

CSMA in 2024 increasingly supports Zero Trust security models, which require verification of every access request, regardless of origin. The architecture facilitates the implementation of Zero Trust principles by providing robust identity management, continuous authentication, and adaptive access controls. This is particularly valuable in hybrid and remote work environments, where traditional perimeter-based security models are insufficient.

- **Improved Compliance and Data Sovereignty:** Another significant advancement in 2024 is CSMA's enhanced support for regulatory compliance and data sovereignty requirements. The architecture helps organizations align their security practices with local and international regulations, such as the EU Cybersecurity Act and the NIS2 directive. CSMA includes features for data localization, encryption controls, and sovereign cloud offerings, which are particularly important in regions with stringent data protection laws.

- **AI-Driven Threat Detection and Response:** In 2024, CSMA leverages artificial intelligence (AI) and machine learning more extensively to enhance threat detection and response capabilities. The integration of AI-driven tools allows CSMA to analyze large volumes of data in real-time, identify patterns indicative of threats, and automate responses to mitigate risks quickly. This significantly reduces the mean time to detect (MTTD) and the mean time to respond (MTTR) to incidents.[56]


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55. checkpoint
56. Eviden

Economic Overview [57]

The Cybersecurity Mesh Architecture (CSMA) market is experiencing significant growth, driven by several key factors:

- Increasing Cyber Threats and Attacks: The rise in sophisticated cyberattacks, including ransomware and zero-day exploits, has heightened the need for advanced security solutions. Organizations are recognizing that traditional security approaches may not sufficiently protect their assets against these evolving threats, leading to a growing demand for CSMA.

- Adoption of Multi-Cloud and Hybrid Environments: As businesses increasingly utilize multi-cloud and hybrid cloud environments, the complexity of securing diverse and distributed digital assets has intensified. CSMA offers a scalable and modular solution to extend security controls across these widely dispersed assets, ensuring consistent protection.

- Technological Advancements: The integration of artificial intelligence (AI), machine learning (ML), and automation within CSMA enhances threat detection, response capabilities, and predictive analytics. These technologies enable more efficient and proactive cybersecurity measures, contributing to the growing adoption of CSMA solutions.
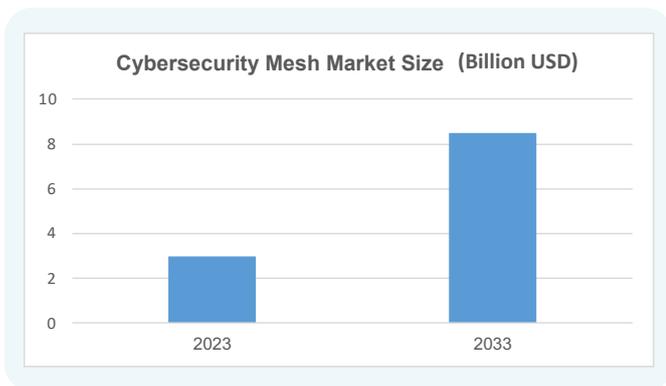
Cybersecurity Mesh Market Size (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through the:
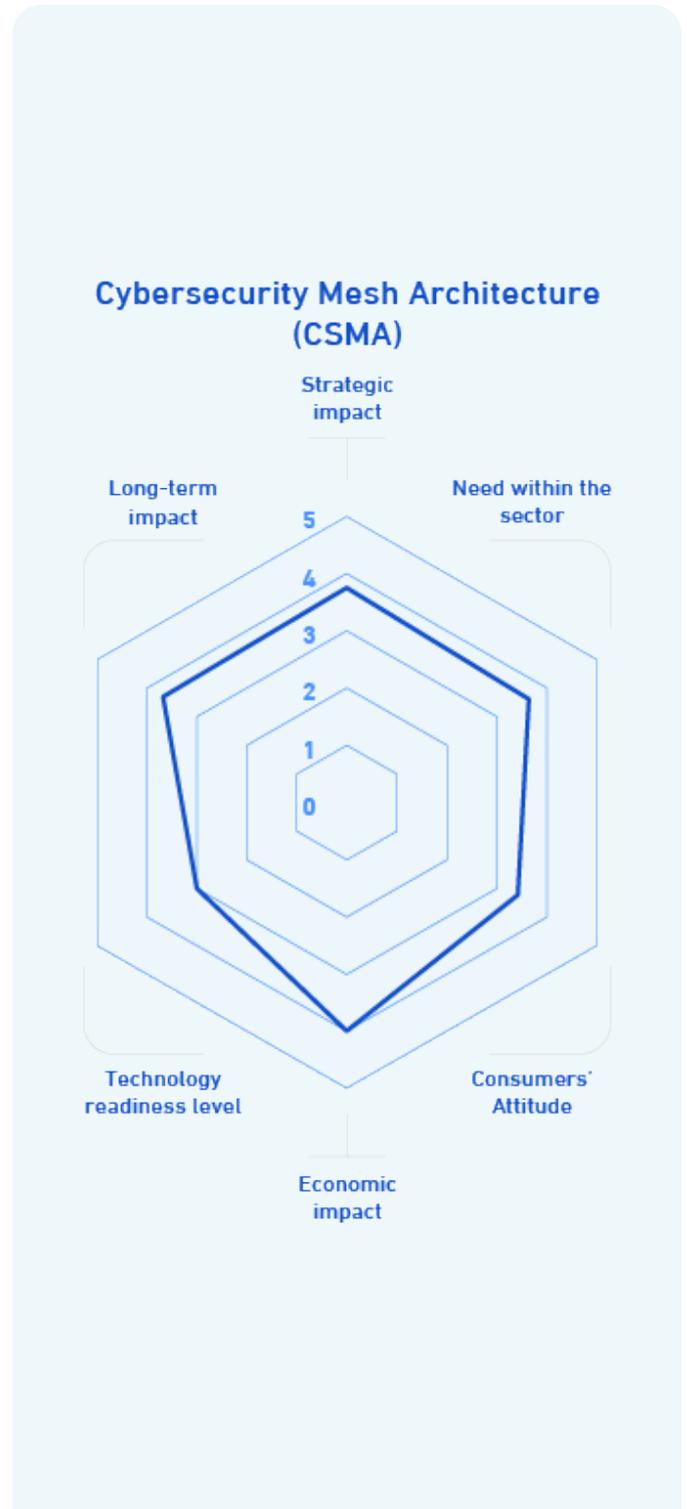
- Development of the digital economy.

