

Accelerating the Future: The Synergy of 5G and Edge Computing in Realizing Saudi Arabia's Vision 2030

Abass Abdelaziz Abass Kheder

Senior Communication Engineer Core Network consultant, Riyadh, Saudia Arabia

ABSTRACT: This article provides a comprehensive analysis of the synergistic role of Fifth Generation (5G) mobile networks and edge computing in advancing the strategic objectives of Saudi Arabia's Vision 2030. It begins by defining the core technical capabilities of 5G—high bandwidth, ultra-low latency, massive connectivity—and edge computing—distributed processing near data sources—highlighting their complementary nature in enabling next-generation applications. The analysis then aligns these technologies with the key pillars of Vision 2030, particularly those focused on economic diversification, digital transformation, smart city development, and technological localization. Specific use cases within the Kingdom are examined, including smart city infrastructure exemplified by projects like NEOM, Industrial Internet of Things (IIoT) applications in energy, manufacturing, and logistics, advanced digital healthcare services, and enhanced connectivity for tourism and entertainment mega-projects. The potential economic benefits, such as GDP growth, investment attraction, and productivity gains, alongside societal impacts concerning quality of life and digital inclusion, are evaluated. The current status of 5G and edge infrastructure deployment in Saudi Arabia, including operator activities, data center growth, and government initiatives, is assessed. Key challenges, encompassing cybersecurity risks, data privacy regulations (PDPL), regulatory hurdles (CST), infrastructure costs, and the critical digital skills gap, are identified and analyzed. Finally, the article explores the future trajectory, considering national RDI priorities, the transition towards 5G-Advanced, and the strategic preparations for the 6G era within the framework of Vision 2030. The findings underscore the critical importance of 5G and edge computing as foundational technologies for Saudi Arabia's national transformation, while emphasizing the need for continued strategic focus on overcoming adoption barriers, particularly in cybersecurity and workforce development, to fully realize their potential.

KEYWORDS: 5G, Digital Transformation, Technology adoption, smart city Saudi Arabia, Vision 2030.

Date of Submission: 13-05-2025

Date of acceptance: 27-05-2025

I. INTRODUCTION

The global technological landscape is undergoing a profound transformation, driven significantly by the advent and proliferation of Fifth Generation (5G) mobile networks and edge computing. These technologies are not merely incremental upgrades but represent fundamental shifts in connectivity and data processing, promising to unlock unprecedented capabilities across industries and societies. 5G offers a trifecta of enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC), while edge computing brings computational power closer to the data source, enabling real-time processing and analysis. The convergence of these technologies is widely anticipated to power the next wave of digital innovation, from autonomous systems and smart cities to immersive experiences and the large-scale Internet of Things (IoT), with predictions suggesting a significant shift of data processing towards the network edge.

Simultaneously, the Kingdom of Saudi Arabia (KSA) is pursuing one of the world's most ambitious national transformation plans: Vision 2030. Launched in 2016, this strategic framework outlines a comprehensive roadmap to diversify the Kingdom's economy away from its historical reliance on oil revenues, modernize its society, and establish itself as a global investment powerhouse and logistics hub connecting three continents. Central to achieving these multifaceted goals is a deep commitment to digital transformation, the development of a robust Information and Communications Technology (ICT) sector, and the adoption of cutting-edge technologies. The Kingdom views digital capabilities not just as economic drivers but as essential enablers for enhancing government efficiency, improving citizen quality of life, and fostering innovation across all sectors.

This context sets the stage for a critical research inquiry: How are the synergistic technologies of 5G and edge computing being strategically leveraged to achieve the diverse objectives outlined in Saudi Vision 2030, and what are the resultant impacts, prevailing challenges, and future prospects for their deployment within the Kingdom? To address this question, this article pursues several interconnected objectives. First, it defines 5G and edge computing, elucidating their technical underpinnings and inherent synergy. Second, it maps these technological capabilities onto the specific goals and programs of Vision 2030 related to digital advancement. Third, it analyzes concrete applications and use cases where 5G and edge computing are being implemented or planned within Saudi Arabia. Fourth, it evaluates the potential and observed economic and societal impacts of these technologies in the Saudi context. Fifth, it assesses the current deployment status of 5G networks and edge computing infrastructure within the Kingdom. Sixth, it identifies and scrutinizes the significant challenges and barriers hindering large-scale adoption. Finally, it explores the future roadmap for 5G and edge development in KSA, considering national strategies and the evolution towards next-generation networks.

An examination of the timelines surrounding Vision 2030 and the development of 5G and edge computing offers an important contextual understanding. Vision 2030 was launched in 2016, a point in time when 5G standards were still under development (with the first full set, Release 15, finalized in 2018) and edge computing was not yet the prominent industry focus it is today. This temporal relationship suggests that the ambitious digital transformation goals embedded within Vision 2030 likely created a strong strategic 'pull' for advanced technological solutions like 5G and edge computing. Rather than the technologies themselves dictating the national strategy, the pre-existing national ambition appears to have driven the rapid evaluation and adoption of these technologies once they became viable. This positions Saudi Arabia's journey as a notable case study of top-down, strategy-led technology adoption aimed at accelerating national development objectives, potentially differentiating its approach from more organically evolving, market-driven technology uptake patterns observed elsewhere. The significant government commitment stemming from Vision 2030 is therefore a primary factor influencing the pace and scale of investment and deployment in the Kingdom's digital infrastructure.

This article employs a methodology based on the synthesis and analysis of information gathered from academic journals, conference proceedings, government reports, reputable industry analyses, and official documentation related to Saudi Vision 2030, 5G, and edge computing, aligning with the research scope outlined in the user query. The scope is specifically focused on the intersection of these technologies within the Kingdom of Saudi Arabia.

The subsequent sections will delve into the technical foundations of 5G and edge computing (Section 2), their alignment with Vision 2030 (Section 3), specific applications within KSA (Section 4), their economic and societal impacts (Section 5), the current state of implementation (Section 6), the challenges faced (Section 7), and the future directions (Section 8), culminating in a concluding synthesis (Section 9).

II. The Technological Imperative: Understanding 5G and Edge Computing

A thorough understanding of the technical capabilities and architectural shifts introduced by 5G and edge computing is essential to appreciate their transformative potential and synergistic relationship, particularly in the context of ambitious national development plans like Saudi Vision 2030.

5G Capabilities, Standards, and Architecture: 5G represents the fifth generation of wireless cellular technology, standardized by the International Telecommunication Union (ITU) under the IMT-2020 framework and specified by the 3rd Generation Partnership Project (3GPP) through a series of releases (starting with Release 15 in 2018 and evolving through Releases 16, 17, and beyond). It is designed to be a unified, more capable platform compared to its predecessor, 4G LTE, offering significant advancements across multiple dimensions.

The key technical capabilities that distinguish 5G include:

Higher Bandwidth and Speed: 5G networks achieve significantly higher data rates, with peak download speeds theoretically reaching up to 20 Gigabits per second (Gbps) and peak upload speeds up to 10 Gbps, compared to 1 Gbps download for 4G. Average data rates are also substantially higher, often exceeding 100 Megabits per second (Mbps). This capability, known as enhanced Mobile Broadband (eMBB), supports demanding applications like high-definition video streaming, immersive virtual reality (VR) and augmented reality (AR), and rapid large file transfers. These speeds are enabled by utilizing wider channel bandwidths (up to 1 GHz compared to 20 MHz in 4G), accessing new, broader spectrum bands (including sub-6 GHz frequencies and high-frequency millimeter wave (mmWave) bands between 30-300 GHz), and employing techniques that yield greater spectral efficiency (more bits per Hertz).

- **Ultra-Low Latency:** 5G is engineered to reduce network latency—the time delay in data transmission—to less than 1 millisecond (ms), a tenfold improvement over 4G's typical latency of around 10-50 ms. Some specifications target latencies as low as 0.5 ms for uplink and downlink. This ultra-reliable low-latency communication (URLLC) capability is critical for real-time applications such as industrial automation, remote surgery, autonomous vehicles, and tactile internet experiences.
- **Massive Connectivity:** 5G networks are designed to support a vastly higher density of connected devices, potentially exceeding 1 million devices per square kilometer. This massive machine-type communication (mMTC) capability is essential for the proliferation of the Internet of Things (IoT), enabling seamless connectivity for billions of sensors, smart meters, wearables, and other devices in smart cities, smart agriculture, and industrial settings.
- **Increased Reliability and Availability:** 5G aims for higher network availability (e.g., 99.999% or "five nines") and reliability, making it suitable for mission-critical communications where uninterrupted service is paramount, such as public safety networks, critical infrastructure control, and advanced industrial processes.

These capabilities are underpinned by core technologies including Orthogonal Frequency Division Multiplexing (OFDM) modulation (adapted for greater flexibility in 5G New Radio - NR), advanced antenna systems like Massive MIMO (Multiple-Input Multiple-Output) and beamforming (which focuses signals towards specific users, improving efficiency and reducing interference), and the 5G NR air interface.

Architecturally, 5G marks a significant departure from previous generations. It moves away from traditional point-to-point network architectures towards a cloud-native, Service-Based Architecture (SBA) for the core network. This approach decouples network functions (NFs) into modular, software-based components that can be flexibly deployed, scaled, and chained together, often using containerization and microservices principles. A key innovation enabled by this architecture is **Network Slicing**. This allows a physical 5G network infrastructure to be partitioned into multiple virtual, end-to-end logical networks, each tailored with specific characteristics (e.g., high bandwidth for eMBB, low latency for URLLC, high density for mMTC) to meet the diverse requirements of different services, applications, or enterprise customers. Network slicing provides greater

flexibility, resource efficiency, and customization compared to the one-size-fits-all approach of previous networks.

The following table provides a concise comparison of key technical capabilities between 5G and 4G LTE, quantitatively illustrating the advancements that underpin 5G's potential.

Feature	4G LTE	5G	Improvement Factor (Approx.)	Supporting Snippets
Peak Download Speed	~1 Gbps	Up to 20 Gbps	20x	
Peak Upload Speed	~0.2 Gbps (200 Mbps)	Up to 10 Gbps	50x	
Latency	~10-50 ms	< 1 ms (as low as 0.5 ms)	>10-50x	
Connection Density	~100,000 devices/km ²	> 1,000,000 devices/km ²	10x	
Spectrum Bands	Primarily Sub-3 GHz	Sub-6 GHz & mmWave (up to 100 GHz+)	Wider Range	
Channel Bandwidth	Up to 20 MHz	Up to 1 GHz (mmWave)	Up to 50x	
Core Architecture	Evolved Packet Core (EPC)	Service-Based Architecture (SBA), Cloud-Native	More Flexible/Scalable	
Key Use Cases	Mobile Broadband, Voice (VoLTE), Video	eMBB, URLLC (Industrial Automation, AVs), mMTC (Massive IoT), FWA	Broader Scope	

Table 1 : 5G vs. 4G Technical Capabilities Comparison

III. Edge Computing: Paradigms, Architectures (MEC), and Benefits

Edge computing represents a paradigm shift in how and where data is processed. It is a distributed computing model that strategically moves computation and data storage resources away from centralized data centers (the cloud) and closer to the physical location where data is generated or consumed—the "edge" of the network. This proximity aims to overcome the limitations inherent in relying solely on distant cloud servers, particularly for applications demanding rapid responses or handling large data volumes.

