

Case Report

Geopolitical Sustainability of Powering Distributed Artificial Intelligence in Pakistan

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Abstract

Artificial intelligence (AI) is increasingly deployed across a continuum ranging from stationary data centers and semi-stationary computing platforms to autonomous vehicles, robots, wearable devices, implants, and Internet of Things nodes. Across this distributed continuum, reliable power supply and the availability of critical raw materials become system-level constraints. This study investigates how power-supply requirements of distributed AI propagate into material and geopolitical dependencies, with particular attention to Pakistan. A Design Science Research approach is applied to a representative wearable-edge-cloud healthcare architecture for assisting visually impaired persons. The artefact is decomposed into power, sensing, communication, computation, and interaction subsystems; representative components are mapped to critical materials; materials are grouped by affinity; and mining, refining, and geographic concentration are examined using peer-reviewed literature and authoritative mineral and energy sources. The analysis identifies recurring dependencies on lithium, graphite, copper, cobalt, rare-earth elements, semiconductor materials and, for prospective hydrogen configurations, platinum-group metals. It also shows that cloud offloading shifts rather than removes material dependency because communication, data center, grid, and backup-energy infrastructures introduce additional upstream requirements. For Pakistan, the study distinguishes documented mineral production and resource development from prospective geological occurrences and downstream refining capability. The results indicate that geological endowment alone does not ensure access to technology-grade materials. The paper therefore contributes a traceable analytical chain linking AI service architecture, power subsystems, component/material dependencies, geographic supply concentration, and geopolitical vulnerability. Scenario analysis is used as a stress test rather than a prediction, highlighting the value of diversified sourcing, processing capability, strategic cooperation, and adaptable system design for resilient distributed AI deployment.

Keywords

Supply Chain, Platinum, Rare-Earth Elements, Energy Metals, Precious Metals, Graphene, Semiconductors

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1. Introduction

In recent years, artificial intelligence (AI) has developed as Moore's Law has brought us increasing amounts of computing power and memory that is now feasible to run large language models and neural networks enabling useful AI applications such as healthcare systems [1-3]. Once a mostly academic pursuit, AI has evolved into an industry with future domination at stake and geopolitical competition as well because AI has also military applications.

The environmental and energy implications of large-scale AI systems have recently become a significant research topic. Studies indicate that training and operating large neural models can require substantial electrical energy and associated infrastructure, motivating research into sustainable AI computing architectures and energy-efficient deployment strategies [1, 2]. As AI applications move toward distributed and edge environments, power supply architectures and their material dependencies become critical design constraints.

Most of the business investments are currently focused on AI data centers whose power supply requirements are in a scale of megawatts up to gigawatts [4]. Current public electric grids cannot serve such demands without serious rebuilding which is not possible due to long delivery times of necessary gear and lack of investment funding sources. For these reasons AI data center companies are turning to onsite power supply solutions, such as natural gas, solar, wind and BESS-type batteries [5, 6]. Besides fixed location AI data centers there is a scale of distribution for AI servers: From semi-fixed, container-built AI servers that can be transported and installed in rugged environments, such as construction sites; desktop AI-hardware-accelerated computers, AI-accelerated tablets, AI-accelerated smart phones, smart vehicles, drones and robots; wearable; implants; ubiquitous; and nano-devices also foreseen in long run [7]. Over the whole scale of distribution, power supply is critical for the operation of AI. Power needs to be available on need, usable, reliable, resilient, sustainable, and delivery times and cost predictable and manageable.

In this paper we present a literature survey of critical power supply technologies for AI. We analyse the key raw materials upon which these technologies are dependent and further analyse upon which fundamental elements availability they rely on. We further look at the supply chain and geographical sources for these elements mining and refining operations with the aim to understand geopolitical sustainability for AI power supply critical elements supply chain now and in the foreseeable future.

Existing research has examined AI energy consumption, critical-mineral supply chains, edge and distributed computing, and sustainable energy technologies largely as separate research domains. However, limited attention has been given to tracing how the power-supply requirements of a distributed AI architecture propagate from application-level subsystems to component-level critical-material dependencies and subse-

quently to geopolitical supply-chain exposure. This gap is particularly relevant for developing countries such as Pakistan, where deployment of distributed AI may depend simultaneously on imported technologies and internationally concentrated mineral processing and refining capacity. This study addresses this gap by integrating a Design Science-based distributed AI case architecture with systematic subsystem decomposition, critical-element mapping, and geopolitical supply-chain analysis. The resulting contribution is a traceable analytical chain linking AI service architecture to power subsystems, component and material dependencies, geographic supply concentration, and geopolitical vulnerability, demonstrated through a healthcare-oriented distributed AI case study.

2. Literature Review on Distributed AI Power Supply

Regardless of the scale of distributed AI server it consists of a selection of basic building blocks that form the subsystems for power supply, see Figure 1. In the following paragraphs these subsystems will be described at a high level sufficient to understand their functionality and characteristics at a level of detail sufficient for understanding their basic limitations and value to distributed AI server.

A growing trend is to use natural gas (natgas) or liquefied natural gas (LNG) supply [8]. Benefit is overcoming grid capacity or buildup delay constraints. Energy content of natgas is very high and emissions are very low. In stationary and semi-stationary applications, the energy is connected by pipes/hoses and for mobile applications connection is by hoses for charging intermediate tanks or by removable cartridges.

Renewable energy sources are typically solar cells, wind generators or some kind of energy harvesting devices. Characteristic feature is unpredictable flow of energy in time requiring buffering of energy is some form of local storage device usually in electrical form or in hydrogen gas proposed by the hydrogen economy concept [8].

Electrical energy is stored in AI servers in Battery Energy Storage Systems (BESS), which is an advanced energy storage technology solution widely adopted in the renewable energy sector, but it is employed also for regular electric grid to improve availability [4]. BESS core function is to store electricity generated from grid or from renewable sources such as solar, wind or harvested energy, and release it on demand, such as power outages, or times of high electricity prices. A typical application scenario for BESS is integration with solar/wind systems: charging during sunny/windy daytime hours and releasing electricity at night or during windless periods of power shortages, reaching energy self-sufficiency, cost optimization, and power reliability. Especially in addressing the local power generation issues of renewable energy, BESS technology plays a critical role.

Most common source of energy is high-voltage electrical energy from electrical grid [4, 6]. Grid adapter structure depends on the level of maximum power rating. In stationary and semi-stationary application, the energy is connected by wires and for mobile applications connection is by wire-plug or wireless capacitive charging setup that requires proximity to charging station.

Hydrogen is emerging and promising form of clean energy storage [8]. Hydrogen is typically generated utilising intermittent electricity from renewable source, such as solar or wind. Hydrogen's value lies in applications where energy storage in electrical form is technically or economically not feasible [6, 8], or where its hydrogen storage properties offer mobility advantages, such as weight compared to BESS installation. Hydrogen offers also possibility to build hybrid natgas-hydrogen systems. Hydrogen technology is less mature than BESS but there are large strategic programs for development which may bring forward its adoption.