- Localization of technologies and knowledge.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Missions:

- Future of connectivity: building sustainable 6G technologies by 2035

Multi-Dimensional Evaluation

Cybersecurity Mesh Architecture (CSMA)

57. precedenceresearch

09
Unmanned Aerial Vehicles (UAVs)

Unmanned aerial vehicles (UAVs), or drones, have significantly transformed various civil sectors by enhancing efficiency, safety, and accessibility. Their applications span numerous fields, including agriculture, infrastructure inspection, delivery services, and emergency response. One of the most significant trends in drone technology is the integration of artificial intelligence (AI). AI-powered drones are capable of autonomous flight, real-time data processing, and decision-making, making them invaluable for tasks like precision agriculture, where they can monitor crop health and apply fertilizers or pesticides with pinpoint accuracy. Additionally, AI enables drones to perform complex search and rescue operations, where they can navigate challenging terrains and locate missing persons quickly.

Another notable advancement is the improvement in battery technology. Modern drones now have longer flight times and faster charging capabilities, allowing them to be more efficient and practical for commercial use. This has opened up new possibilities for drone delivery services, where companies like Amazon and UPS are experimenting with drone deliveries to reduce delivery times and costs.

The implementation of 5G technology has also played a crucial role in enhancing drone operations. With 5G, drones can transmit data in real-time, enabling seamless communication and coordination for tasks such as traffic management, emergency response, and infrastructure inspection. This connectivity is essential for creating a cohesive and effective counter-drone strategy, ensuring airspace safety and security. Following is a summary about some recent applications of UAVs.

1. **Agriculture:** In modern agriculture, drones equipped with multispectral sensors and high-resolution cameras enable farmers to monitor crop health, assess irrigation needs, and detect pest infestations with precision. This technology facilitates precision agriculture, allowing for optimized resource utilization and improved yields. For instance, drones can capture aerial images that provide real-time data on crop conditions, enabling timely interventions.[58]

2. **Infrastructure Inspection:** Drones have become indispensable tools for inspecting critical infrastructure such as bridges, power lines, and wind turbines. They offer a safer and more efficient alternative to traditional inspection methods, reducing the need for manual inspections in hazardous locations. Companies like Drone Volt have developed specialized drones capable of inspecting high-voltage power lines without interrupting the power supply, enhancing maintenance efficiency and safety.[59]

3. **Delivery Services:** The logistics industry has embraced drone technology to expedite deliveries, particularly in remote or congested areas. Companies such as Amazon and Wing have initiated drone delivery services, aiming to reduce delivery times and operational costs. In the UK, Amazon received approval to test drone deliveries for packages under 5 pounds, marking a significant step toward integrating drones into mainstream logistics.[60]