The primary benefits driving the adoption of edge computing include:

- **Reduced Latency:** By processing data locally or nearby, edge computing significantly minimizes the round-trip time required for data to travel to a central cloud and back. This reduction in latency is crucial for applications requiring near real-time responsiveness, such as industrial control systems, autonomous vehicles, real-time analytics, AR/VR, and remote medical procedures. Delays measured in milliseconds can be critical in these scenarios.
- **Bandwidth Conservation:** Processing data at the edge reduces the sheer volume of raw data that needs to be transmitted over wide area networks to the cloud. Only essential results, summaries, or alerts might be sent centrally, conserving network bandwidth, reducing transmission costs, and alleviating network congestion.
- **Improved Reliability and Availability:** Edge systems can often continue operating locally even if connectivity to the central cloud is disrupted or intermittent. This enhances the resilience of critical applications, ensuring continued functionality in challenging network environments or during outages.
- **Enhanced Privacy and Security:** Keeping sensitive data localized at the edge can reduce the risks associated with transmitting it over public networks to the cloud. Processing data locally can minimize exposure and potentially give end-users more control over their data. However, the distributed nature of edge also introduces new security challenges, as edge devices themselves can become targets and require robust security measures independent of the cloud.

Edge computing architectures typically involve multiple tiers or nodes. A common model includes the **Device Edge** (sensors, actuators, cameras, smartphones generating data), the **Local Edge** (on-premises servers, gateways, or nearby micro-data centers providing compute and storage resources), and the **Cloud** (centralized resources for large-scale processing, storage, and orchestration).

A particularly relevant and increasingly standardized implementation of edge computing in the context of mobile networks is **Multi-access Edge Computing (MEC)**. Initially known as Mobile Edge Computing, MEC is defined by the European Telecommunications Standards Institute (ETSI) as a network architecture concept that provides IT service environments and cloud-computing capabilities at the edge of the network, typically within or close to the Radio Access Network (RAN). MEC aims to offer applications ultra-low latency, high bandwidth, and real-time access to radio network information. Key components include MEC platforms hosting applications (often as Virtual Machines or containers) on MEC servers located at base stations, cell aggregation sites, or central offices. MEC can be deployed in different models: **Public MEC** (offered by operators over their public network), **Private MEC** (dedicated on-premise infrastructure for an enterprise), or **Hybrid MEC**. The MEC framework is designed to be access-agnostic, supporting not only cellular (like 5G) but also Wi-Fi and fixed networks.

Standardization is crucial for interoperability and ecosystem development in edge computing. Key bodies involved include ETSI ISG MEC, which works closely with 3GPP to integrate MEC capabilities natively into the 5G system. Other relevant initiatives come from organizations like the Linux Foundation (LF Edge, OPNFV, ONAP), OpenStack, and the Cloud Native Computing Foundation (CNCF) with Kubernetes.

IV. Synergistic Relationship: Enabling Next-Generation Applications

5G and edge computing are not independent technologies but possess a powerful synergistic relationship, where each enhances the capabilities and value proposition of the other.

5G acts as a critical enabler for edge computing. The high bandwidth provided by 5G allows the vast amounts of data generated by edge devices (sensors, cameras, IoT devices) to be collected and transmitted efficiently to nearby edge processing nodes. The ultra-low latency of 5G is essential for edge applications that require real-time control loops or immediate responses, ensuring that data can be processed and acted upon locally without significant delay. Furthermore, 5G's ability to reliably connect a massive number of devices (mMTC) provides the necessary scale for large-scale IoT deployments that feed data into edge analytics platforms.

Conversely, edge computing is vital for realizing the full potential of 5G networks. While 5G provides the high-speed pipe, edge computing provides the localized intelligence to process the data flowing through it. For latency-sensitive URLLC applications, processing data at the edge is often the only way to meet the stringent sub-millisecond response time requirements, as the round-trip delay to a distant cloud would be too long, even with 5G speeds. Edge computing also helps manage the massive data volumes generated by 5G-connected devices (especially in mMTC scenarios) by processing data locally, reducing the burden on the core network and backhaul infrastructure.

The integration of MEC within the 5G architecture exemplifies this synergy. MEC servers deployed within the 5G RAN (e.g., at the Distributed Unit - DU, or gNodeB) can leverage 5G's low latency and high bandwidth directly. 3GPP standards are evolving to natively support MEC functionalities within the 5G Core (5GC), facilitating discovery of edge application servers (EASs) and efficient routing of user traffic to the edge. Network slicing in 5G can also be used to create dedicated network resources optimized for specific edge applications or MEC deployments.

Together, 5G and edge computing unlock a new class of demanding applications that were previously impractical or impossible. These include real-time industrial automation and robotics requiring precise control (URLLC + Edge Processing), connected and autonomous vehicles needing instantaneous communication and local decision-making (URLLC + Edge AI), truly immersive AR/VR experiences requiring high bandwidth and low latency (eMBB + URLLC + Edge Rendering), advanced telemedicine including remote diagnostics and potentially remote surgery (URLLC + eMBB + Edge), and sophisticated smart city applications involving real-time data analytics from numerous sensors (mMTC + Edge Analytics).

The relationship between 5G and edge computing extends beyond technical enablement to encompass the economic viability of 5G itself. Deploying nationwide 5G networks requires substantial capital investment. While enhanced mobile broadband (eMBB) offers faster speeds to consumers, the revenue uplift from this alone may not fully justify the massive investment costs, especially for the advanced URLLC and mMTC capabilities. Edge computing, particularly MEC, enables a new range of high-value enterprise and industrial applications – such as private 5G networks with dedicated edge processing for factories, logistics hubs, or hospitals – that specifically leverage these advanced 5G features. These latency-sensitive, data-intensive, or mission-critical services represent significant new revenue streams for communication service providers (CSPs) and other ecosystem players. Therefore, edge computing acts as a crucial catalyst for monetizing the advanced capabilities of 5G networks, providing a stronger business case for the continued investment and build-out required. The synergy is thus reciprocal: 5G provides the connectivity foundation for the edge, while the edge unlocks the high-value applications needed to economically sustain and justify advanced 5G deployments.

V. Strategic Alignment: Saudi Vision 2030 and the Digital Future

The deployment and integration of 5G and edge computing technologies in Saudi Arabia are not occurring in a vacuum. They are intrinsically linked to and driven by the overarching national strategy, Saudi Vision 2030, which provides the framework and impetus for the Kingdom's digital transformation journey.

Vision 2030 Pillars and Digital Transformation Objectives

Saudi Vision 2030 is structured around three core pillars: creating a **Vibrant Society**, building a **Thriving Economy**, and fostering an **Ambitious Nation**. Within these pillars, numerous strategic objectives directly relate to or are significantly enabled by advancements in digital technologies like 5G and edge computing.

Under the **Thriving Economy** pillar, the key objectives relevant to 5G and edge computing include :

- **Developing the digital economy:** This is an explicit goal, recognizing technology as a primary engine for future growth.
- **Growing the contribution of the private sector:** Enabling private enterprises with advanced digital tools and infrastructure is crucial for their growth.
- **Unlocking the potential of non-oil sectors:** Vision 2030 targets diversification into sectors like manufacturing, logistics, tourism, mining, and retail, all of which can be significantly enhanced by 5G/Edge-enabled applications (e.g., IIoT, smart logistics, enhanced tourism experiences).
- **Localizing promising industries and technology:** This includes localizing manufacturing, military industries, and broader non-oil sectors, as well as localizing advanced technology and knowledge, potentially through initiatives involving the Public Investment Fund (PIF).
- **Maximizing value from the energy sector:** While diversifying away from oil dependence, the vision also aims to increase localization within the oil and gas sector and develop adjacent industries, potentially leveraging IIoT and automation. Growing the contribution of renewables is also a key objective.
- **Attracting Foreign Direct Investment (FDI) and enhancing the business environment:** Providing world-class digital infrastructure is a key factor in attracting global companies and making it easier to do business.

The **Vibrant Society** pillar includes objectives such as :

- **Improving livability in Saudi cities:** This directly links to the development of smart cities, enabled by advanced connectivity and data processing.
- **Promoting culture and entertainment:** Supporting the development of mega-projects and digital platforms for cultural and entertainment experiences.
- **Promoting a healthy lifestyle:** Leveraging technology for advanced healthcare services and accessibility.
- **Enhancing social development:** Strengthening education and healthcare systems, potentially through digital tools and platforms.

The **Ambitious Nation** pillar focuses on government effectiveness and engagement, with relevant objectives including :

- **Improving the performance of government apparatus:** Developing e-government services, improving service quality for citizens, and enhancing government efficiency.
- **Engaging effectively with citizens:** Enhancing transparency and using digital channels for communication and feedback.

These objectives are pursued through various **Vision Realization Programs (VRPs)**, such as the National Transformation Program (NTP), the Public Investment Fund (PIF) Program, the Human Capability Development Program (HCDP), the National Industrial Development and Logistics Program (NIDLP), and the Financial Sector Development Program (FSDP), among others. These programs provide the operational frameworks for implementing the strategic goals, often involving significant digital components.

National Strategies for ICT, AI, and Smart Cities (MCIT, SDAIA)

Spearheading the digital aspects of Vision 2030 are key government bodies with dedicated strategies:

- **Ministry of Communications and Information Technology (MCIT):** MCIT plays a central role in developing the Kingdom's digital infrastructure and fostering the ICT sector. Its ICT Strategy (e.g., the 2019-2023 strategy) outlines ambitious goals, including growing the ICT sector size by 50%, increasing its contribution to GDP by SAR 50 billion (approx. USD 13.3 billion), achieving 50% workforce localization in the sector, and attracting significant foreign investment. Key focus areas include building robust digital infrastructure (implying 5G, fiber, data centers), promoting emerging technologies like AI and IoT, enabling e-commerce and digital government, enhancing cybersecurity, and developing digital skills. A significant policy initiative is the "Cloud First Policy," introduced in 2019, which mandates government entities to prioritize cloud-based solutions over traditional IT infrastructure when making new investments, thereby driving cloud adoption across the public sector. MCIT also launched an \$18 billion plan in 2021 to establish a network of large-scale data centers, aiming to make KSA a regional hub.
- **Saudi Data and Artificial Intelligence Authority (SDAIA):** Established in 2019, SDAIA is the primary authority responsible for overseeing the national data and AI agenda. It launched the National Strategy for Data & AI with the goal of positioning Saudi Arabia among the global leaders in AI by 2030. AI is recognized as a major economic contributor, with projections suggesting it could add USD 135 billion to the Saudi economy by 2030, making KSA the largest beneficiary in the Middle East. Significant investments are being channeled into AI development and adoption.
- **Smart City Vision:** The development of smart cities is a prominent feature of Vision 2030, integrating technology to enhance urban living, sustainability, and economic competitiveness. The Kingdom aims to have several cities, including Riyadh, Jeddah, and Dammam, rank among the top 100 smartest cities globally by 2030. This ambition is most visibly manifested in the numerous giga-projects under development, such as NEOM, Qiddiya, The Red Sea Project, Diriyah Gate, and New Murabba, all of which are designed with smart technologies at their core. Enabling these smart cities requires a sophisticated digital foundation comprising advanced ICT infrastructure, widespread IoT deployment, AI-driven analytics and management systems, and critically, high-speed, reliable connectivity provided by technologies like 5G. The focus extends beyond technology to encompass sustainability, quality of life, and innovative urban planning models.

The successful execution of these national strategies reveals a deep level of interdependence. MCIT's efforts to build world-class digital infrastructure, including nationwide 5G networks, extensive fiber optics, and a robust data center ecosystem, form the essential foundation upon which SDAIA's AI ambitions and the nation's smart city projects rely. Advanced AI applications require vast amounts of data, powerful computing resources (often cloud-based or at the edge), and high-speed connectivity for training and inference. Similarly, sophisticated smart city functions, from autonomous transport to real-time environmental monitoring and predictive public services, are heavily dependent on seamless connectivity (5G), distributed sensing (IoT), and intelligent processing (AI and edge computing). Conversely, the demanding requirements of AI workloads and complex smart city operations provide a strong justification and business case for MCIT's continued investment in cutting-edge ICT infrastructure like 5G-Advanced, edge computing nodes, and high-capacity data centers. This intricate web of dependencies means that progress in one strategic area is inextricably linked to progress in others. Achieving the

overarching digital goals of Vision 2030 therefore necessitates exceptionally strong coordination, collaboration, and alignment between MCIT, SDAIA, the PIF, various giga-project authorities, and other relevant government and private sector entities. Any significant lag in one domain, such as infrastructure deployment or AI development, could create bottlenecks that hinder advancements across the entire digital ecosystem, highlighting inter-agency synergy as a critical success factor.