Electrolyzers [9] use electricity to split water into hydrogen and oxygen. If nuclear or renewable-generated electricity is used, the resulting hydrogen has minimal related carbon emissions. Electrolyzers have the potential to support the energy system both by producing hydrogen for use elsewhere and at other times and by providing a controllable load for the grid. If the electrolyzer capital costs are sufficiently low, hydrogen can be produced at a lower cost by reducing or stopping production when electricity prices are high and increasing production up to the maximum load when electricity prices are low, instead of operating at all times.

Fuel cells [9, 10] are essentially the opposite of electrolyzers. They react hydrogen and oxygen to generate electricity with water as a byproduct. Electric power output is controlled by the gas volume fed to the fuel-cell. Because electrolyzers produce hydrogen and fuel cells consume it, they can be used in combination to provide energy storage for the grid where low-cost hydrogen storage is available.

Supercapacitors [11, 12] are ultrafast stabilizers connected to power unit output voltage rails required by spiky AI server loads that are caused by power-hungry parallel computing operations [12]. If spiky load is not stabilized sufficiently, BESS systems would encounter frequent charging/discharging-cycles wearing them out quickly. Powering mobile nodes requires compact and lightweight yet robust construction for supercapacitors.

Beyond conventional electronic hardware, future distributed AI ecosystems increasingly rely on photonic and optoelectronic technologies for sensing, communication, and energy-efficient data transport. These technologies are particularly relevant for edge-cloud AI architectures where large volumes of sensor data must be transmitted with low latency and reduced power consumption. Such technologies improve energy efficiency compared to purely electronic architectures. Recent research has highlighted the growing importance of photonic transport and optical front-haul networking for next-generation distributed computing and AI infrastructures.

Christofidis et al. [13] evaluated interleaver filters for next-generation mobile transport systems, demonstrating the importance of optical communication architectures in supporting scalable high-capacity distributed services. Similarly, Marom et al. [14] proposed fine-resolution optical interlacer approaches for subcarrier-level optical front-haul networking, which are relevant for future AI-enabled edge-cloud communication infrastructure.

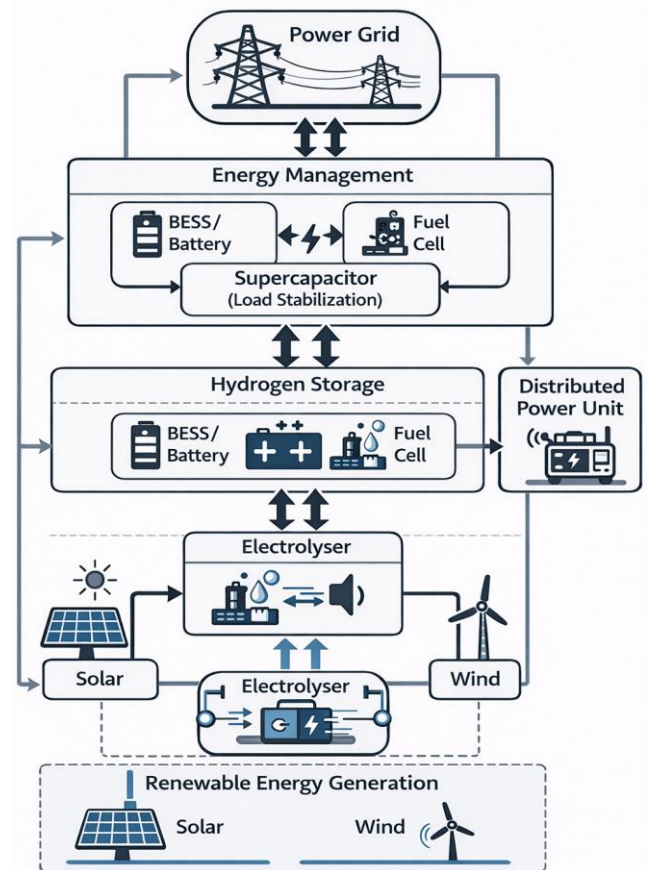


Figure 1. Block diagram of distributed AI server power supply sub-systems.

Taken together, the literature demonstrates that no single power technology satisfies the full range of requirements across the distributed AI continuum. Stationary systems can combine grid electricity, renewable generation, BESS, and potentially hydrogen or natural-gas backup, whereas mobile and wearable nodes impose stricter constraints on energy density, mass, charging accessibility, and power stabilization. Importantly, these technologies are not materially independent: batteries, supercapacitors, power electronics, permanent-magnet devices, fuel cells, and photonic components create overlapping dependencies on lithium, graphite, copper, cobalt, rare-earth elements, platinum-group metals, and specialized semiconductor materials. Existing studies generally evaluate these technologies from energy-performance, environmental,

component, or supply-chain perspectives. Comparatively less attention is given to how their material dependencies accumulate across a distributed AI architecture and translate into geopolitical supply-chain exposure. This cross-layer dependency constitutes the analytical focus of the present study.

3. Research Problem: Potential Supply Chain Disruptions

Recently Gardiner et al [15] discusses potential black-swan eruptions to lithium supply chain caused by global geopolitics subject to unexpected and significant changes that can drive to the reshaping of the current supply chains. Co-author [16] considered an imaginary geopolitical scenario, where due to deteriorating trade relations between U.S. and China, they somehow get into military conflict over Taiwan islands, resulting Pacific Ocean ship transport routes to be partly blocked from regular ship transport. The blockage is two-sided as both US enforces it with its allies and China enforces it with its allies to prevent opposing coalition from benefitting from the embargo. This would mean that shipping of lithium ore would be immediately halted to China and South Korea. Japan would become the only ore refining capability remaining. After a month or so, as ore storages ran out, lithium production would drop dramatically both in China and South Korea. China would be able to keep some 25-30% capacity due to its domestic resources. South Korea goes to less than 10%. Japan would be able to produce 100% level, but its production capacity would be shipped to mostly to U.S, probably leading to a situation that developing nations, such as Pakistan, would get very little refined lithium, because U.S. would need the Japan refining capacity for military priority needs. So looking at it from a Pakistani point of view, this is a very worrisome scenario within the next few years.

Based on the above scenario, Co-author [16] advised for nations to mitigate these kinds of supply chain risks by building up scalable supply chain front-end for lithium, i.e. mining reserves, mining infrastructure and refining capacity. Scalable means that under business-as-usual conditions lithium supply chain front-end is hibernating with small costs, but under black-swan type abnormal conditions, the front-end can be activated rather quickly. Scaling is in principle similar to the concept of renewable sun/wind energy grid backed by coal-powered power-stations, but in a much longer time frame. Potential enabling technologies to implement scalability are smart mining technologies [17] that utilize artificial intelligence to control autonomous drilling, hoisting and transporting of ore; long-distance ultra high-speed photonics [13, 14]; and on-site underground wireless communications technology [18] to control the operations of various autonomous mining equipment.