4. **Emergency Response and Healthcare:** Drones play a crucial role in emergency response by delivering medical supplies to inaccessible regions and assisting in disaster relief operations. During the COVID-19 pandemic, drones were utilized to transport test kits and medical samples, minimizing human contact and expediting logistics. In Scotland, drones were employed to carry COVID-19 samples, demonstrating their utility in healthcare logistics.[61]
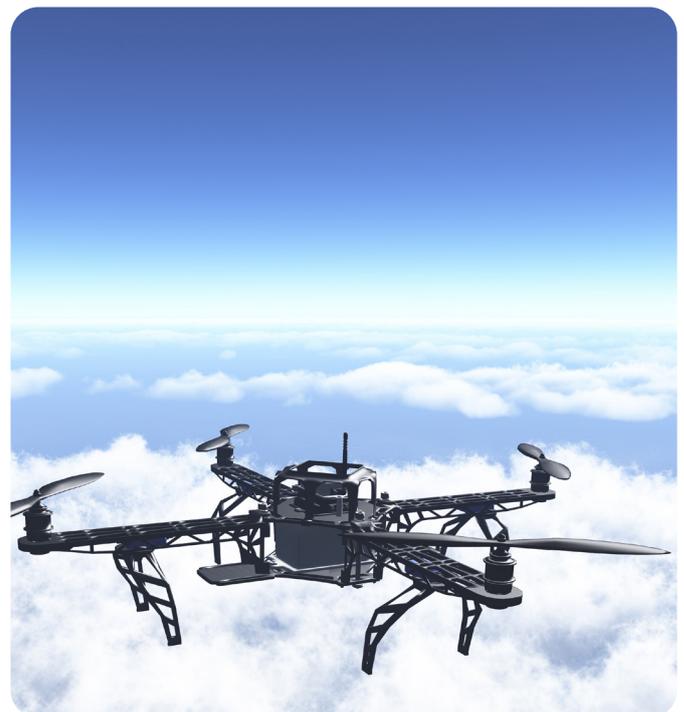
58. Cadena SER
59. Le Monde
60. Theguardian

61. The Wall Street Journal

Tech Signal: Revolutionizing Drone Technology: Autonomous Swarms, AI Precision, and 5G-Enabled Connectivity

The year 2024 witnessed several technological shifts in the field of unmanned aerial vehicles (drones), including: the development of autonomous swarms, neuromorphic image processing, 5G-enabled communication, and green drones.

1. **Autonomous Swarms:** One of the most significant advancements in drone technology is the development of autonomous swarming. Quantum Systems in Germany recently showcased this with their AI-driven Unmanned Aerial Systems (UAS) that can fly as swarms. These drones operated efficiently, even when individual units failed or encountered radio interference. The key innovation here is how AI enables the drones to coordinate their actions in real-time, processing reconnaissance data and adjusting their mission based on evolving conditions.[62] This has promising applications in both military and disaster response operations, where drone swarms can execute reconnaissance, surveillance, and even combat missions without direct human control. Additionally, drone swarms are increasingly being tested for disaster management, where they can cover large areas and coordinate in real time to assess damage, locate survivors, or deliver aid. [63]

2. **Neuromorphic Image Processing:** Another groundbreaking development is neuromorphic AI for drone operations. This system mimics the brain's efficiency in processing sensory data, allowing drones to process images faster and more efficiently. Neuromorphic processors allow drones to autonomously navigate complex environments, such as indoor spaces or areas with dense obstacles, with much less energy than traditional methods. This is especially useful in applications where smaller drones are needed, such as greenhouse crop monitoring, warehouse management, or precision agricultural tasks. These drones can autonomously assess crop health, monitor stock, or perform other intricate tasks without requiring continuous human intervention.[64]

3. **5G-Enabled Connectivity:** The integration of 5G technology is another game-changer for drones. With high-speed, low-latency communication, 5G allows drones to transmit vast amounts of data in real time, supporting applications like live-streaming high-definition video or coordinating multi-drone operations. This also expands their potential in sectors like logistics and emergency services, where reliable and instant communication between drones and control centers is crucial for safe and effective operations.[65]

4. **Green Drones:** Finally, sustainability is also becoming a key trend, with the development of green drones powered by renewable energy sources or more energy-efficient designs. These eco-friendly drones are emerging as ideal tools for wildlife monitoring, environmental conservation, and other applications where a lower carbon footprint is essential. As global focus shifts towards reducing emissions, green drones are poised to play a significant role in reducing the environmental impact of aerial operations.[66]