VI. Applications Landscape: 5G and Edge Computing Powering Vision 2030

The convergence of 5G and edge computing is not merely theoretical; it is actively enabling a diverse range of applications across Saudi Arabia, directly supporting the goals of Vision 2030. From futuristic smart cities to modernized industries and enhanced public services, these technologies are becoming integral to the Kingdom's transformation.

Realizing Smart Cities: NEOM and Beyond

Smart city development is a cornerstone of Vision 2030's ambition to improve urban livability, drive economic diversification by attracting talent and investment, and promote environmental sustainability. 5G and edge computing are fundamental enablers for the advanced functionalities envisioned in these future urban environments.

NEOM, the USD 500 billion futuristic region being built in northwest Saudi Arabia, serves as the flagship project embodying this vision. It aims to be a "cognitive city," going beyond traditional smart city concepts by leveraging AI, robotics, IoT, and human-machine fusion to create predictive intelligence and enable faster decision-making across all sectors. NEOM is designed to operate on 100% renewable energy and prioritizes sustainability and human well-being. Central to its operation is an advanced digital infrastructure. NEOM has contracted stc Group to establish a cutting-edge 5G network infrastructure, intended to be among the most advanced globally, supporting proactive data exchange between residents and city systems. This 5G network, coupled with extensive IoT deployments, will enable a wide array of applications, including data analytics, AR/VR, smart homes, autonomous vehicles, and the public safety network. Specific NEOM developments heavily reliant on this digital backbone include:

- **THE LINE:** A revolutionary 170km linear city designed without cars or roads, built around nature, and prioritizing walkability (all essentials within a 5-minute walk) and high-speed transit. Its operation necessitates seamless connectivity and intelligent management systems.
- **Oxagon:** A floating industrial city and logistics hub focused on advanced, sustainable manufacturing, which will host a major AI data center powered by renewable energy.
- **Trojena:** A year-round mountain tourism destination featuring unique architectural designs and experiences, requiring sophisticated connectivity and management.
- **Sindalah:** A luxury island destination in the Red Sea.

Beyond NEOM, other giga-projects and initiatives contribute to the smart city landscape, including **Qiddiya** (entertainment city), **The Red Sea Project** and **Amaala** (regenerative tourism), **New Murabba** (modern downtown Riyadh), and **Diriyah** (historical/cultural site), all incorporating smart technologies. Partnerships are forming to deliver these solutions, such as stc Group's collaboration with New Murabba Development Company and Zain KSA's partnership with AWS and Atos using the Atos Smart Destination platform. The national goal extends to upgrading existing cities like Riyadh, Jeddah, and Dammam to rank among the world's top 100 smart cities.

Specific smart city functions enabled by the low latency, high bandwidth, and massive connectivity of 5G, coupled with the local processing power of edge computing, include:

- **Intelligent Transport Systems (ITS):** Real-time traffic monitoring and management to reduce congestion, support for connected infrastructure (vehicle-to-infrastructure communication), and enabling autonomous vehicles (AVs) which require URLLC for safe operation.

- **Public Safety and Security:** High-definition video surveillance with AI-powered analytics performed at the edge for faster threat detection and response; real-time coordination of emergency services leveraging reliable communication networks.
- **Utility Management:** Smart grids for optimizing energy distribution and consumption , smart water meters and leak detection systems , and intelligent waste management optimizing collection routes. These rely heavily on mMTC for sensor connectivity and edge analytics for localized optimization.
- **Enhanced Citizen Services:** Development of digital twins for personalized services , ubiquitous high-speed connectivity in public spaces (potentially building on initiatives like the free Wi-Fi hotspot program), and improved access to e-government platforms.

The heavy emphasis on integrating cutting-edge 5G, edge, AI, and IoT technologies into greenfield giga-projects like NEOM, Qiddiya, and The Red Sea Project from their inception suggests these developments may be functioning as large-scale, controlled testbeds or "living laboratories". This approach allows the Kingdom to pilot and de-risk highly innovative technologies and complex integrated systems (like NEOM's cognitive city concept or The Line's car-free model) in a less constrained environment compared to retrofitting existing, densely populated urban centers. The lessons learned regarding technical feasibility, operational models, cost-effectiveness, scalability, and social acceptance within these giga-projects are likely to be invaluable in informing the subsequent, potentially more challenging, strategy for upgrading and transforming established cities like Riyadh and Jeddah to meet Vision 2030's smart city goals. Thus, the success or failure of specific technological implementations within these flagship projects could significantly shape the future trajectory of smart city development across the entire Kingdom.

Transforming Industries: IIoT in Energy, Manufacturing, and Logistics

The adoption of the Industrial Internet of Things (IIoT), powered by the capabilities of 5G and edge computing, is a critical enabler for achieving Vision 2030's goals related to economic diversification, enhancing productivity, localizing industries, and establishing Saudi Arabia as a global logistics hub. The combination of 5G's URLLC for real-time control, mMTC for connecting vast sensor networks, and eMBB for data throughput, along with edge computing's ability to perform local analytics and enable rapid decision-making, provides the foundation for Industry 4.0 transformations.

Key sector applications in Saudi Arabia include:

- **Energy (Oil & Gas):** As the historical backbone of the economy, the energy sector is leveraging 5G and edge for modernization and efficiency gains, aligning with the Vision 2030 objective of maximizing value from the sector. Aramco, the national oil company, is actively involved. Use cases include deploying sensors for predictive maintenance of equipment to reduce downtime , remote monitoring and control of hazardous or distant facilities , AI-driven optimization of extraction processes , pipeline integrity monitoring , and enhancing worker safety through connected devices and real-time data. A notable initiative is the collaboration between Aramco Digital and Qualcomm to develop the world's first 5G and AI-enabled industrial smartphone, specifically supporting the 450 MHz spectrum band suitable for wide-area industrial IoT and edge computing applications, directly supporting Vision 2030's industrial transformation goals.
- **Manufacturing:** Vision 2030 heavily emphasizes the development and localization of the manufacturing sector. 5G and edge are enabling the creation of hyper-connected smart factories. Applications include real-time quality control using edge-based image and audio analysis , enhanced automation with collaborative robots (cobots) communicating seamlessly via 5G , widespread predictive maintenance based on sensor data processed locally , and optimization of internal logistics and supply chains. The government's "Future Factories Program" aims to support 4,000 factories in adopting automation and advanced industrial practices by 2027, further driving demand for IIoT solutions.
- **Logistics:** Aligning with the goal of becoming a global logistics hub connecting Asia, Europe, and Africa , KSA is investing in smart logistics solutions. 5G and edge enable supply chain automation and optimization through real-time tracking and analytics , intelligent fleet management systems utilizing IoT data , and the deployment of autonomous transport systems, including drones and vehicles. Saudi Arabia has set ambitious targets for autonomous mobility, aiming for 15% of public transport and 25% of goods transport vehicles to be autonomous by 2030.

The deployment of 5G-enabled IIoT solutions across these key sectors represents more than just a technological upgrade; it serves as a fundamental mechanism for achieving the core economic diversification and localization mandates of Vision 2030. By significantly boosting productivity, operational efficiency, and automation in manufacturing and logistics, these technologies directly contribute to strengthening the competitiveness of non-oil industries and reducing economic reliance on hydrocarbons. Furthermore, initiatives like Aramco Digital's collaboration with Qualcomm on specialized 5G industrial devices signal a strategic move towards not only *using* advanced technologies but also *localizing* their development and production. This fosters a deeper, more self-sufficient technological base within the Kingdom, creating high-value jobs and intellectual property, fully aligning with the spirit and objectives of Vision 2030's industrial strategy. The success of IIoT adoption is therefore intrinsically tied to the successful economic transformation envisioned for the Kingdom.

Advancing Healthcare: Telemedicine and Remote Services

The healthcare sector is another critical area where 5G and edge computing are poised to make significant contributions, aligning with Vision 2030 objectives focused on enhancing the quality and accessibility of healthcare services, promoting preventative care and healthy lifestyles, and utilizing technology to improve public service delivery. The Health Sector Transformation Program is a key VRP guiding these efforts.

The technical characteristics of 5G, particularly its high bandwidth and ultra-low latency, combined with the local processing capabilities of edge computing, are enabling a new generation of digital health applications :

- **Telemedicine and Virtual Consultations:** 5G's ability to support high-definition video conferencing with minimal delay facilitates seamless remote consultations between patients and doctors. This is particularly beneficial for improving healthcare access for populations in remote or underserved areas. The Saudi Ministry of Health (MoH) actively promotes telemedicine , and platforms like 'Seha' and 'Mawid' provide citizens with access to virtual consultations, appointment booking, and online medical advice.
- **Remote Diagnostics:** The high throughput of 5G allows for the rapid transmission of large medical data files, such as high-resolution imaging scans (MRI, CT), enabling specialists to remotely diagnose patients accurately and efficiently. Edge computing can assist in pre-processing images or running AI-driven diagnostic algorithms locally before transmitting results, potentially speeding up the process and managing data privacy.
- **Real-Time Patient Monitoring:** 5G's reliable connectivity supports the continuous monitoring of patients' vital signs and health parameters through wearable devices and remote monitoring systems. This is particularly valuable for managing chronic diseases, post-operative care, and enabling concepts like tele-ICU platforms. Edge computing can process sensor data locally, triggering alerts in real-time if anomalies are detected.
- **Remote Surgery (Future Potential):** The ultra-low latency (URLLC) offered by 5G opens the possibility for complex remote surgical procedures performed using robotic systems controlled by surgeons located elsewhere, although this remains a more futuristic application requiring stringent reliability and security.

The Saudi government is actively driving this transformation through its national digital health strategy, which aims to improve care coordination, disease monitoring, diagnosis, and treatment delivery using technology. Significant investments have been allocated towards healthcare IT and digital transformation, estimated at around EUR 1.4 billion (USD 1.5 billion), covering EMRs, telemedicine, analytics, and AI tools. Key institutions like the MoH and leading hospitals such as King Faisal Specialist Hospital and Research Centre are instrumental in implementing these innovative solutions.

Enhancing Tourism and Entertainment: Mega-Project Connectivity

Developing the tourism and entertainment sectors is a major pillar of Vision 2030's economic diversification strategy, aiming to attract millions of visitors (both tourists and pilgrims), increase domestic spending on leisure, and create world-class destinations. Giga-projects like Qiddiya (the entertainment capital), The Red Sea Project and Amaala (luxury regenerative tourism), AlUla (heritage tourism), and Diriyah (cultural tourism) are central to this ambition. Providing seamless, high-quality connectivity and innovative digital experiences within these large-

scale developments is crucial for visitor satisfaction and operational efficiency, creating significant demand for 5G and edge computing solutions.