Research problem in this paper is wider than just lithium-related, we would like to find out:

1) What critical elements [19] are necessary for powering

distributed AI systems? (RQ1);

2) Where can they be sourced? (RQ2);

3) What geopolitical risks and bottlenecks there are now and in future? (RQ3)

4) What related natural resources does Pakistan potentially have? (RQ4)

5) What AI subsystems are affected? (RQ5)

Research hypothesis is: By limiting study to a representative enough AI-enabled wearable-edge-cloud ecosystem relying on layered energy subsystems, their material sourcing dependencies will propagate into geopolitical supply chain risks.

Research method applied is *design science* where iterative design and validation is employed to construct a model defining an artefact representing goal of a deployable system for its intended users.

Data collection method for this paper is carried out by *iterative decomposition* of the system model of artefact into architectural subsystems whose current or near future implementation is further decomposed into components, and their raw material down to critical elements.

Analysis method is *affinity grouping* of identified critical elements into logical groups that *match taxonomies* used in supply chain, mineral mining and element refining literature.

Dependencies between research method, data collection and analysis method are illustrated in Appendix I. The research procedure is operationalized in five stages. Stage 1 decomposes the distributed AI artefact into local/wearable, edge, communication, cloud, and power-supply subsystems, focusing on components that influence energy availability, conversion, stabilization, storage, sensing, communication, and computation. Stage 2 maps representative implementation components - including lithium-ion batteries, supercapacitors, permanent-magnet actuators, semiconductor devices, wireless charging circuits, sensors, fuel cells, and power electronics - to their critical raw-material dependencies using the literature and documentary sources cited in this study. Stage 3 applies affinity grouping to classify the identified materials into lithium/battery materials, carbon-based materials, platinum-group metals, rare-earth elements, energy metals, precious metals, and semiconductor materials. Stage 4 maps mining and refining locations for these groups and examines geographic concentration, refining bottlenecks, and exposure to the geopolitical disruption scenario. Stage 5 compares Pakistan's reported mineral resources, infrastructure, and processing capabilities with the material dependencies identified in the case study, while distinguishing documented resource development from prospective geological potential where commercial extraction or refining capacity has not been established.

Source selection prioritizes peer-reviewed publications and authoritative institutional datasets where available, including the energy, mineral-commodity, geological, and supply-chain sources listed in references. Industry and market sources are used primarily for emerging technologies or recent developments where peer-reviewed evidence is limited. The analytical

objective is not to estimate a complete bill of materials for a commercial device, but to identify material-dependency pathways sufficiently important to expose potential supply-chain vulnerabilities.

Validation of the resulting dependency mapping is through triangulation across three levels. First, subsystem and component requirements are compared with technical literature describing the corresponding energy, sensing, communication, and assistive technologies. Second, identified critical-material dependencies are cross-checked against the mineral, energy, and commodity sources used in the study. Third, the material groups are mapped back to the distributed AI case architecture to verify that each identified dependency can be traced to a specific subsystem or implementation requirement. The Design Science process illustrated in Appendix I provides an additional iteration mechanism whereby changes in energy-source or critical-material availability can trigger redesign or reconfiguration of the artefact.

4. Results of Case Study

Assistive technologies and telepresence-based systems represent two complementary but distinct approaches to navigation support for Visually Impaired Persons (VIP). Assistive mobility technologies span electronic travel aids, smart canes, wearable sensors, and mobile navigation applications. These systems focus on obstacle detection, route guidance, or object recognition and can improve situational awareness. However, reviews highlight persistent challenges related to robustness, usability, and real-world adoption, particularly in dynamic environments where semantics and safety-critical decisions matter [20-23].

Telepresence-based navigation systems enable a remote helper to provide real-time assistance through audio and video, leveraging human interpretation in ambiguous or socially complex situations [24-26]. While user experience can be positive, scalability remains limited due to helper availability, single-session designs, and insufficient support for multi-helper coordination and handover. Ethical, trust-related, and responsibility-boundary challenges further complicate large-scale deployment [27].

Earlier research [26, 27] indicate that effective navigation assistance for VIP should be designed as a service-oriented solution rather than a standalone device, supporting continuity over time. Such services must accommodate multi-actor involvement (family members, volunteers, professionals) and provide structured handover mechanisms to preserve contextual information during transitions. Assistance should adapt dynamically to environment and user state through multi-modal interaction, while AI should function as a supporting and filtering component that preserves human oversight in safety-critical situations. Effective systems must also facilitate

learning and increasing autonomy rather than permanent reliance on external support. Edge- and cloud-based healthcare services raise regulatory and deployment challenges related to privacy, accountability, and traceability [28], as well as large-scale deployment and integration [29-32].

Based on these implications, a scalable digital health service must support real-time bi-directional interaction, coordination among multiple helpers, and context-aware handover. Non-functional requirements include low latency, high reliability across environments, and robustness to network disruptions. Ethical and accessibility requirements include user consent, preservation of user agency, avoidance of cognitive overload, inclusive design, and clearly defined responsibility boundaries [27, 33-37].

4.1. Distributed AI Architecture

The proposed assistance model follows a Human-AI cooperative paradigm in which the VIP remains the primary decision-maker. Human caretakers provide contextual interpretation and adaptive guidance in dynamic or unfamiliar environments, while AI functions as an advisory component supporting perception, information filtering, and prioritization without assuming autonomous control. Assistance is continuous across environmental zones and over time. Guided by the validated zone-based model, assistance intensity and modality adapt to environmental familiarity and situational complexity. Repeated assisted navigation supports skill acquisition and confidence building, enabling a mentor-apprentice dynamic in which external support gradually decreases as user independence increases. Scalability is achieved by integrating community and volunteer-based assistance alongside professional care, with clear roles and coordination to ensure accountability and availability. AI supports perception, prioritization, and routine context inference (e.g., scene summarization and anomaly detection), while decision authority remains with human caretakers. This distributes assistance capacity without replacing human judgment, enabling scalable and trustworthy Human-AI cooperation.

As shown in Figure 2, the architecture follows a three-tier design integrating intelligent local devices, edge computing, and cloud-based learning and analytics [25, 29].

Assistance orchestration is implemented as a unified, role-aware process supporting both full handover and collaborative assistance (Figure 3). Contextual information—including environmental state, task progress, and interaction history—is synchronized at handover to preserve continuity. Users receive unified feedback regardless of caretaker transitions, reducing perceived disruption and supporting scalable Human-AI collaboration. Secure data exchange, identity management, and accountability mechanisms support trust and regulatory compliance [27].