Together, these innovations signal a future where drones are not only more autonomous and capable but also smarter, more sustainable, and more integral to industries ranging from agriculture to defense. Each breakthrough contributes to a rapidly evolving ecosystem where drones can perform increasingly complex tasks with minimal human intervention.
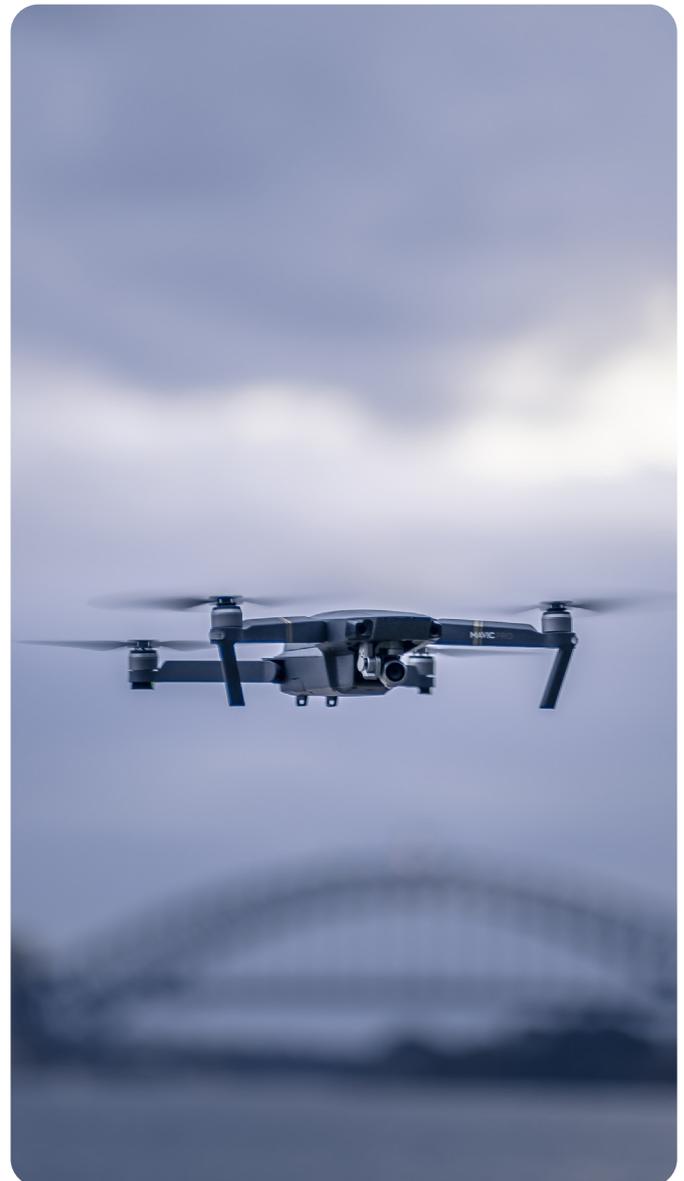
62. TNW | The heart of tech
63. Aerologix
64. DroneXL.co
65. Drones Reviews
66. Aerologix

Economic Overview [67]

The Unmanned Aerial Vehicle (UAV) market is experiencing significant growth, driven by several key factors:

- Technological Advancements: Continuous improvements in UAV technology, such as enhanced battery life, advanced sensors, and increased flight capabilities, have expanded their applications across various industries.

- Commercial and Industrial Uses: Industries such as agriculture, logistics, construction, and public safety are adopting UAVs for tasks like aerial mapping, crop monitoring, infrastructure inspection, and delivery services, contributing to market expansion.

- Regulatory Support and Integration: Evolving regulations and supportive policies in various regions are facilitating the integration of UAVs into national airspaces, promoting their commercial use.

- Cost Efficiency and Accessibility: The decreasing costs of UAV technology have made drones more accessible to businesses and consumers, further driving market growth.
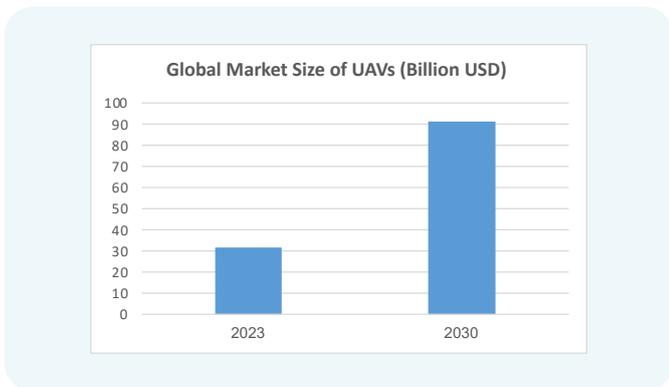
Global Market Size of UAVs (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through:

- Improving the quality of services provided in Saudi cities

- Localization of technologies and knowledge

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Mission:
- Achieve 50% automation of in-Kingdom logistics shipments by 2040.