Key applications in this domain include:

- **Immersive Experiences (AR/VR):** 5G's high bandwidth and low latency are essential for delivering high-fidelity, interactive AR and VR experiences that can enhance tourist attractions, museum exhibits, entertainment offerings, and cultural storytelling. Edge computing can handle the intensive rendering tasks locally, ensuring smooth and responsive user experiences critical for avoiding discomfort (e.g., motion sickness).
- **Enhanced Connectivity for Crowds:** Mega-projects, theme parks, stadiums, and pilgrimage sites (like Hajj and Umrah in Mecca) attract massive crowds, placing extreme demands on network capacity. 5G's ability to handle high connection densities and deliver high throughput is vital for ensuring visitors can stay connected, share experiences, and access digital services. stc is deploying 5G solutions in Qiddiya , while Zain KSA, in collaboration with Nokia, successfully trialed and deployed a MEC platform during Hajj to provide smart navigation applications and efficiently deliver video feeds (Edge Video Orchestration) to pilgrims in crowded areas. Red Sea Global has partnered with Zain KSA to deploy the world's first zero-emission 5G network across its destination.
- **Smart Venue Operations:** Beyond visitor connectivity, 5G and edge computing enable smarter management of large venues. IoT sensors connected via 5G can provide real-time data on crowd flow, resource usage (energy, water), and environmental conditions. Edge analytics can process this data locally to optimize operations, personalize visitor services, enhance security, and improve overall efficiency.
- **Efficient Content Delivery:** Edge caching and MEC platforms can store popular content (videos, interactive guides, application data) closer to users within the venue, reducing latency and core network load when delivering high-definition media or application updates.

The scale and ambition of Saudi Arabia's giga-projects in tourism and entertainment serve as powerful catalysts for advanced network deployment. Projects like Qiddiya , The Red Sea , NEOM , and the unique demands of the Hajj pilgrimage create specific, high-profile scenarios requiring the most advanced 5G capabilities (high capacity, low latency, massive IoT support) and associated edge infrastructure (MEC). These projects arguably pull forward the deployment of cutting-edge technologies at a faster pace than might occur based solely on typical urban or industrial demand. They function not only as destinations but also as prominent showcases for the Kingdom's technological prowess under Vision 2030, demonstrating the practical application of 5G and edge in creating next-generation experiences and pushing the boundaries of network performance.

VII. Evaluating the Impact: Economic and Societal Dimensions in KSA

The large-scale deployment of 5G and edge computing, driven by Vision 2030, is anticipated to have profound economic and societal impacts within Saudi Arabia. Evaluating these dimensions is crucial for understanding the return on investment and the broader contribution to national development goals.

Economic Diversification and Growth Potential (GDP, Investment, Productivity)

A primary objective of Vision 2030 is economic diversification and sustainable growth beyond the oil sector. Digital technologies, particularly 5G and edge computing, are seen as key enablers of this transformation.

- **GDP Contribution:** Various forecasts attempt to quantify the economic impact. MCIT's ICT Strategy aimed to increase the sector's GDP contribution by SAR 50 billion (USD 13.3 billion) , with the sector already accounting for 4.1% of GDP (valued at over \$40.9 billion). AI, heavily reliant on digital infrastructure, is projected by PwC to contribute a substantial USD 135 billion to the Saudi economy by 2030. Specific forecasts for 5G's impact include a potential USD 18 billion boost to the KSA economy by 2030 (Oliver Wyman) , contributing to a projected USD 60 billion impact across the MENA region (GSMA). Market forecasts indicate significant growth trajectories: the KSA 5G infrastructure market is expected to grow from USD 137.6 million in 2024 to USD 4.8 billion by 2033 (IMARC) , the overall 5G market value from USD 2.1 billion in 2023 to USD 13.41 billion by 2029 (TechSci) , and the KSA 5G edge computing market from USD 65.9 million in 2024 to USD 777.7 million by 2030 (Grand View Research). These investments are contributing to the tangible success in diversification, with non-oil activities reaching a record 50% share of real GDP in 2023.

- **Investment Attraction:** The commitment to digital transformation has attracted significant domestic and foreign investment. Notable examples include USD 9 billion in ICT investments announced during the Leap 2023 tech conference, MCIT's USD 18 billion plan for data center development, a USD 5.3 billion commitment from Amazon Web Services (AWS) for new data centers, Microsoft's ongoing construction of a major Azure cloud region, Mobily's USD 905 million investment in data centers and subsea cables, and DataVolt's USD 5 billion investment in an AI data center in NEOM's Oxagon. The Public Investment Fund (PIF) is also a major driver, backing initiatives like a USD 100 billion AI fund. This influx of capital aligns directly with the Vision 2030 goal of attracting FDI.
- **Productivity Gains:** 5G and edge computing are expected to drive significant productivity improvements across industries by enabling automation, real-time data analytics, predictive maintenance, and operational efficiencies, particularly in sectors targeted by Vision 2030 like manufacturing, logistics, and energy (Industry 4.0). Enhanced productivity is central to the vision's goal of building a competitive, diversified economy. Globally, IoT alone is estimated to generate trillions of dollars in value by 2030, much of it through productivity enhancements.
- **Job Creation:** The digital transformation is expected to create numerous jobs. MCIT's ICT Strategy targeted the creation of over 25,000 jobs in the sector. Giga-projects like NEOM are projected to create hundreds of thousands of jobs, many in high-tech fields. The growth fueled by 5G and AI is anticipated to generate new employment opportunities across various sectors. However, it is also important to acknowledge that automation enabled by these technologies may lead to job displacement in certain traditional roles, necessitating workforce adaptation and reskilling efforts.

While the projected economic contributions from 5G, edge computing, AI, and the broader ICT sector are substantial and align with Vision 2030's goals, interpreting these figures requires careful consideration. There is a complex causal relationship and potential for overlap between the economic impact attributed to foundational enabling technologies (like 5G networks and edge infrastructure) and the growth generated within the specific sectors and applications that utilize them (such as AI services, smart manufacturing, or digital healthcare). For instance, the projected \$135 billion contribution from AI is inherently dependent on the underlying digital infrastructure, including 5G and cloud/edge computing. Similarly, the \$18 billion boost attributed to 5G likely incorporates the economic activity it enables in other sectors. Disentangling the precise, non-overlapping economic multiplier effect of investments in foundational infrastructure versus the applications built upon it is a complex task. While the overall positive economic trajectory driven by digital transformation under Vision 2030 is evident, achieving accurate attribution of value across different technological layers remains a challenge and an important area for future economic analysis to inform policy evaluation and optimize investment strategies.

Societal Advancement: Quality of Life and Digital Inclusion

Beyond economic metrics, the deployment of 5G and edge computing aims to contribute significantly to the 'Vibrant Society' pillar of Vision 2030, enhancing the quality of life for citizens and residents and promoting digital inclusion.

- **Quality of Life Improvements:** Several applications directly impact daily life and well-being:
 - **Smart Cities:** Promise more efficient urban mobility through intelligent traffic management, enhanced public safety via real-time monitoring and response, improved environmental conditions through smart utility management (energy, water, waste), and more responsive public services.
 - **Healthcare:** Telemedicine improves access to medical expertise, particularly for remote populations, while remote monitoring enhances preventative care and management of chronic conditions, potentially leading to better health outcomes.
 - **Education:** Digital tools enabled by robust connectivity, such as AR/VR applications, online learning platforms, and personalized educational content, can create more engaging and effective learning experiences, fostering digital literacy from an early age.
 - **Entertainment and Culture:** Increased access to diverse, high-quality digital entertainment and immersive cultural experiences contributes to leisure and well-being.
- **Digital Inclusion:** Saudi Arabia has explicitly stated its commitment to ensuring that the benefits of digital transformation are accessible to all segments of society. This includes promoting equal access to digital services, education, and job opportunities, with a particular focus on empowering potentially vulnerable groups such as women, the elderly, people with disabilities, low-income families, and residents of remote

areas. Key initiatives include efforts to eradicate digital illiteracy through training programs and building essential technical skills across the population. Expanding high-quality connectivity infrastructure, including 5G and fiber, to cover all regions, including remote areas, is recognized as crucial for bridging the digital divide between urban and rural populations. The government is also considering web accessibility standards (like WCAG) to ensure digital platforms are usable by people with disabilities.

- **Citizen Empowerment:** Digitalization enhances the relationship between citizens and the state. E-government platforms like Absher and Tawakkalna provide convenient access to a wide range of public services, streamlining processes and improving efficiency. Digital channels can also foster greater transparency and enable e-participation, allowing citizens to provide feedback on policies and engage more directly in governance. Research suggests MEC could further enhance the usability and adoption of mobile government (M-Government) services.

However, despite the strong focus on digital inclusion and efforts to expand basic broadband connectivity to rural areas, the rapid advancement and deployment of sophisticated technologies like 5G and edge computing present a potential challenge to equitable access. Current advanced 5G coverage is significantly higher in major cities like Riyadh compared to the national average. Furthermore, fully leveraging the transformative potential of many advanced applications enabled by this infrastructure—such as complex AI-driven services, AR/VR experiences, or sophisticated data analytics tools—requires not just connectivity but also a relatively high level of digital literacy and specific technical skills. Groups often targeted for inclusion initiatives, such as the elderly or those in remote regions, may face greater hurdles in acquiring these advanced skills or accessing the necessary high-end infrastructure (beyond basic connectivity). Consequently, there is a risk that the most significant benefits of Vision 2030's digital transformation could disproportionately accrue to the already digitally savvy and well-connected urban populations. While access to *basic* digital services might improve broadly, ensuring equitable access to the truly *transformative* capabilities enabled by 5G and edge requires sustained and targeted efforts in both advanced infrastructure deployment beyond major hubs *and* comprehensive digital skills development programs that reach all segments of society. Without such proactive measures, the digital drive could inadvertently exacerbate existing socio-economic disparities, potentially running counter to the inclusive aspirations of Vision 2030.

VIII. Implementation Status: 5G and Edge Infrastructure in Saudi Arabia

Saudi Arabia has moved rapidly to deploy 5G networks and is actively building the ecosystem for edge computing, driven by Vision 2030 and supported by significant investment and government initiatives.

5G Network Deployment: Coverage, Spectrum, and Operators

The Kingdom stands out as a regional leader in 5G adoption:

- **Early Deployment:** KSA was among the first countries in the Middle East and North Africa (MENA) region to launch commercial 5G services. All three major mobile network operators (MNOs)—stc (Saudi Telecom Company), Mobily (Etihad Etisalat), and Zain KSA—initiated rollouts in 2019 or early 2020, following the issuance of trial licenses in 2018 and spectrum auctions.
- **Coverage Expansion:** Significant progress has been made in network coverage. Reports indicate national 5G coverage reaching 53% and later figures suggesting 77%, both substantially higher than the global average. The capital, Riyadh, boasts particularly high coverage, exceeding 94%. 5G penetration (as a share of connections) was estimated at 17% by the end of 2022, far exceeding the MENA average, and is projected to account for half of all mobile connections in the region by 2030.
- **Spectrum Allocation:** The Communications, Space and Technology Commission (CST), formerly CITC, has played a proactive role in making spectrum available for 5G. Key allocations include the prime mid-band (C-Band) frequencies between 3.4 GHz and 3.8 GHz, where each of the three MNOs was allocated a contiguous 100 MHz block following an auction in March 2019. This band is considered foundational for initial 5G services. Operators also utilize other bands like 2.6 GHz, and the regulator has indicated plans for utilizing existing LTE bands and future mmWave spectrum (above 24 GHz). CST's National Spectrum Strategy 2025 aims to allocate over 23 GHz of spectrum across various applications by 2025, including IMT (for 5G/6G), Wi-Fi, Fixed Wireless Access (FWA), and satellite services. Notably, KSA was the first country in the EMEA region to allocate the full 1200 MHz in the 6 GHz band for Wi-Fi 6E, demonstrating a commitment to enabling high-capacity wireless connectivity.
- **Network Performance:** Saudi Arabia consistently ranks highly in regional and global comparisons for

5G speeds and performance. The average mobile internet speed in the Kingdom has reportedly doubled to 181 Mbps, significantly exceeding the global average, reflecting the impact of digital infrastructure investments. The speed uplift experienced when moving from 4G to 5G has been substantial, measured at approximately 7.3 times.