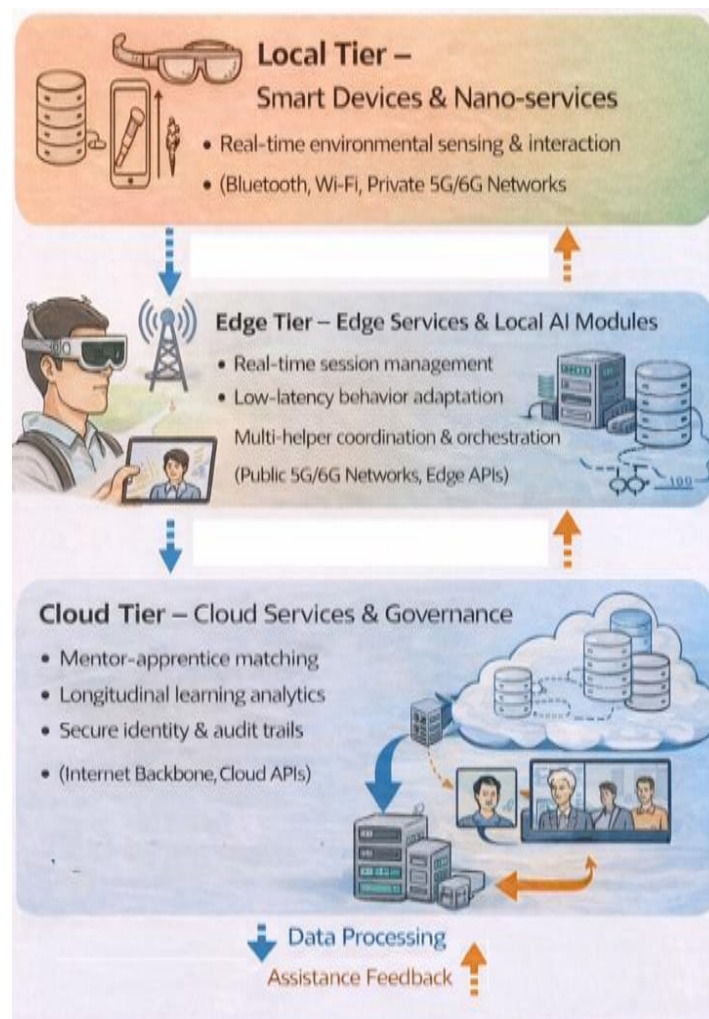


Figure 2. Distributed AI service architecture for visually impaired.

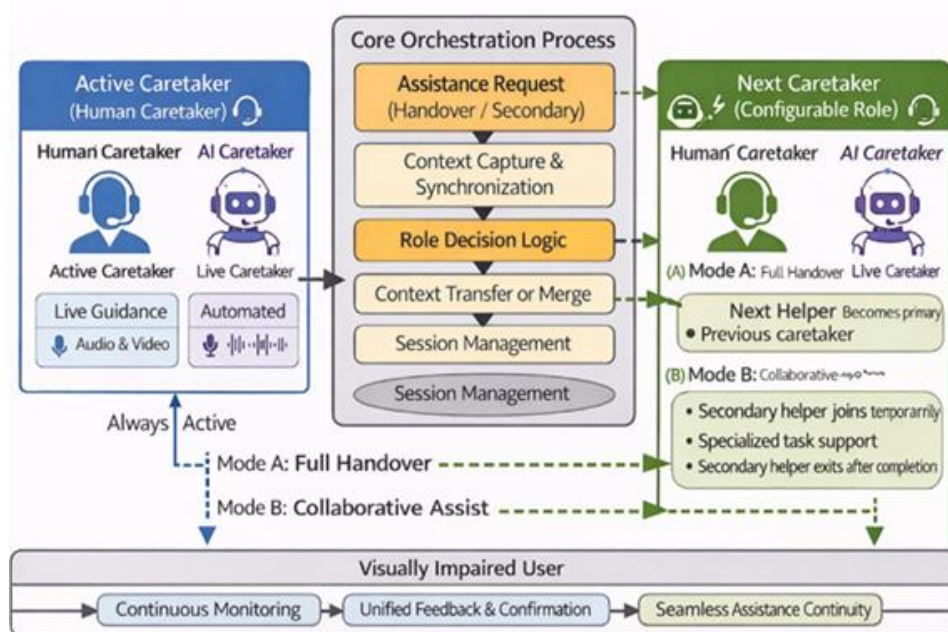


Figure 3. Orchestration workflow for full and collaborative assistance handover.

4.2. Signal Conversion for Visually Impaired Users

Assistive technologies for visually impaired persons (VIPs) rely on non-visual human-machine interaction modalities, because conventional graphical user interfaces are inherently vision dependent. To compensate for the absence of visual feedback, assistive devices transform environmental information into tactile, vibrotactile, kinesthetic, or auditory signals that can be perceived through other sensory channels [38, 39]. Several classes of non-standard user interface (UI) devices have emerged to support mobility, navigation, and situational awareness.

4.2.1. Smart Cane

The smart cane represents one of the most widely used electronic mobility aids. Modern smart canes extend the traditional white cane by integrating embedded electronics that detect obstacles and convey information through haptic feedback [40, 41]. Typical subsystems include:

- 1) ultrasonic or LiDAR sensors for obstacle detection
- 2) cameras for object recognition and scene understanding
- 3) microcontrollers or embedded processors for signal processing
- 4) wireless communication modules (Bluetooth/Wi-Fi)
- 5) vibrotactile actuators embedded in the handle
- 6) rechargeable lithium-ion batteries

Sensor data is processed locally or in a connected smartphone and converted into vibration patterns or spatial audio cues, enabling the user to perceive distance and direction of obstacles [38, 40].

4.2.2. Vibrotactile Wearable Interface

Wearable tactile interfaces provide navigation cues through arrays of small vibration motors embedded in belts, gloves, wristbands, or clothing [39]. Examples include:

- 1) navigation belts that provide directional cues via vibration
- 2) smart shoes with haptic navigation signals
- 3) wrist-mounted vibrotactile devices for guidance

These devices rely on miniature electromagnetic motors,

which typically use neodymium-based permanent magnets to achieve high vibration strength in compact form factors.

4.2.3. Tactile Display and Braille Interface

Another important class of assistive interface technologies consists of refreshable tactile displays, which present information through arrays of actuated pins. Examples include:

- 1) refreshable braille displays
- 2) pin-matrix tactile displays
- 3) electro-tactile feedback surfaces
- 4) piezoelectric haptic displays

These devices allow users to read digital information through touch, enabling access to text, navigation information, and graphical representations [43].

4.2.4. Audio-Based Assistive Interface

Spatial audio systems guide users through three-dimensional acoustic cues delivered via headphones or bone-conduction devices. These systems often combine:

- 1) environmental microphones
- 2) digital signal processors
- 3) spatial audio rendering algorithms
- 4) bone-conduction transducers

Such devices allow users to maintain environmental awareness while receiving directional information [39].

4.3. Power Supply Architecture Decomposition Into Critical Elements

Figure 4 presents simplified architecture of power supply subsystems with specific attention to powering atypical user interaction modalities requiring atypical power conversions for visually impaired: haptic interfaces, collision detection radar and smart canes. For continuous power assurance, the assistive device architecture includes additional mobile power bank carried in a backpack and wearable docking pads integrated into the backpack, smart cane and optional body-worn harness or jacket (Figure 4). Physical hardware details have been abstracted away due to preserving and protecting future potential intellectual property development.