Multi-Dimensional Evaluation

Unmanned Aerial Vehicles (UAVs)
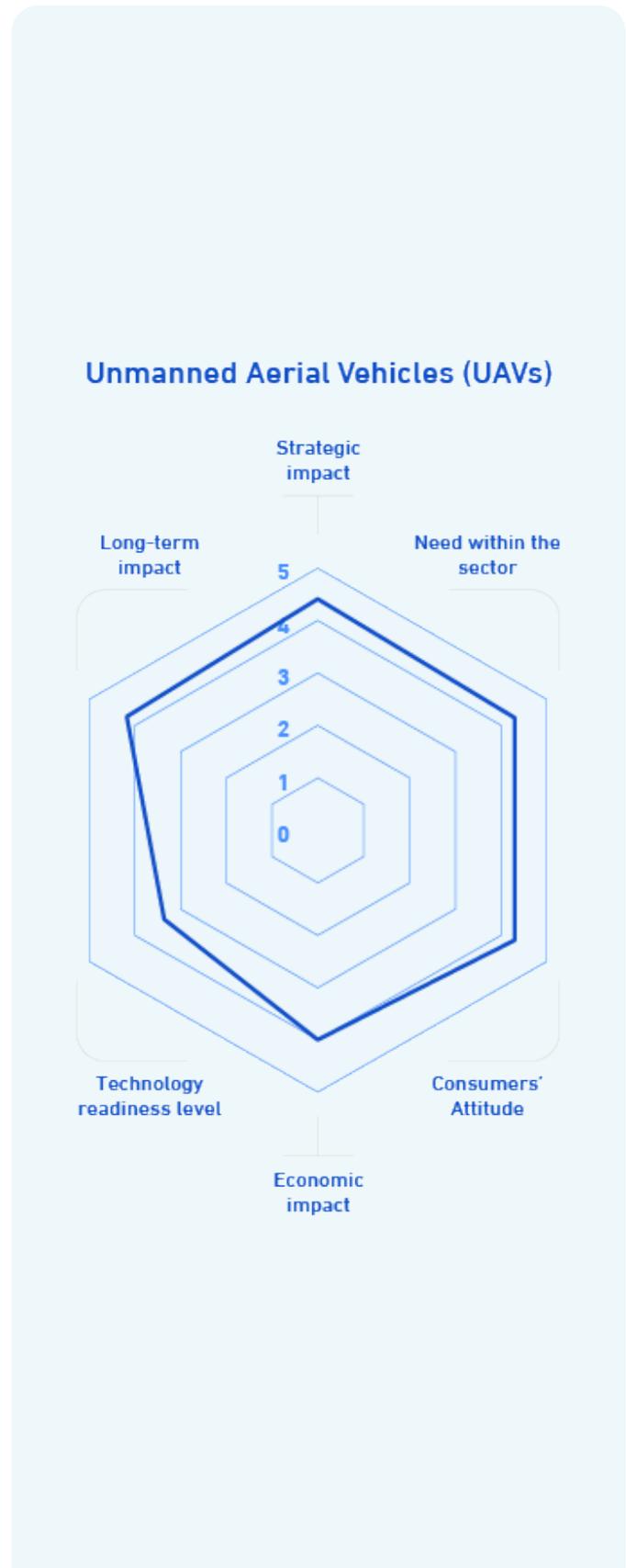
67. fortunebusinessinsights

10
Smart Cities and Traffic Congestion Solutions

Over 57% of the world's population currently lives in urban areas,[68] a proportion that is expected to increase to 68% by midcentury.[69] The trend toward greater urbanization puts pressure on governments to ensure that cities remain livable, sustainable, and vibrant. Fortunately, a new breed of so-called smart cities are meeting the challenge by weaving digital technologies into the fabric of urban existence. By integrating artificial intelligence (AI), sensors, and other cutting-edge technologies into their core services, these and other smart cities are redefining how residents, businesses, and governments will live, interact, and operate in the coming years. Megacities are leading the way, and their efforts foreshadow the gains that can be made by cities around the world. By studying the initiatives of smart cities and regions, other urban centers can learn to manage—if not alleviate—issues such as overcrowding, gridlock, safety, and water shortages.