- **Operator Activities:** MNOs continue to invest in expanding and enhancing their 5G networks. For example, stc announced plans to expand its 5G services to cover 75 cities and regions, upgrading its core network with 400G routing technology from Juniper Networks. Zain KSA has conducted trials of advanced technologies like Cloud RAN with Nokia, achieving high download speeds and preparing for future network evolutions like AI-RAN and Open RAN.

Edge Computing Ecosystem: MEC Rollout and Data Center Growth

Parallel to 5G network deployment, the ecosystem for edge computing, including MEC and supporting data center infrastructure, is rapidly developing in Saudi Arabia.

- **MEC Deployment by Operators:** MNOs are actively exploring and deploying MEC capabilities, often in partnership with technology vendors and targeting specific use cases:
 - **stc:** Is deploying the advanced 5G and IoT network for NEOM, which inherently requires edge capabilities to support the project's cognitive city ambitions. Through its stc.AI arm, it has launched a sovereign Large Language Model (LLM) cloud platform, leveraging edge concepts for secure, localized AI processing. Its core network and data center expansions are explicitly aimed at supporting 5G and edge services.
 - **Mobily:** Is involved in research exploring the use of MEC to enhance M-Government services. More tangibly, Mobily is making substantial investments (over USD 533 million) in building out its data center capacity (planning 39 MW total), specifically citing the need to support demanding AI, GPU, and edge applications. It is also collaborating with Ericsson on network automation and Open RAN technologies relevant to edge environments.
 - **Zain KSA:** Has demonstrated early MEC adoption through its partnership with Nokia to deploy a MEC platform during the Hajj pilgrimage, enabling smart navigation and efficient video delivery in a high-density environment. It is also partnering with cloud providers (AWS) and system integrators (Atos) to deliver smart city solutions that likely leverage edge computing. Furthermore, Zain KSA is collaborating with Nokia on developing local talent in cloud and edge computing domains and has trialed Cloud RAN technology.
- **Data Center Infrastructure Growth:** The foundation for both cloud and edge computing is robust data center infrastructure, an area experiencing massive investment and growth in KSA. This is driven by the government's Cloud First Policy, the surge in demand for cloud services, the computational needs of AI and large-scale data analytics, and the data generated by expanding IoT deployments.
 - **Major Investments and Projects:** As previously noted, MCIT has an \$18 billion plan for data centers. Global hyperscalers are establishing significant presence: AWS is investing \$5.3 billion, and Microsoft is constructing a large Azure region with three availability zones, expected to be operational in 2026. Local players are also expanding aggressively, exemplified by Mobily's \$533M+ investment program and DataVolt's \$5bn plan for an AI-focused data center in NEOM's Oxagon.
 - **Strategic Advantages:** KSA offers several advantages for data center development, including relatively low costs for land and power (with access to increasingly cheap renewable energy), its strategic geographic location facilitating connectivity via numerous submarine cable systems, strong access to capital through sovereign wealth funds like PIF, and supportive government policies, including tax benefits within initiatives like the Cloud Computing Special Economic Zone (CCSEZ).

Investment Climate and Government Support

The rapid progress in 5G and edge infrastructure deployment is underpinned by a favorable investment climate strongly supported by government policy aligned with Vision 2030.

- **Vision 2030 as Primary Driver:** The national transformation plan serves as the overarching strategic driver, signaling long-term commitment and creating demand for digital infrastructure.

- **Government Initiatives:** Multiple government actions create a supportive ecosystem: MCIT's strategies and direct investment plans ; CST's proactive spectrum management and enabling regulatory frameworks (e.g., for IoT, cloud, spectrum trading) ; SDAIA's national AI strategy creating demand for compute power ; the mandatory Cloud First Policy driving public sector adoption ; the establishment of special economic zones offering incentives ; and substantial direct and indirect investment channeled through the PIF.
- **Investment Momentum:** The significant investment figures cited earlier (e.g., \$24.8 billion in digital infrastructure over six years , multi-billion dollar commitments from hyperscalers and operators) and strong market growth projections reflect high investor confidence in the Saudi digital market.

Examining the nature of early, sophisticated 5G edge and MEC deployments in Saudi Arabia reveals a pattern potentially influenced by the top-down, strategy-led approach of Vision 2030. Many of the prominent examples cited involve government-driven initiatives or state-linked entities: stc's deployment for the NEOM giga-project , Zain's MEC trial for the government-managed Hajj pilgrimage , Mobily's research focusing on M-Government services , and Aramco's specialized industrial device development. Similarly, the rapid growth in data center capacity is significantly spurred by government policies like the Cloud First directive and large contracts potentially tied to serving government agencies or giga-projects hosted by hyperscalers like AWS and Microsoft. While private MEC deployments are noted as scaling globally , documented examples of broad adoption by private sector enterprises (especially SMEs) within KSA seem less prevalent in the reviewed materials compared to these large, public-sector-linked projects. This suggests that initial demand and funding for the most advanced edge infrastructure are heavily catalyzed by public sector requirements. While this approach effectively kickstarts infrastructure build-out and aligns with national strategic goals, a crucial next step for maximizing the economic diversification impact of Vision 2030 will be to stimulate wider adoption and innovation on these platforms by the broader private sector, moving beyond the initial anchor projects and government use cases.

IX. Navigating the Hurdles: Challenges to Large-Scale Adoption

Despite the rapid progress and strong government backing, the large-scale adoption of 5G and edge computing in Saudi Arabia faces several significant challenges that require careful management and strategic mitigation.

Cybersecurity Threats and Data Privacy Concerns (NCA, PDPL)

The very nature of 5G and edge computing architectures introduces new and expanded cybersecurity risks. The shift towards software-defined networking (SDN), network function virtualization (NFV), network slicing, massive IoT deployments, and distributed edge nodes significantly increases the potential attack surface compared to centralized, hardware-centric 4G networks. Specific threats include the potential for physical tampering with geographically dispersed edge devices, cyberattacks targeting edge nodes, security vulnerabilities within the vast number of connected IoT devices (many potentially lacking robust security), risks associated with network slicing (e.g., cross-slice attacks impacting resource isolation), and vulnerabilities at the physical layer of communication.

Saudi Arabia recognizes cybersecurity as a critical national priority, essential for protecting vital interests, national security, critical infrastructure, and the digital economy underpinning Vision 2030. The Kingdom's significant reliance on foreign technology and expertise for cutting-edge capabilities can also introduce supply chain risks and dependencies. Cyber threats remain a major challenge for the nation.

To address these risks, KSA has established a comprehensive regulatory framework:

- **Cybersecurity Governance:** The **National Cybersecurity Authority (NCA)**, established to be the central authority, spearheads the national cybersecurity strategy. Key legislation includes the **Anti-Cybercrime Law** and the **Cybersecurity Law**. The NCA has issued mandatory controls, including the **Essential Cybersecurity Controls (ECC)**, which set minimum requirements for organizations and were updated in 2024 (ECC-2:2024) to align with international best practices, and the **Cloud Cybersecurity Controls (CCC)**. The NCA enforces compliance through audits and assessments, promotes awareness campaigns, and fosters public-private partnerships to share threat intelligence.
- **Data Privacy Regulation:** The **Personal Data Protection Law (PDPL)**, developed by SDAIA and coming into full effect after a grace period ending in September 2024, governs the collection, processing,

storage, and transfer of personal data. It aims to align KSA with global data protection standards like GDPR, granting individuals rights over their data and imposing significant obligations on organizations (controllers and processors) regarding data privacy and security, with substantial penalties for non-compliance.

Despite this robust framework, challenges persist in keeping regulations and defenses current with the rapidly evolving cyber threat landscape, ensuring consistent compliance across diverse public and private sector organizations, and fostering a strong cybersecurity culture nationwide. Balancing stringent security requirements with the need for innovation and operational flexibility in dynamic 5G/edge environments also remains a key consideration.

Regulatory Frameworks and Data Governance (CITC/CST)

Beyond cybersecurity and privacy, other regulatory aspects influence 5G and edge deployment:

- **Data Localization:** KSA enforces data localization requirements through multiple regulations. The PDPL includes restrictions on transferring personal data outside the Kingdom. More stringently, the CST's Cloud Computing Services Provisioning Regulations (CCSPRs) explicitly prohibit the transfer of any data belonging to Saudi public sector entities outside the country, even temporarily (e.g., for caching), and require CST and customer consent for transferring other types of data hosted by registered Cloud Service Providers (CSPs). Government data hosted in Government Cloud or Commercial Governmental Cloud environments must reside geographically within KSA. Sector-specific regulations, such as those for insurance, tax, and labor records, also impose data residency or retention requirements. These rules, while aimed at enhancing data sovereignty and security, can pose challenges for organizations utilizing global cloud platforms or requiring cross-border data flows for their operations.
- **IoT and Emerging Tech Regulation:** The CST (formerly CITC) established an IoT Regulatory Framework in 2019, addressing key areas like spectrum usage, IoT device technical specifications (radio, EMC, safety compliance), and numbering/identifiers. The regulator continues to monitor global developments and aims to enhance policies to foster emerging technologies as part of the national ICT strategy. However, the rapid pace of technological change requires ongoing regulatory agility.
- **Spectrum Policy:** While CST's proactive spectrum allocation for 5G has been lauded as a key success factor, ensuring continued availability of sufficient spectrum, particularly in bands needed for 5G-Advanced and future 6G networks, requires a clear and updated long-term roadmap beyond the current 2025 strategy. Ongoing initiatives include developing regulations for spectrum trading and evolving policies for fixed wireless access and backhaul.
- **Infrastructure Sharing:** Regulatory support for passive and active infrastructure sharing aims to reduce deployment costs and accelerate rollouts.

The primary regulatory challenges involve striking a balance between control (security, privacy, sovereignty) and enablement (innovation, flexibility, global integration), ensuring regulations remain fit-for-purpose amidst rapid technological evolution, and coordinating effectively across multiple regulatory bodies (CST, NCA, SDAIA) with overlapping interests in the digital domain.

Infrastructure Investment and Deployment Complexities

Deploying nationwide 5G networks and the associated edge infrastructure (MEC nodes, distributed data centers, fiber backhaul) is inherently complex and costly.

- **Investment Costs:** Significant capital expenditure (CAPEX) is required from operators and infrastructure providers. While KSA benefits from strong government backing and access to capital, ensuring sustainable funding models and efficient resource allocation remains important.
- **Deployment Challenges:** Technical complexities arise in managing distributed edge resources, which often involves heterogeneous devices operating under dynamic conditions with varying reliability. Ensuring consistent Quality of Service (QoS) can be difficult in edge environments that may have constrained computing or power resources. Optimizing task scheduling and resource allocation in MEC systems, especially considering the trade-off between the delay introduced by complex management algorithms (inference delay) and the resulting task processing delay, is an ongoing research and operational challenge. Furthermore, robust and high-capacity backhaul and midhaul connectivity, often requiring

extensive fiber optic networks, is essential to connect edge nodes back to the core network and other resources.

Bridging the Digital Skills Gap

Perhaps one of the most critical challenges is ensuring the availability of a skilled workforce capable of deploying, managing, securing, and innovating with these advanced technologies.