Figure 4. Energy subsystems structure of distributed wearable edge-cloud AI system case study.

4.3.1. Energy Storage and Conversion

Energy storage occurs in:

- 1) Wearable lithium-ion cells
- 2) Smartphone lithium-ion batteries
- 3) External backup power banks

These Battery Energy Storage Systems (BESS) perform:

- 1) Energy buffering
- 2) Peak load smoothing
- 3) Availability assurance

Key materials include:

- 1) Lithium
- 2) Nickel
- 3) Manganese
- 4) Cobalt
- 5) Silver
- 6) Graphite
- 7) Copper
- 8) Aluminum
- 9) If future designs integrate: natgas/hydrogen micro-fuel cells (future scenario) then additional elements required

- 1) Platinum group metals

- a) Platinum
- b) Palladium

- c) Iridium

- 2) Rare Earth Elements

- a) Lanthanum

- b) Cerium

- c) Gadolinium

- 3) Zirconium

- 4) Scandium

- 5) Yttrium

- 6) Strontium

- 7) Rubidium

- 8) Titanium

- 9) Cobalt

- 10) Manganese

- 11) Molybdenum

- 12) Nickel

- 13) Ferrite

- 14) Graphite

- 15) Stainless Steel

4.3.2. Energy Stabilization

AI workloads generate spiky computational loads, particularly during:

- 1) Real-time seizure detection
- 2) Deep learning inference
- 3) Wireless data transmission bursts

Supercapacitors and voltage regulation circuits stabilize power rails to:

- 1) Prevent brownouts
- 2) Protect battery longevity
- 3) Ensure uninterrupted inference

Supercapacitor production depends on:

- 1) Advanced carbon materials, such as graphene
- 2) Various doping elements for graphene to improve parameters
- 3) Aluminium

4.3.3. AI Computational Energy Profile

Unlike static IoT devices, distributed AI systems require:

- 1) Continuous sensing
- 2) Periodic machine learning inference
- 3) Event-triggered escalation bursts
- 4) Persistent wireless connectivity

Energy demand is therefore:

- 1) Continuous baseline load
- 2) Intermittent high-power bursts

The smartphone edge layer represents the most energy-intensive node, particularly when deep learning models operate locally for privacy-preserving inference.

Cloud processing shifts part of the computational burden off-device but introduces dependency on:

- 1) Data center energy infrastructure
- 2) Grid stability
- 3) Backup generation systems

Thus, distributed AI system is indirectly dependent on:

- 1) Data center BESS installations
- 2) Hydrogen and/or NatGas backup systems
- 3) Renewable intermittency management

4.4. Critical Element Dependency Mapping

Mapping the distributed AI architecture to material dependency reveals the following hierarchy:

4.4.1. Assistive Device Hardware

Although assistive technologies are primarily evaluated from usability and accessibility perspectives, their hardware architectures depend on numerous critical raw materials [6]. Critical materials appear in several core subsystems:

- 1) actuators and vibration motors
- 2) sensors and imaging systems
- 3) rechargeable batteries
- 4) integrated electronics and communication modules

Rare-earth elements and strategic metals are particularly

important for the miniaturization and performance of assistive devices [41-45]. Most vibrotactile actuators and miniature motors rely on NdFeB permanent magnets, which contain several rare-earth elements. Important elements include:

- 1) Neodymium (Nd) - primary magnetic material
- 2) Dysprosium (Dy) - improves high-temperature magnet stability
- 3) Praseodymium (Pr) - enhances magnetic strength
- 4) Samarium (Sm) - used in high-temperature magnets

These materials enable compact and energy-efficient actuators used in:

- 1) vibration motors
- 2) micro-speakers
- 3) bone-conduction transducers
- 4) haptic feedback systems

Critical Elements in Sensors

Advanced sensors used in assistive technologies depend on specialized semiconductor and their doping materials [42] include:

- 1) Gallium (Ga) used in compound semiconductors and laser emitters
- 2) Indium (In) used in photodetectors and displays
- 3) Germanium (Ge) used in infrared sensors
- 4) Antimony (Sb) used in infrared detectors

These elements are essential for technologies such as:

- 1) LiDAR distance measurement
- 2) CMOS imaging sensors
- 3) infrared cameras
- 4) depth sensing modules

Future distributed AI infrastructures increasingly depend on photonic and optoelectronic hardware for high-speed communication, low-latency front-haul networking, and energy-efficient sensing. These systems further increase dependency on critical semiconductor materials, such as

- 1) Gallium
- 2) Indium
- 3) Germanium
- 4) Rare-earth doping for optical materials

Wireless charging antennas transfer energy from the power bank to the smart cane, regular smart phone and other optional devices when brought to immediate proximity without requiring the user to manually connect cables during navigation. This is especially important for visually impaired users because manual cable handling during mobility may increase cognitive load and safety risk.

The wireless power subsystem consists of a transmitter coil, receiver coil, power-management circuitry, shielding layers, alignment magnets, and local voltage-regulation electronics. The transmitter coil is typically integrated with the backup battery module, while the receiver coil is placed in a wearable docking pad or smart-cane charging interface. When the cane is near the docking zone, energy is transferred inductively and used either to recharge the cane battery and to power its sensing and haptic subsystems directly. This functionality introduces additional critical-material dependencies. Copper is the

dominant material for wireless charging coils because of its high electrical conductivity. Ferrite materials are commonly used for magnetic flux guidance and electromagnetic shielding. These ferrites may contain iron oxides combined with manganese, nickel, zinc, or cobalt depending on the magnetic design. Permanent magnets used for mechanical alignment may rely on neodymium-based rare-earth magnets, while charging-control circuits require silicon power electronics and may use gallium nitride devices in high-efficiency converters.

Capacitors, connectors, and printed circuit boards further introduce tantalum, gold, silver, tin, and nickel dependencies. Thus, although wireless charging improves usability and power availability, it expands the critical-material footprint of the assistive device. In addition to battery materials such as lithium, cobalt, nickel, and graphite, the system becomes dependent on copper coils, ferrite magnetic materials, rare-earth alignment magnets, and power-management semiconductors. Wireless charging critical materials are summarized in [Table 1](#).

Table 1. Critical materials breakdown analysis for wireless charging system case study illustrated in [Figure 4](#).