The rapid progress in sensor and actuator technology has significantly contributed to the development of smart cities. These technologies form the backbone of data-driven urban environments by seamlessly integrating with the Internet of Things (IoT). A comprehensive review paper examines the essential role of sensors and actuators in shaping smart cities, addressing key topics like technology types, data security, regulatory frameworks, and future potential.[70]

The review starts by highlighting the critical role of sensors and actuators in IoT networks that serve as the foundation for smart cities. It also provides insights into the diverse range of sensors designed for various IoT applications and the factors that influence their lifespan, emphasizing the importance of accuracy and durability. The paper offers a detailed analysis of actuators, which are the dynamic counterparts of sensors, explaining how they can be utilized to develop smarter urban environments.

This review also explores data security in the exchange of big data among actuators, the legal frameworks supporting smart city growth, and the essential components for building a smart city. It underscores the advantages of integrating advanced actuator technology with sensors and identifies emerging trends such as AI-driven urban management and blockchain-enhanced data security. Serving as a resource for researchers, policymakers, and urban planners, the illustrates the diverse advancements in sensor and actuator technologies and their critical role in creating smarter, more sustainable cities. There are several benefits and advantages in this technology, such as:

- Cost Efficiency: This system significantly reduces the cost of traffic signal optimization. Traditional systems require expensive sensors and frequent manual recalibrations, but this cloud-based solution only needs vehicle trajectory data from as little as 6% of vehicles, making it more affordable for municipalities. The system's cost is a fraction of that of adaptive systems.

- Reduction in Congestion: The system has shown the ability to decrease traffic congestion and reduce vehicle delays. In trials, it led to a 20% to 30% reduction in the number of stops at intersections.[71]

- Energy Savings: By reducing stop-and-go traffic, the system indirectly lowers fuel consumption, thus decreasing vehicle emissions and contributing to environmental benefits.

- Scalability: The system can be applied to any traffic signal, including those without built-in detectors, and it scales easily to large networks of intersections.

- Real-Time Adaptability: As traffic patterns change, the system can be quickly recalibrated to reflect the latest traffic dynamics, a task that is typically delayed in conventional systems due to high costs and time constraints.[72]
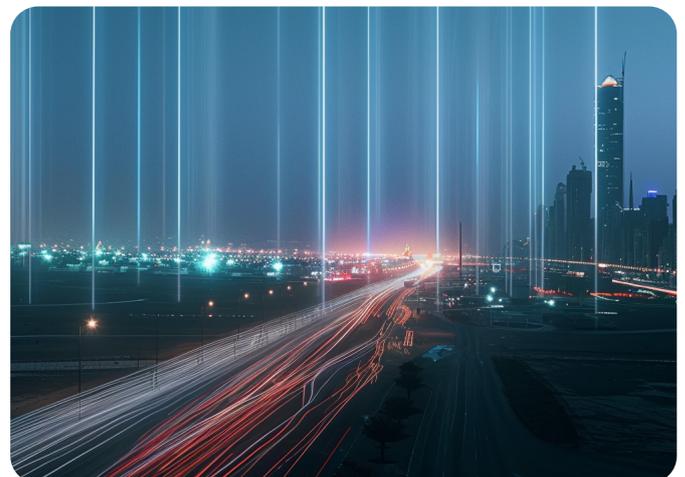
68. macrotrends
69. bcg.com
70. link.springer

71. University of Michigan News
72. Mcity

Tech Signal: Reducing Traffic Congestion and Emissions: A New GPS-Based System Revolutionizes Traffic Signal Timing

There are around 320,000 traffic signals in the U.S., with annual congestion costs—both direct and indirect—totaling $22.9 billion. These costs include time wasted at lights and unnecessary energy consumption due to inefficient signal timings.

Most traffic signals follow a time-of-day schedule, with preset patterns for morning, afternoon, evening, and nighttime. Traffic engineers aim to synchronize these cycles with nearby intersections to minimize stop-and-go driving. Traffic is constantly changing, for instance, traffic patterns shifted significantly in the year before and the two years following COVID-19, with many people working from home. When such changes occur, signal timings need to be adjusted.