- **The Critical Need:** Vision 2030's goal of transitioning to a diversified, knowledge-based economy hinges on having citizens equipped with future-ready digital skills. Expertise in areas like 5G network management, edge computing architecture, cloud platforms, AI and machine learning, IoT development, and cybersecurity is essential.
- **The Existing Gap:** Like many countries, Saudi Arabia faces a digital skills gap. Globally, critical shortages exist in areas like cybersecurity, cloud computing, and software development. Many business leaders report being under-resourced in AI talent, viewing the lack of skilled personnel as a primary barrier to AI implementation. While Saudi Arabia ranked well in digital skills in a 2020 WEF report, the demand for highly specialized skills associated with 5G, edge, and AI is rapidly increasing, requiring continuous upskilling and reskilling efforts.
- **KSA's Mitigation Efforts:** Recognizing this challenge, KSA has launched several initiatives under Vision 2030:
 - The **Human Capability Development Program (HCDP)** focuses broadly on equipping citizens with skills for the evolving labor market through education, training, and lifelong learning.
 - **MCIT** runs programs like "Fuel," which aimed to train 100,000 citizens in digital skills, and has partnered with companies like Microsoft to establish Centers of Excellence for AI and cloud skills training. MCIT also targets 50% localization of the ICT workforce.
 - The **Digital Sector Skills Council** was established to work with government, industry, and education providers to define required skills, develop standards and career pathways, align training programs with market needs, and ultimately bridge skills gaps. It has produced resources like a Sector Skills Framework and a Digital Skills Dictionary.
 - The **Education Sector** receives significant government funding, with reforms focused on updating curricula to emphasize critical thinking, practical skills, and digital literacy. The ambition includes having Saudi universities rank among the world's best.
- **Ongoing Challenges:** Despite these efforts, challenges remain in ensuring training programs keep pace with the rapid evolution of technology, precisely matching skills development to the specific needs of industry, attracting and retaining top digital talent in a competitive global market, and ensuring equitable access to high-quality training opportunities across all regions and demographics.

The digital skills gap represents more than just a human resource challenge; it poses a potential systemic bottleneck to the successful realization of Vision 2030's digital ambitions. The Kingdom is making massive investments in building state-of-the-art digital infrastructure—5G networks, edge computing facilities, cloud data centers, AI platforms. Simultaneously, it has set highly ambitious goals for leveraging this infrastructure through advanced applications in smart cities, IIoT, digital government, and other sectors. However, this sophisticated infrastructure requires a correspondingly skilled workforce to operate, maintain, secure, and, crucially, innovate upon it. Without sufficient local talent possessing the necessary expertise in network engineering, cloud architecture, data science, AI development, cybersecurity, and edge application development, the Kingdom may struggle to fully utilize the deployed infrastructure effectively. This could limit the return on investment from the substantial capital expenditures and hinder the achievement of the desired economic diversification, productivity gains, and societal benefits outlined in Vision 2030. Therefore, the success of national skills development initiatives, such as the HCDP and the work of the Digital Sector Skills Council, is not merely complementary but fundamentally critical to translating infrastructure investments into tangible, long-term economic and social value.

The following tables summarize the key players involved in the KSA 5G and edge ecosystem and the main challenges alongside potential mitigation strategies.

Category	Key Players	Key Roles & Activities (Based on Snippets)
----------	-------------	--

Regulators & Policy	CST (formerly CITC), NCA, SDAIA, MCIT, RDIA	Spectrum allocation & management, IoT/Cloud regulation , Cybersecurity framework & enforcement , Data protection (PDPL) , National ICT & AI strategies , RDI strategy
Mobile Network Operators	stc, Mobily, Zain KSA	5G network deployment & expansion , MEC platform deployment & trials , Data center investment , Partnerships for smart cities/IIoT
Infrastructure Vendors	Nokia, Ericsson, Huawei, Juniper Networks	Supplying 5G RAN & Core network equipment, MEC platforms, Cloud RAN solutions
Cloud & Data Center Providers	AWS, Microsoft Azure, Google Cloud, Mobily, DataVolt, other local providers	Building/operating large-scale data centers & cloud regions , Providing cloud & edge computing services, Partnering with MNOs & enterprises
Key Enterprise Users/Partners	Aramco, NEOM, Qiddiya, Red Sea Global, Various Ministries (Health, Education)	Driving demand for advanced applications (IIoT, Smart Cities, Digital Health) , Forming strategic partnerships for technology deployment
System Integrators	Atos, others	Integrating technologies for specific solutions, e.g., Smart Cities
Investment & Funding	Public Investment Fund (PIF), Private Equity, Government Budgets	Providing capital for infrastructure projects, RDI initiatives, and strategic investments

Table 2 : Key Players in KSA 5G and Edge Ecosystem

Challenge	Potential Mitigation Strategies (Based on Snippets)
Cybersecurity Threats	Robust legal framework (Anti-Cybercrime Law, Cybersecurity Law) , NCA oversight & enforcement , Mandatory controls (ECC, CCC) , Public-private threat intelligence sharing , Awareness campaigns , Focus on physical layer security research , Adoption of strong encryption & zero-trust principles
Data Privacy & Localization	PDPL implementation providing clear rules & rights , SDAIA oversight , CST Cloud regulations defining rules for government data , Consent mechanisms for data transfer , Development of secure sovereign cloud/edge capabilities
Regulatory Agility & Coordination	CST's proactive spectrum strategy & ongoing policy development (IoT, fixed links, trading) , Use of public consultations & international benchmarking , Clear mandates for key authorities (CST, NCA, SDAIA), Vision 2030 framework providing overarching alignment
Infrastructure Cost & Complexity	Government investment & PIF support , Attracting foreign investment (Hyperscalers, PE) , Regulatory support for infrastructure sharing , Leveraging KSA's cost advantages (land, power) , Phased deployment approach (e.g., giga-projects as testbeds), Use of efficient technologies (e.g., Cloud RAN, advanced routing)
Digital Skills Gap	National strategies (HCDP) , MCIT training programs ("Fuel", Centers of Excellence) , Digital Sector Skills Council for alignment & standards , Education sector reforms & investment , Attracting foreign talent , Industry partnerships for training (e.g., Zain/Nokia) , Focus on localizing workforce

Table 3 : Summary of Challenges and Potential Mitigation Strategies for 5G/Edge Adoption in KSA

X. The Path Forward: Future Directions for 5G and Edge in KSA

As Saudi Arabia progresses through the implementation phases of Vision 2030, the strategic direction for 5G, edge computing, and related digital technologies continues to evolve, focusing on deeper integration, next-generation capabilities, and solidifying the Kingdom's position as a global technology hub.

Evolving National Strategies and RDI Priorities

Vision 2030 is a dynamic plan, designed to unfold in stages. Having established foundational reforms in the first phase, the second phase (roughly 2021-2025 and beyond) emphasizes accelerating growth in promising sectors, enhancing implementation effectiveness, deepening private sector engagement, and making further strategic investments.

Within this framework, there is a clear intensification of focus on "**Deep Tech**"—advanced technologies often based on scientific discovery or engineering innovation, such as AI, IoT, robotics, blockchain, quantum computing, and advanced materials. A report launched by MCIT and King Abdullah University of Science and Technology (KAUST) highlights the growth of the deep tech ecosystem in KSA, particularly in AI and IoT, and outlines a roadmap focusing on investment, infrastructure, talent, and supportive policies to position the Kingdom as a global hub.

This aligns with the national priorities set by the **Research, Development, and Innovation Authority (RDIA)**. The "**Economies of the Future**" RDI national priority specifically targets areas where 5G and edge are crucial enablers, including:

- **Cognitive Cities:** Moving beyond smart cities to environments that use predictive analytics and AI to tailor urban experiences.
- **Future of Connectivity:** Explicitly targeting the development of sustainable 6G technologies by 2035 and exploring technologies like Open RAN.
- **Advanced Computing:** Including research into Artificial General Intelligence (AGI) and quantum computing.
- **Frontier Technologies:** Such as space architecture (targeting habitats on the Moon and Mars) and deep-sea exploration, which require highly advanced communication and autonomous systems.

The commitment to continued digitalization remains strong across government services (e-government) , industrial modernization (smart factories, smart grids) , and the adoption of emerging technologies like generative AI and blockchain.

Transitioning to 5G-Advanced and Preparing for 6G

The evolution of mobile network technology does not stop at the initial 5G deployments. Saudi Arabia is actively engaged in the transition towards more advanced capabilities:

- **5G Evolution (5G-SA and 5G-Advanced):** The move from 5G Non-Standalone (NSA), which relies on the 4G core, to **5G Standalone (SA)**, which uses a dedicated 5G Core network, unlocks the full potential of 5G, particularly low latency and network slicing. Several operators in the MENA region, including potentially in KSA, have already deployed 5G SA networks. The next major step is **5G-Advanced**, based on 3GPP Release 18 and subsequent releases. 5G-Advanced promises significant enhancements in network performance (capacity, mobility), sustainability (energy efficiency), and intelligence through deeper integration of AI and machine learning into the RAN and Core. It will further refine capabilities for demanding use cases like Extended Reality (XR), industrial automation (supporting time-sensitive communication), low-power IoT devices (Reduced Capability or RedCap), enhanced network slicing, and high-precision positioning. Operator trials in KSA, such as Zain KSA's Cloud RAN deployment with Nokia, are explicitly positioned as steps towards enabling future AI-RAN, Open RAN (a Vision 2030 priority) , and potential 6G innovations.
- **Preparing for 6G:** Even as 5G-Advanced is being defined, strategic planning for the **Sixth Generation (6G)** of wireless technology (expected commercially around 2030) is already underway in Saudi Arabia. 6G is envisioned to deliver capabilities far exceeding 5G, potentially including Terabit-per-second data rates, sub-millisecond latency, integrated communication and sensing capabilities, native AI/ML integration throughout the network architecture, and seamless unification of terrestrial, satellite (Non-Terrestrial Networks - NTN), and potentially other communication domains. Accessing new spectrum bands, such as the upper 6 GHz band identified at WRC-23 and potentially Terahertz (THz) frequencies , will be critical. KSA's inclusion of **sustainable 6G development by 2035** as a national RDI mission and the emergence of academic roadmaps exploring 6G deployment in the Kingdom signify this forward-looking approach.

This proactive stance on future network generations, particularly 6G, is noteworthy. By incorporating 6G into national RDI strategies and setting long-term development goals well before the technology's standardization (~post-2025) and commercialization (~2030), Saudi Arabia signals an ambition that extends beyond simply adopting the next wave of technology. This early strategic focus, coupled with investments in RDI and talent development, suggests a desire to potentially contribute to and shape the development of 6G standards and technologies, rather than merely being a consumer. Such an approach aligns perfectly with Vision 2030's overarching goal of transforming the Kingdom into a global leader in innovation and a diversified, knowledge-based economy, positioning it favorably to capitalize on the opportunities presented by the next era of wireless communication.

XI. Conclusion

The convergence of 5G and edge computing represents a potent technological force with the capacity to significantly accelerate Saudi Arabia's ambitious transformation journey outlined in Vision 2030. The high throughput, ultra-low latency, and massive connectivity offered by 5G, combined with the localized processing power and responsiveness of edge computing, create a synergistic foundation for a new generation of digital applications. This analysis has demonstrated how this synergy is being strategically harnessed within the Kingdom to drive progress across multiple fronts aligned with Vision 2030's core pillars.

From enabling the futuristic visions of cognitive cities like NEOM and enhancing the operational efficiency of existing urban centers, to revolutionizing key industrial sectors such as energy, manufacturing, and logistics through IIoT, and advancing the accessibility and quality of healthcare and education via digital platforms, the applications of 5G and edge computing are diverse and impactful. Furthermore, these technologies are crucial for realizing the Kingdom's goals in developing world-class tourism and entertainment destinations capable of offering seamless connectivity and immersive experiences.

The economic implications are substantial, with significant projected contributions to GDP growth, driven by the ICT sector itself and the productivity gains unlocked across the wider economy. The commitment to digital transformation has successfully attracted considerable domestic and international investment in digital infrastructure, particularly in 5G networks and data centers, positioning KSA as a major regional hub. Societally, these technologies hold the promise of enhancing the quality of life through smarter services, improved healthcare, and enriched educational opportunities, while national initiatives actively promote digital inclusion to ensure broad access to these benefits.