Subsystem	Function	Critical materials
Transmitter coil	Wireless power emission from backpack power bank	Copper, ferrite materials
Receiver coil / docking pad	Wireless power reception at cane or wearable pad	Copper, ferrite materials
Magnetic alignment	Improves charging position and coupling efficiency	Neodymium, praseodymium, dysprosium
Power-management circuit	Rectification, voltage regulation, charging control	Silicon, gallium, tantalum, gold, silver
Power bank	Energy reserve for extended use	Lithium, cobalt, nickel, graphite
Connectors and PCB foils	Electrical interconnection	Copper, gold, tin, nickel

4.4.2. Wearable & Smartphone Layer

- 1) Lithium (battery)
- 2) Cobalt (cathode chemistry)
- 3) Nickel
- 4) Graphite
- 5) Copper (wiring, PCB)
- 6) Gold (connectors)
- 7) Silicon (chips)
- 8) Germanium (displays, optoelectronics)
- 9) Rare earth elements (vibration motors, sensors)

4.4.3. Cloud Infrastructure

- 1) Lithium (grid-scale BESS)
- 2) Nickel, cobalt
- 3) Platinum group metals and rare earth elements (hydrogen backup fuel cells)
- 4) Silicon (servers)
- 5) Gallium (power electronics)
- 6) Neodymium (cooling systems, generators)

4.5. Geopolitical Exposure

The case study reveals several systemic vulnerabilities:

- 1) Lithium concentration risk
 - a) Mining concentrated in few countries

- b) Refining heavily centralized
- 2) Cobalt supply fragility
 - a) High geographic concentration
 - b) Ethical and political instability concerns
- 3) Rare earth dominance

Refining capacity concentrated geographically
- 4) Platinum group metals

Critical for hydrogen future scenarios
- 5) Semiconductor supply chains

Advanced fabrication concentrated in limited regions

Because healthcare AI systems are safety-critical, supply disruptions may:

 - Delay deployment
 - Increase device cost
 - Reduce accessibility
 - Exacerbate digital health inequality

4.6. Sustainability Implications

The distributed AI for visually impaired case study demonstrates:

- 6) AI-driven healthcare is not only algorithmically constrained;
 - 7) It is also materially constrained, and
 - 8) It is also geopolitically constrained.
- Energy sustainability and geopolitical stability therefore become preconditions for:
- 1) Digital care pathway scalability
 - 2) Trustworthy AI deployment

3) Long-term healthcare equity

Delegated autonomy mechanisms require:

- 1) Continuous device availability
- 2) Reliable power buffering
- 3) Predictable maintenance cycles
- 4) Battery degradation or supply shortages directly impact system reliability and use safety.

4.7. Lessons from Sustainability

This case highlights five broader insights:

- 1) Even small-scale distributed AI depends on lithium, carbon/graphite/graphene, platinum group, and rare earth elements supply chain ecosystems.
- 2) Distributed AI architectures multiply material dependency layers.
- 3) Energy stabilization components are as critical as storage.
- 4) Cloud offloading shifts but does not remove material dependency.
- 5) Healthcare AI sustainability must include critical element foresight.

This case study system therefore serves as a microcosm of the broader distributed AI power challenge discussed in this paper.

4.8. Transition to Critical Element Analysis

Having established the technical dependency chain from wearable sensor to cloud infrastructure, the next section systematically identified

- 1) Critical elements embedded in each subsystem
- 2) Mining and refining concentration
- 3) Supply chain bottlenecks
- 4) Geopolitical exposure pathways

The case study demonstrates how material sustainability directly influences the resilience and ethical scalability of AI-enabled healthcare services.

5. Geopolitical Sustainability Analysis

To understand geopolitical risks in supply chain it is necessary to present overview of geographical and regional distribution of supply chain for critical raw material depending basic elements summarised in Appendix II.

Lithium supply chain was analysed recently in [16] and remains problematic. Refining is highly concentrated in S-E Asia and highly vulnerable to geopolitical scenario as discussed in [16]. There has been some development to mitigate risks in Europe, such as opening of new lithium mines and refineries most notably in Kaustinen/Kokkola in Finland by Sibanye-Stillwater [46] and large-scale mining and refinery operations in South-America in Argentina by Eramet S. A. [47]. This is a model that could be extended to developing

countries, who have potential for low-cost brine lithium resources.

Platinum group metals supply chain mining is highly concentrated in South-Africa and Russia. Refining is less concentrated but both South Korea and China are vulnerable in presented geopolitical scenario [48].

Rare-earth elements are vulnerable to geopolitical scenario since refining of REs is highly centralized in China. Also export licensing of REs by China limits availability. However, US and its allies have started to build refining capacity but it will take years to run it up in quantity and quality. Recent geopolitical gyrations related to Greenland can be understood by desire to guarantee mining access to REs [49].

Energy metals are less critical because their mining and refining is more evenly distributed around the world. But since demand is increasing along decarbonisation activities there can be bottlenecks which affect price and delivery time. Most critical energy metals are copper and cobalt because their refining by smelting are concentrated in Africa and South America and are dependent on steady supply chain for sulphuric acid [50] which is vulnerable to our geopolitical risk scenario [16]. Copper has beside AI also demand growth in many other energy related fields as well and is often difficult to replace with inferior substitutes such as aluminium [51].

Precious metals silver can improve critical parameters in distributed AI system designs, especially BESS systems. Price and availability of silver in larger quantities may raise issues as well. An example is Samsung delaying already announced new high-performance silver-dependent EV battery type due to not being able to guarantee sufficient silver supply for large-scale production [52].

Semiconductors gallium and germanium are needed in high-power and optoelectronic applications. In most applications they can be substituted with silicon semiconductors but parameters such as size, thermal loss and noise may be compromised. Gallium and germanium mining and refining is largely concentrated in China [53].

Carbon based raw materials have generally abundance in nature and mining itself is not a problem but processing to synthetic graphite, graphene, carbon nanostructures is highly specialized and is concentrated in China, Japan and South Korea although there are activities also in Europe especially as related to supercapacitors [54].

Appendix II also describes authors' current understanding of *Pakistan critical minerals reserves* which are significant but not yet fully explored [55]. Pakistan has significant proven mining reserves in copper, gold, silver and graphite. Geology of Pakistan infers significant reserves in lithium, rare earths and energy metals [56, 57]. Pakistan has under-developed rail- and road transport networks and electric grid. Most potential export port is Gwadar [58] and it is also most potential site for refineries utilizing LNG as energy source. International cooperation in geological exploration, transport infrastructure, mining and refining with developing countries who have untapped potential geology for critical minerals, but who suffer

from lack of funding and infrastructure, such as Pakistan, could open long-term opportunities to reduce vulnerability to geopolitical supply chain risks.

Authoritative sources support somewhat cautious interpretation of Pakistan's critical-mineral position. The U.S. Geological Survey reports that Pakistan produced copper and a range of other mineral commodities in 2024, while lithium and rare-earth elements were not listed among the country's reported mineral production [59]. The Geological Survey of Pakistan documents the Saindak copper-gold deposit and reports established copper, gold, and silver production there, while also identifying Reko Diq as a major copper-gold resource [60]. Reko Diq remains a development project rather than current large-scale production; its development schedule has also been subject to continuing review [61]. Geological studies report prospective occurrences of lithium and other critical minerals in parts of northern Pakistan [57], but these occurrences should not be treated as demonstrated economic reserves or established supply. The available evidence therefore indicates stronger empirical support for copper-gold resource development than for domestic lithium or rare-earth supply. It also does not demonstrate broad domestic refining capacity for the technology-grade lithium, rare-earth, semiconductor, or battery materials required by distributed AI systems. Accordingly, Pakistan's potential contribution to these supply chains depends not only on geological exploration but also on future extraction, beneficiation, processing, refining, infrastructure, and economic feasibility.