However, optimizing traffic signals to adapt to changing traffic patterns is not easy. The costs and time required for traffic counts and recalibration mean that most municipalities reassess signal timings only every two to five years, or even less frequently. Although adaptive signals have been around since the 1970s, and they can reprogram signals in near real-time by detecting vehicles at intersections, their high costs have limited their widespread use. Installing an adaptive system at a single intersection can cost up to $50,000, with regular maintenance needed, which is often beyond the financial reach of many communities. [73]

Using GPS data from as little as 6% of vehicles on the road, researchers at the University of Michigan have developed a system to recalibrate traffic signals, reducing congestion and delays at intersections. In an 18-month pilot study in Birmingham, Michigan, the team utilized connected vehicle data provided by General Motors, achieving a 20% to 30% reduction in stops at traffic signals. General Motors vehicles account for 6-10% of cars on U.S. roads.

This is the world's first large-scale traffic signal retiming system that operates via the cloud, presenting a significant opportunity for communities to adjust their signal patterns at a lower cost. The research received partial funding from the U.S. Department of Transportation and General Motors. The project's findings were published in Nature Communications.

This system uses GPS data from a portion of vehicles on the road to derive traffic patterns. For example, a connected vehicle stopping approximately 100 feet from an intersection suggests it is behind at least three or four other vehicles. While detectors at intersections can provide traffic counts and estimated speeds, having access to vehicle trajectory data, even with low penetration rates, offers more valuable information, including vehicle delays, the number of stops, and route selection.

Optimizing traffic lights is recognized as a cost-effective way to reduce congestion and energy use in urban settings without altering the physical road infrastructure. However, because installing and maintaining vehicle detectors is expensive, most intersections rely on fixed-time traffic signals that are rarely optimized. To address traffic congestion at intersections, the team introduced a large-scale traffic signal re-timing system that utilizes a small fraction of vehicle trajectories as its sole input, eliminating the need for detectors. The team created a probabilistic time-space diagram that connects a stochastic point-queue model with vehicle trajectories using the proposed Newellian coordinates. This model allows us to reconstruct the regular spatial and temporal traffic patterns by compiling enough historical data. The team then developed optimization algorithms to adjust traffic signal parameters for intersections that have room for improvement. This system offers a scalable, sustainable, and efficient approach to traffic light optimization and could potentially be applied to all fixed-time signalized intersections worldwide. [74]
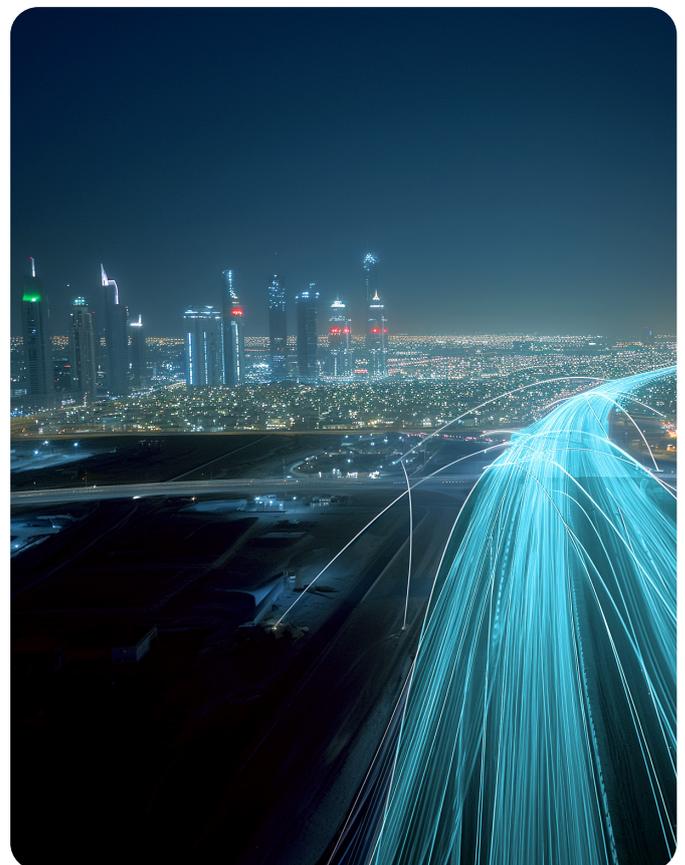

73. nature
74. sciencedaily

Economic Overview [75]

Governments are embracing "smart cities" to promote and fund digital services in their countries. The trend toward greater urbanization puts pressure on governments to ensure that cities remain livable, sustainable, and vibrant. By integrating AI, sensors, and other cutting-edge technologies into core services, smart cities are redefining how residents, businesses, and governments will live, interact, and operate in the coming years.