Saudi Arabia's rapid progress in deploying 5G infrastructure and fostering an edge computing ecosystem is evident, propelled by strong government commitment, proactive regulatory measures by bodies like CST and NCA, substantial investments from the public (PIF) and private sectors (MNOs, hyperscalers), and strategic partnerships. The initial adoption patterns, heavily influenced by public sector demand and mega-projects, reflect the top-down, strategy-led nature of Vision 2030's implementation.

However, realizing the full potential of 5G and edge computing requires navigating significant challenges. The expanded attack surface necessitates continuous vigilance and evolution in cybersecurity strategies and robust enforcement of regulations like the ECC and PDPL. Balancing data localization requirements with the needs of a globalized digital economy requires careful policy calibration. The inherent cost and complexity of deploying and managing distributed edge infrastructure demand efficient resource allocation and technological innovation. Most critically, the digital skills gap presents a potential bottleneck; bridging this gap through sustained investment in education, training, and talent development via programs like HCDP and the Digital Sector Skills Council is paramount to effectively utilize the deployed infrastructure and drive innovation.

Looking forward, Saudi Arabia's path involves deepening its commitment to digital transformation, moving towards 5G-Advanced and strategically positioning itself for the 6G era. The national focus on RDI, particularly in "Economies of the Future" and deep tech, underscores the ambition to transition from a technology adopter to a potential technology leader and innovator.

In conclusion, 5G and edge computing are indispensable tools in Saudi Arabia's pursuit of Vision 2030. The Kingdom has laid a strong foundation through strategic planning, significant investment, and rapid infrastructure deployment. Continued success will depend on effectively mitigating the associated challenges, particularly in cybersecurity and workforce development, fostering broader private sector adoption beyond initial anchor projects, and maintaining a forward-looking approach to technological evolution. If these hurdles are successfully navigated, 5G and edge computing will undoubtedly play a pivotal role in transforming Saudi Arabia into the diversified, innovative, and globally competitive nation envisioned by its leadership. Future research should focus on quantitatively disentangling the specific economic impacts of infrastructure versus applications, conducting longitudinal studies on the effectiveness of digital skills initiatives in meeting industry demands, and undertaking comparative analyses of the outcomes and scalability of technologies piloted within the Kingdom's various mega-projects.

REFERENCES

1. motive.com, <https://motive.com/glossary/what-is-5g#:~:text=5G%20is%20the%20fifth%20cities%2C%20and%20industrial%20automation.>
2. What is 5G | Everything You Need to Know About 5G | 5G FAQ - Qualcomm, <https://www.qualcomm.com/5g/what-is-5g>
3. Edge computing - Wikipedia, https://en.wikipedia.org/wiki/Edge_computing
4. 5G and Edge Computing: Empowering the Future of IT - ZNetLive, <https://www.znetlive.com/blog/5g-and-edge-computing-empowering-the-future-of-it/>
5. 3GPP 5G Core Network: An Overview and Future Directions - Journal of Information and Communication Convergence Engineering, <https://www.jicce.org/journal/view.html?pn=myread&uid=2&vmd=Full>
6. Vision 2030 | GOV.SA, <https://my.gov.sa/en/content/saudivision>
7. Overview, <https://www.vision2030.gov.sa/en/overview>
8. Saudi Vision 2030: Saudi Arabia's Transformation Program Explained - Centuro Global, <https://www.centuroglobal.com/article/saudi-arabia-vision-2030/>
9. A STORY OF TRANSFORMATION, https://www.vision2030.gov.sa/media/qnxn3igg/vision-2030_story-of-transformation.pdf
10. THE KINGDOM OF SAUDI ARABIA'S VISION 2030 AND ITS EFFORTS TO BUILD A DIVERSIFIED ECONOMY, <https://www.middlebury.edu/institute/sites/default/files/2023-07/WP-%20Saudi%20Arabia%27s%20Vision%202030-%20Derendinger%20%26%20Frank%20.pdf>
11. Saudi Arabia - Digital Economy - International Trade Administration, <https://www.trade.gov/country-commercial-guides/saudi-arabia-digital-economy>
12. Saudi Arabia Technology Transformation Driven by the Government - 7startup, <https://www.7startup.vc/post/saudi-arabia-technology-government/>
13. Saudi Arabia - Information and Communications Technology, <https://www.trade.gov/country-commercial-guides/saudi-arabia-information-and-communications-technology>
14. Vision 2030 and the Digital Governance Revolution in Saudi Arabia, <https://thegulfentrepreneur.com/vision-2030-and-the-digital-governance/>
15. Vision 2030, https://www.vision2030.gov.sa/media/xi2jlj0y/english_vision2030_annual_report_2023.pdf
16. The Digital Transformation of Saudi Arabia from Spectrum Management Perspective, <https://accesspartnership.com/the-digital-transformation-of-saudi-arabia-from-spectrum-management-perspective/>
17. Vision 2030 in Saudi Arabia: A Shift to Digital Governance - Azeus Convene, <https://www.azeusconvene.com/articles/vision-2030-and-digital-governance-in-saudi-arabia>
18. Digital Inclusion | GOV.SA, <https://my.gov.sa/en/content/digital-inclusion>
19. Saudi Arabia 5G Edge Computing Market Size & Outlook, 2030 - Grand View Research, <https://www.grandviewresearch.com/horizon/outlook/5g-edge-computing-market/saudi-arabia>
20. Spectrum and Network Evolution in MENA: Insights from GCC Markets | Opensignal, <https://www.opensignal.com/2024/11/14/spectrum-and-network-evolution-in-mena-insights-from-gcc-markets>
21. The ITU Vision and Framework for 6G: Scenarios, Capabilities and Enablers - arXiv, <https://arxiv.org/html/2305.13887v5>
22. What is 5G? - 5G Network Explained - AWS, <https://aws.amazon.com/what-is/5g/>
23. What is 5G? How will it transform our world? - Ericsson, <https://www.ericsson.com/en/5g>
24. Technical Report - ITU, https://www.itu.int/dms_pub/itu-t/opb/tut/T-TUT-HOME-2018-PDF-E.pdf
25. Advanced MEC Task Offloading and Resource Management in 5G Networks - arXiv, <https://arxiv.org/html/2501.06242v1>
26. 6G Technology - C4IR Saudi Arabia, <https://www.c4irsaudiarabia.org/docs/6G%20Technology.pdf>
27. Effects of Transport Network Slicing on 5G Applications - MDPI, <https://www.mdpi.com/1999-5903/13/3/69>
28. Edge Computing and 5G Networks: Enabling the Future of Connectivity - ijsret, https://ijsret.com/wp-content/uploads/2025/03/IJSRET_V11_issue2_381.pdf
29. Comprehensive Analysis of Network Slicing for the Developing Commercial Needs and Networking Challenges - PMC, <https://pmc.ncbi.nlm.nih.gov/articles/PMC9459685/>
30. Moving Beyond Cloud Computing to Edge Computing - CableLabs, <https://www.cablelabs.com/blog/moving-beyond-cloud-computing-to-edge-computing>
31. Edge computing architecture and use cases, <https://lfdge.org/edge-computing-architecture-and-use-cases/>
32. Edge Computing - 3GPP, <https://www.3gpp.org/technologies/edge-computing>
33. Go 100 Times Faster with 5G and Edge Computing - Simply NUC, <https://simplynuc.com/blog/5g-and-edge-computing/>
34. Edge Computing and 5G: Emerging Technology Shaping the Future of IT | Akamai, <https://www.akamai.com/blog/edge/edge-computing-5g-emerging-technology-shaping-future-it>
35. Multi-access Edge Computing - Standards for MEC - ETSI, <https://www.etsi.org/technologies/multi-access-edge-computing>
36. Multi-access edge computing - Wikipedia, https://en.wikipedia.org/wiki/Multi-access_edge_computing
37. What is MEC and How Can It Help Edge Developers? - Intel, <https://www.intel.com/content/www/us/en/developer/articles/technical/what-is-mec-and-how-can-it-help-edge-developers.html>
38. Multi-Access Edge Computing: A nascent opportunity focused on private networks today, <https://transformainsights.com/blog/mec-nascent-opportunity-private-networks>
39. ETSI MEC ramps up Phase 3 work on multi-access edge computing, <https://www.edgecomputing-news.com/news/etsi-mec-ramps-up-phase-3-work-on-multi-access-edge-computing/>
40. A 5G-Edge Architecture for Computational Offloading of Computer Vision Applications, <https://arxiv.org/html/2501.04267v1>
41. Delivering 5G Low-Latency Applications at the Edge with Scalable MEC Platforms, <https://www.lannerinc.com/applications/telecommunication/delivering-5g-low-latency-applications-at-the-edge-with-scalable-mec-platforms>
42. Saudi Arabia 5G Infrastructure Market Size, Report 2025-33 - IMARC Group, <https://www.imarcgroup.com/saudi-arabia-5g-infrastructure-market>
43. Connecting the Kingdom: Saudi Arabia's 5G revolution - Arab News, <https://www.arabnews.com/node/2585243/business-economy>
44. Vision 2030 | The Embassy of The Kingdom of Saudi Arabia, <https://www.saudiembassy.net/vision-2030>
45. World Advanced Manufacturing Saudi, <https://www.wamsaudi.com/>
46. Qualcomm and Aramco Digital launch 5G AI-enabled industrial smartphone - WAM Saudi, <https://www.wamsaudi.com/news-articles/qualcomm-aramco-digital-launch-5g-ai-enabled-industrial-smartphone>