For interpretation of these data, this study distinguishes geological occurrence or prospective potential from economically recoverable reserves, current production, and downstream refining capacity. Possession of geological resources does not by itself provide a secure supply of technology-grade materials required by distributed AI hardware. Consequently, the Pakistan analysis treats geological potential, demonstrated resource development, and refining/processing capability as separate indicators of supply-chain resilience.

This study has several limitations. First, the critical-material mapping represents a subsystem-level dependency analysis rather than a quantitative bill-of-materials assessment of a specific commercial product. Material composition can vary according to device design, supplier, battery chemistry, semiconductor technology, and manufacturing generation. Second, mineral-resource information for Pakistan remains incomplete for several critical materials; therefore, reported geological potential should not be interpreted as equivalent to economically recoverable reserves or current production capacity. Third, geopolitical supply-chain conditions are dynamic, and the disruption scenario considered in this study is exploratory rather than predictive. Its purpose is to examine dependency propagation and system vulnerability under supply disruption rather than to forecast a specific geopolitical event. Finally, future technologies considered in the architecture, including hydrogen-based micro-fuel cells and some advanced material applications, represent prospective design alternatives rather

than components necessarily deployed in the present case-study system.

6. Conclusions

Power supply is highly critical for any AI systems construction due to spiky load characteristics by AI computing loads and high availability requirements. Adding distribution to AI brings additional requirements for power supply such as size, weight and wireless hot-plug connectivity.

As a case study of a distributed AI we analyzed medical AI system for visually impaired persons which is autonomous personal device with high requirements on usability, durability, availability, safety, connectivity, and light-weight modular design. In this paper we further decomposed this medical AI case study power supply subsystems, their critical raw materials breakdown to basic elements.

Evidence-based findings are the following: The case-study decomposition shows that distributed AI power and interaction subsystems create recurring dependencies on battery materials, carbon-based materials, copper and other energy metals, rare-earth elements, semiconductor materials and, for prospective hydrogen configurations, platinum-group metals. Cloud offloading does not remove physical-resource dependency; it relocates part of that dependency to communication, data center, grid, and backup-energy infrastructure. The analysis also identifies geographic concentration in mining or refining for several material groups, creating potential supply-chain bottlenecks.

Scenario-based implications are the following: The geopolitical disruption scenario used in this study is not presented as a forecast of a specific future event. It is a stress scenario used to examine how geographically concentrated mining, refining, transport, and processing dependencies could propagate into distributed AI deployment constraints. Under such disruptions, countries dependent on imported technology-grade materials may experience higher costs, longer delivery times, or reduced access. Resilience options therefore include diversified sourcing, geological exploration, processing and refining capability, recycling, strategic cooperation, and adaptable system design; their feasibility requires separate technical, economic, environmental, and geopolitical assessment.

Overall, the study shows that resilience of distributed AI depends on both technical architecture and upstream material systems. For Pakistan, the evidence supports treating mineral-resource development, processing/refining capability, infrastructure, and international cooperation as distinct policy and industrial challenges. Future work should quantify component-level material intensity, compare alternative subsystem designs, and evaluate supply-chain resilience under multiple disruption scenarios rather than a single geopolitical stress case.

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Abbreviations

AI	Artificial Intelligence
BESS	Battery Energy Storage System
BOM	Bill of Materials
COTS	Commercial Off The Shelf
DSR	Design Science Research
GDPR	General Data Protection Regulation
IoT	Internet of Things
LiDAR	Light Detection and Ranging
LNG	Liquefied Natural Gas
PCB	Printed Circuit Board
REE	Rare-Earth Element
RQ	Research Question
UI	User Interface
UML	Unified Modeling Language
VIP	Visually Impaired Person(s)

Author Contributions

Babar Shahzad Chaudary: Conceptualization, Data curation, Formal Analysis, Visualization, Writing – original draft

Petri Pulli: Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing

Data Availability Statement

The data supporting the outcome of this research work has been listed in references in this article.

Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

Appendix I

Overview of the research process that uses typical Design Science [62] iteration cycles (requirements, design and rigor) supported by two additional adaptation cycles to partially redesign and/or reconfigure system to comply with emerging changes in critical resource sources availability (energy, materials) is presented in Figure 5. Legend: UML=Unified Modelling Language; COTS=Commercial Off The Shelf; BOM=Bill Of Materials.

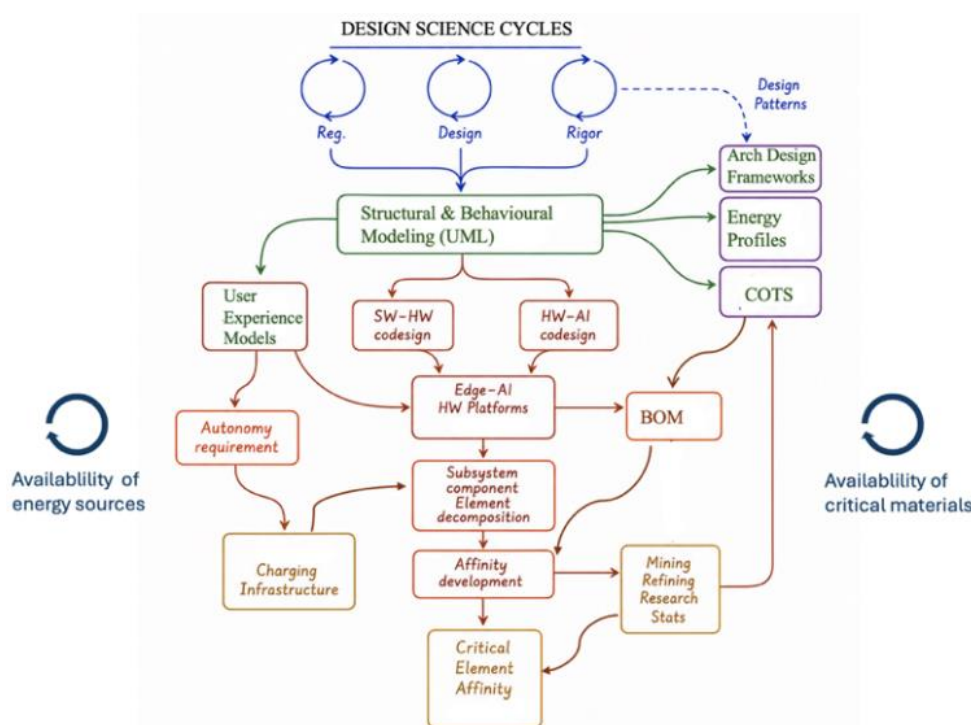


Figure 5. Design Science research process for distributed AI architecture and critical-resource adaptation.