Several governments have made great strides in using digital technology to provide government benefits and distribute information. An analysis of 11 G20 member nations' smart-city strategies reveals how leaders can take the next step and create a vision, engage stakeholders, and adopt policies to build smart cities; which lead to the growth of this market.[76]
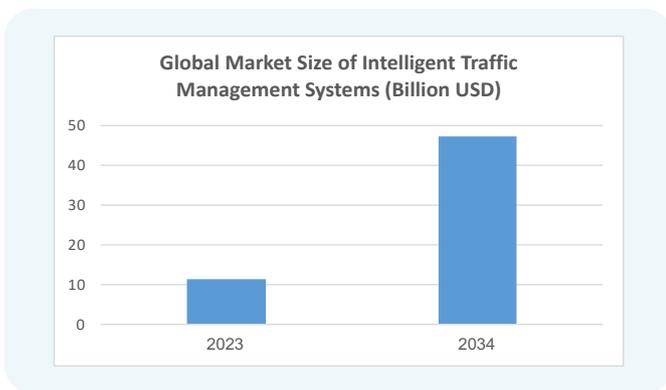
Global Market Size of Intelligent Traffic Management Systems (Billion USD)

Linking to Saudi Vision 2030

This technology can contribute to achieving the Saudi Vision 2030 through:

• Improving the quality of services provided in Saudi cities.
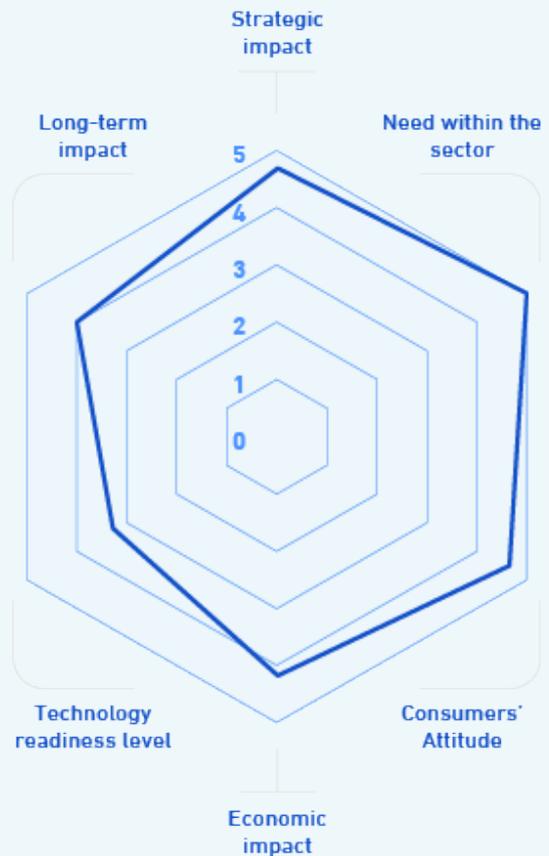
• Enhancing traffic safety.

Alignment with the National RDI Missions

This technology can be aligned with the National RDI Mission:

• Going beyond Smart Cities, establish five Cognitive Cities in KSA by 2040.

Multi-Dimensional Evaluation

Smart Cities and Traffic Congestion Solutions

75. precedenceresearch
76. BCG

05

CONCLUSION

The convergence of emerging technologies is fundamentally reshaping the global economic landscape, offering unprecedented opportunities to address critical challenges and unlock new avenues for growth. By leveraging advancements in computing, artificial intelligence, communication, and urban systems, societies can position themselves at the forefront of innovation, driving sustainable progress and competitive advantage.

This report has highlighted the pivotal role these technologies play in fostering economic diversification, enhancing productivity, and addressing the complexities of a rapidly evolving world. Their integration into key sectors holds the potential to revolutionize industries, improve quality of life, and create new pathways for collaboration across regions and disciplines.

In the pursuit of ambitious development goals under the framework of Saudi Vision 2030, research, development, and innovation take center stage as essential drivers of progress. The technologies highlighted in this report underscore the critical need for visionary policies, strategic investments, and collaborative efforts to fully harness their transformative potential.

By providing a comprehensive analysis and expert-driven evaluation, this report serves as a catalyst for informed decision-making, enabling stakeholders to navigate the intricate interplay between technology and economic growth. The future of economies will be defined by those who act decisively today to embrace innovation, foster collaboration, and drive meaningful progress.

هيئة تنمية البحث
والتطوير والابتكار
**Research Development
and Innovation Authority**