47. Qualcomm and Aramco Digital introduce the world's first 5G AI-enabled industrial smartphone with support for 450MHz spectrum - ZAWYA, <https://www.zawya.com/en/press-release/companies-news/qualcomm-and-aramco-digital-introduce-the-worlds-first-5g-ai-enabled-industrial-smartphone-with-support-for-450mhz-spectrum-pj0ry47t>
48. IT Market in Saudi Arabia to Grow by USD 5.6 Billion (2025-2029), Driven by National Transformation Program Launch, with AI Driving Market Transformation - Technavio - PR Newswire, <https://www.prnewswire.com/news-releases/it-market-in-saudi-arabia-to-grow-by-usd-5-6-billion-2025-2029-driven-by-national-transformation-program-launch-with-ai-driving-market-transformation---technavio-302372001.html>
49. Ministry of Communications and Information Technology - Plug and Play, <https://www.pluginandplaytechcenter.com/partner/ministry-of-communications-and-information-technology>
50. The Strategy of the Ministry of Communications and Information, <https://www.mcit.gov.sa/en/strategy-ministry-communications-and-information-technology>
51. KSA Cloud First Policy, https://www.mcit.gov.sa/sites/default/files/cloud_policy_en.pdf
52. Saudi Arabia's Vision for Leading the Future of Smart Cities and AI - envnt, <https://www.envnt.sa/post/saudi-arabias-vision-for-leading-the-future-of-smart-cities-and-ai>
53. Exploring the Future of Smart City Saudi Arabia: Innovations and Challenges in NEOM, <https://www.citiesabc.com/resources/smart-city-saudi-arabia/>
54. A Deep Dive into Saudi Arabia's Tech-Driven Smart Cities - Telecom Review, <https://www.telecomreview.com/articles/reports-and-coverage/8846-a-deep-dive-into-saudi-arabia-s-tech-driven-smart-cities>
55. Neom, <https://www.vision2030.gov.sa/en/explore/projects/neom>
56. Unlocking the data centre opportunity in the Middle East - PwC, <https://www.pwc.com/m1/en/media-centre/articles/unlocking-the-data-centre-opportunity-in-the-middle-east.html>
57. Giga-Projects | Public Investment Fund - PIF, <https://www.pif.gov.sa/en/our-investments/giga-projects/>
58. NEOM launches infrastructure work for the world's leading cognitive cities, <https://www.neom.com/en-us/newsroom/neom-cognitive-cities>
59. Economies of the Future RDI National Priority in Saudi Arabia: Analytical Study, https://rdia.gov.sa/media/1zneaqf2/economies-of-the-future-rdi-national-priority-in-saudi-arabia-analytical-study_executive-summary.pdf
60. NEOM: Powering Saudi Vision 2030 With Innovation & Tech - Bombay Softwares, <https://www.bombaysoftwares.com/blog/neom-powering-saudi-vision-2030>
61. 14 Saudi Arabia Giga Projects; Vision 2030 - Neuroject, <https://neuroject.com/saudi-arabia-giga-projects/>
62. Vision 2030 reshaping IoT Landscape in Saudi Arabia - Evalueserve, https://www.evalueserve.com/wp-content/uploads/2023/10/Scope-of-IoT-in-Saudi-Arabia_Oct-2023.pdf
63. Leveraging advanced digital technologies for smart city development in Saudi Arabia: opportunities, challenges, and strategic pathways - Oxford Academic, <https://academic.oup.com/ijlct/article/8087327>
64. Digital Technologies: The Key Driver for Achieving Saudi Vision 2030 (A Comprehensive Guide), <https://www.rmg-sa.com/en/digital-technologies-the-key-driver/>
65. megaprojects shaping an innovative digital future - stc KSA, https://www.stc.com.sa/content/stc/sa/en/business/digital_future.html
66. How the convergence of AI and 5G is transforming Saudi Arabia's smart technologies, <https://www.arabnews.com/node/2572078/saudi-arabia>
67. 5G-Advanced: Setting the Stage for the 6G Revolution - Telecom Review, <https://www.telecomreview.com/articles/reports-and-coverage/8960-5g-advanced-setting-the-stage-for-the-6g-revolution>
68. THE KINGDOM OF SAUDI ARABIA (KSA) HEALTH TECHNOLOGIES Overview, <https://vm.ee/sites/default/files/documents/2024-10/KSA%20HealthTech.pdf>
69. Unlocking the Potential of 5G for Remote Diagnostics in Healthcare, <https://theswissquality.ch/unlocking-the-potential-of-5g-for-remote-diagnostics-in-healthcare/>
70. Telemedicine, <https://www.moh.gov.sa/en/Ministry/Information-and-services/Pages/Telemedicine.aspx>
71. Nokia and Zain KSA use Mobile Edge Computing to help Umrah and Hajj pilgrims better navigate their journey during the holy seasons, <https://sa.zain.com/en/all-news/nokia-and-zain-ksa-use-mobile-edge-computing-help-umrah-and-hajj-pilgrims-better-navigate>
72. Zain Saudi Taps Nokia's Multi-access Edge Computing for Delivery of Smart Apps, <https://www.thefastmode.com/technology-solutions/10524-zain-saudi-taps-nokias-multi-access-edge-computing-for-delivery-of-smart-apps>
73. GSMA M360 Mena commences in Riyadh as new report confirms 5G is driving GDP growth in the region, <https://www.gsma.com/newsroom/press-release/gsma-m360-mena-commences-in-riyadh-as-new-report-confirms-5g-is-driving-gdp-growth-in-the-region/>
74. 5G advanced in Saudi Arabia with launch of first live Cloud RAN site - Arab News, <https://www.arabnews.com/node/2594778/business-economy>
75. Saudi Arabia 5G Edge Cloud Network and Services Market Analysis., Competition, Forecast & Opportunities, 2019-2023 & 2024-2029 - GlobeNewswire, <https://www.globenewswire.com/news-release/2024/09/20/2949549/28124/en/Saudi-Arabia-5G-Edge-Cloud-Network-and-Services-Market-Analysis-Competition-Forecast-Opportunities-2019-2023-2024-2029.html>
76. Microsoft shares progress on data centre region in Saudi Arabia with construction complete on three sites, <https://www.intelligentdatacentres.com/2024/12/04/microsoft-shares-progress-on-data-centre-region-in-saudi-arabia-with-construction-complete-on-three-sites/>
77. Saudi telco Mobily invests \$905m in data centers and subsea cables - DCD, <https://www.datacenterdynamics.com/en/news/saudi-telco-mobily-invests-905m-in-data-centers-and-subsea-cables/>
78. The Skills Gap: How Technology is Reshaping Career Paths - Telecom Review, <https://www.telecomreview.com/articles/reports-and-coverage/8873-the-skills-gap-how-technology-is-reshaping-career-paths>
79. 5G-ADVANCED: - Telecom Review, https://www.telecomreview.com/media/issues/2025/TR_March_2025.pdf
80. The Impact of Saudi Arabia's Education Policies Under Vision 2030 on Student Performance - HS Publishing, <https://hspublishing.org/ASSM/article/download/214/165/244>
81. (PDF) Enhancing M-Government service adoption in Saudi Arabia: the role of mobile edge computing in moderating technology acceptance - ResearchGate, https://www.researchgate.net/publication/384899537_Enhancing_M-Government_service_adoption_in_Saudi_Arabia_the_role_of_mobile_edge_computing_in_moderating_technology_acceptance
82. Digital Sector Skills Framework, https://hrsd.gov.sa/sites/default/files/2025-02/Digital%20Sector%20Skills%20Intro%20Report_EN.pdf
83. The AI Talent Crunch: Preparing Today's Workforce for Tomorrow's Technology, <https://newsroom.arm.com/blog/ai-skills-gap-workforce-readiness>

84. (PDF) TWENTY FIRST CENTURY DIGITAL SKILLS AMONG IMAM ABDULRAHMAN BIN FAISAL UNIVERSITY GRADUATES - ResearchGate, https://www.researchgate.net/publication/369565088_TWENTY_FIRST_CENTURY_DIGITAL_SKILLS_AMONG_IMAM_ABDULRAHMAN_BIN_FAISAL_UNIVERSITY_GRADUATES
85. (PDF) Before and Amid COVID-19 Pandemic, Self-Perception of Digital Skills in Saudi Arabia Higher Education: A Longitudinal Study - ResearchGate, https://www.researchgate.net/publication/362633257_Before_and_Amid_COVID-19_Pandemic_Self-Perception_of_Digital_Skills_in_Saudi_Arabia_Higher_Education_A_Longitudinal_Study
86. 5G spectrum allocation in the GCC - Telecom Review, <https://www.telecomreview.com/articles/reports-and-coverage/3704-5g-spectrum-allocation-in-the-gcc/>
87. A Guide to 5G Spectrum Auctions in the Gulf States: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and UAE - TeleGeography Blog, <https://blog.telegeography.com/5g-spectrum-auctions-in-gulf-states-bahrain-kuwait-oman-qatar-saudi-arabia-and-uae>
88. Continued spectrum supply as a driver of technology change and economic growth - GSMA, <https://www.gsma.com/connectivity-for-good/spectrum/wp-content/uploads/2023/02/Saudi-Arabia-Spectrum-Licensing-Best-Practice.pdf>
89. Spectrum Outlook for Commercial and Innovative Use 2021-2023 MARCH 2021, <https://www.cst.gov.sa/en/ntn/Documents/SpectrumOutlook.pdf>
90. Saudi Telecom Company Embarks on Extensive 5G Expansion with Juniper Networks Core Network Solutions, Revolutionizing User Experience, Transforming Digital Connectivity Access and Modernizing its Data Centers Throughout Saudi Arabia - Business Wire, <https://www.businesswire.com/news/home/20250303036885/en/Saudi-Telecom-Company-Embarks-on-Extensive-5G-Expansion-with-Juniper-Networks-Core-Network-Solutions-Revolutionizing-User-Experience-Transforming-Digital-Connectivity-Access-and-Modernizing-its-Data-Centers-Throughout-Saudi-Arabia>
91. Saudi LLM sovereign cloud platform launched by stc Group - Developing Telecoms, <https://developingtelecoms.com/telecom-technology/telecom-cloud-virtualization/18013-saudi-llm-sovereign-cloud-platform-launched-by-stc-group.html>
92. Zain Saudi Arabia and Nokia collaborate to unlock potential of the local talent for the digital transformation era in domains of cloud and edge computing, <https://sa.zain.com/en/all-news/zain-saudi-arabia-and-nokia-collaborate-unlock-potential-local-talent-digital>
93. Internet of Things - An Overview of the Global Regulatory Practices, <https://www.cst.gov.sa/en/researchs-studies/research-innovation/Documents/CITC-IoT-Global%20Regulatory%20Practices.pdf>
94. Data localization and regulation of non-personal data | Saudi Arabia | Global Data and Cyber Handbook | Baker McKenzie Resource Hub, <https://resourcehub.bakermckenzie.com/en/resources/global-data-and-cyber-handbook/emea/saudi-arabia/topics/data-localization-and-regulation-of-non-personal-data>
95. CYBERSECURITY IN 5G: A REVIEW OF VULNERABILITIES AND THREAT PREVENTION STRATEGIES - The Roman Science Publications and Distributions, <https://romanpub.com/resources/Vol%204%20%2C%20No%203%20-%202031.pdf>
96. Review of Physical Layer Security in 5G Wireless Networks - MDPI, <https://www.mdpi.com/2076-3417/13/12/7277>
97. National Cybersecurity Strategy, https://nca.gov.sa/national_cybersecurity_strategy-en.pdf
98. 9. Saudi Arabia - The International Institute for Strategic Studies, https://www.iiss.org/globalassets/media-library---content-migration/files/research-papers/2023/09/cyber-capabilities-and-national-power-vol-2/cyber-capabilities-and-national-power_volume-2_09-saudi-arabia.pdf
99. Cybersecurity In Saudi Arabia: Legal Perspective - AIGHazzawi & Partners, <https://www.ghazzawilawfirm.com/insights/cybersecurity-in-saudi-arabia-legal-perspective/>
100. Key Data & Cybersecurity Laws | Saudi Arabia | Global Data and Cyber Handbook, <https://resourcehub.bakermckenzie.com/en/resources/global-data-and-cyber-handbook/emea/saudi-arabia/topics/key-data-and-cybersecurity-laws>
101. Hybrid Edge-Cloud Collaborator Resource Scheduling Approach Based on Deep Reinforcement Learning and Multiobjective Optimization - University of Southampton, <https://www.southampton.ac.uk/~sqc/listP/TransComp2024-Jan.pdf>
102. Dynamic Neural Network-Based Resource Management for Mobile Edge Computing in 6G Networks - UNIC Research Group, https://unicxidian.org/publication/dynamic_neural_network-based_resource_management/Dynamic_Neural_Network-Based_Resource_Management.pdf
103. regulatory landscape - Zain, <https://zain.com/annualreport2018/en/regulatory-landscape.html>
104. Saudi Arabia is Among Top 10 Countries in Digital Skills | GOV.SA, <https://my.gov.sa/en/news/8692>
105. MCIT Unveils Roadmap for Building Deep Tech Ecosystem in Saudi Arabia | GOV.SA, <https://my.gov.sa/en/news/16664>
106. Ministry of Communications Unveils Roadmap for Building Deep Tech Ecosystem in Saudi Arabia - Asharq Al-Awsat, <https://english.aawsat.com/technology/5098622-ministry-communications-unveils-roadmap-building-deep-tech-ecosystem-saudi>
107. Research, Development and Innovation (RDI) in Economies of the Future, https://rdia.gov.sa/media/jrwi0i2q/4-20250209_economies-of-the-future_innovation-outlook_vs9.pdf
108. Roadmap for Enabling a Sustainable Development of 6G in Saudi Arabia - ResearchGate, https://www.researchgate.net/publication/390312599_Roadmap_for_Enabling_a_Sustainable_Development_of_6G_in_Saudi_Arabia/download