Appendix II

Geographical and regional distribution of supply chain for selected affinity groupings of critical raw material is presented

in Figure 6. Elements in red font are most critical. Data for mining is from 2025 [63]. Legend: RQ1- RQ5 are research questions.

Table 6. Geographic and regional distribution of mining and refining for selected critical raw-material groups and their relationship to distributed AI subsystems.

Critical element group	Critical element (RQ1)	Mining (RQ2)	Refining (RQ2)	Bottlenecks (RQ3)	Pakistan mineral reserves (RQ4)	Affected subsystems (RQ5)
Lithium	Lithium	South-America, Australia, China, Africa	China, S-Korea, Japan	Refining concentrated	Untapped pegmatite belts in Chitral and Gilgit, and untapped brines in Balochistan Hamuns	Energy storage (BESS)
Graphite, graphene, carbonfibres and nanomaterials	Carbon	China, Africa, Australia, Canada, US, Europe	China, Japan, S-Korea	Refining concentrated	Vast deposits of graphite schists in Katlang Mardan, Bruner and Malakand.	Energy stabilization (supercapacitors)
Platinum group metals	Platinum Palladium Iridium	Africa, Russia, US	Africa, Russia, China, India, Japan, US	Mining concentrated	Drilling results indicate potential in Northern Pakistan; requires systematic drilling programme	Energy sources and storage (natgas and hydrogen)
Rare Earth Elements	Lanthanum, Cerium, Neodymium, Samarium, Gadolinium, Terbium, Dysprosium	China, Australia, US, Canada	China	Refining concentrated and complicated Export licensing	Untapped REE-bearing granites and metamorphic rocks in Khyber Pakhtunkwa	Energy sources and storage (natgas and hydrogen) Energy conversion (motors, vibrators)
Energy metals	Copper Aluminium Cobalt Nickel Manganese Molybdenum Titanium Zirconium Scandium Yttrium	South-America, Australia, Africa, Canada, US, Russia, China, Europe	Same as mining + Japan, S-Korea	Refining vulnerable to supply chain for chemicals such as sulphuric acid	Balochistan has one of worlds largest untapped Copper reserves. High potential for zirconium and yttrium. Untapped monazite, xenotime, bastnasite formations in Himalayan Hindukush belts. Mineral sands in Sindh and Balochistan.	Energy sources and storage (BESS, natgas and hydrogen) Energy stabilization (supercapacitors)
Precious Metals	Gold Silver	South-America, Mexico, Australia, Can-	Same as mining	Mining capacity	Balochistan has one of worlds largest untapped gold and silver reserves	Energy sources and storage (BESS, natgas and hydrogen)

Critical element group	Critical element (RQ1)	Mining (RQ2)	Refining (RQ2)	Bottlenecks (RQ3)	Pakistan mineral reserves (RQ4)	Affected subsystems (RQ5)
		ada, US, Russia, China				Energy stabilization (supercapacitors)
Semiconductors	Gallium Germanium Antimony	China, Russia, Canada, Australia, US, Finland	Same as mining	Refining concentrated	Potential but requires systematic till sampling and rock drilling programme.	Energy storage (BESS)

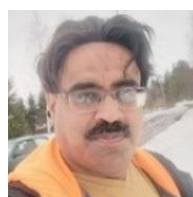
References

- [1] Aminizadeh S., Heidari A., Dehghan M., Toumaj S., Rezaei M., Navimipour N. J., Stroppa F., Unal M., "Opportunities and challenges of artificial intelligence and distributed systems to improve the quality of healthcare service" *Artificial Intelligence in Medicine*. Vol 149, 2024, 102779, ISSN 0933-3657, <https://doi.org/10.1016/j.artmed.2024.102779>
- [2] Strubell E., Ganesh A., and McCallum A., "Energy and policy considerations for deep learning in NLP". *Proc. ACL 2019*, pp. 3645-3650. <https://doi.org/10.18653/v1/P19-1355>
- [3] Schwartz R., Dodge J., Smith N. A., and Etzioni O., "Green AI," *Communications of the ACM*, vol. 63, no. 12, pp. 54-63, 2020. <https://doi.org/10.1145/3381831>
- [4] IEA (2025) "Energy and AI". Report. International Energy Agency. 304 p. Available at www.iea.org
- [5] Bloom Energy, "The AI Race is a Race for Power". Presentation. Bloom Energy Corp. Available: www.bloomenergy.com
- [6] International Energy Agency, "The Role of Critical Minerals in Clean Energy Transitions", IEA Report, 2022.
- [7] Xiaolong T., Anik M., Haoxin W., and Jiang X. "AIEnergy: An energy benchmark for AI-empowered mobile and IoT devices". *ITU Journal on Future and Evolving Technologies*, Volume 6, Issue 2, June 2025. Pp 183-197.
- [8] Göthel J., Corsten A., and Volkova O. (2025) "Evaluating the hydrogen supply chain so far—An assessment and review of critical aspects for an economy supported by a "hydrogen infrastructure"" *Next Energy*, Volume 9, October 2025, 100448.
- [9] US Dept of Energy, "Water Electrolyzers and Fuel Cells Supply Chain. Supply Chain Deep Dive Assessment". U.S. Report. Department of Energy Response to Executive Order 14017, "America's Supply Chains". 91 p. Available from www.energy.gov
- [10] Chen Z., Eli Q., and Yang L., "Study on the comprehensive performance of a hybrid power system based on hydrogen-driven solid oxide fuel cells for green unmanned aerial vehicles". *Energy Conversion and Management* vol 327, March 2025, 119611.
- [11] Sagar P., Hamdani I. R., Levato T., Giannini V., and Das G. (2026) "Graphene and its derivatives in supercapacitors: a comparative review". *Mater. Adv.* 2026, 7, 83-108.
- [12] Simon P. and Gogotsi Y., "Perspectives for electrochemical capacitors and related devices," *Nature Materials*, vol. 19, pp. 1151-1163, 2020.
- [13] Christofidis, C., Otero-Casado A., Torres-Ferrera P., Marom D. M., Parisi G., Napoliet A., "Performance assessment of inter-leaver filters for next-generation mobile transport," *Journal of Optical Communications and Networking*, vol. 18, no. 1, pp. 16-26, 2025.
- [14] Marom D. M., Roeloffzen, C. G. H., Botter, R., Christofidis, C., & Tomkos, I., "Fine-Resolution, Four-Port Optical Interlacer for Subcarrier-Level Optical Front-Haul Networking," *IEEE Photonics Society Summer Topicals Meeting Series (SUM)*, 2024.
- [15] Gardiner N., Jowitt S., and Sykes J. P. (2024) "Lithium: critical, or not so critical?" *Geoenergy* 2(1). 2024. <https://doi.org/10.1144/geoenergy2023-045>
- [16] Pulli P., "Geopolitical Sustainability of Lithium Supply Chain". 2025 IEEE International Conference on Engineering, Technology, and Innovation (ICE/ITMC). Valencia, Spain. IEEE. 8 p.
- [17] Corrigan C. C., Ikonnikova S. A., "A review of the use of AI in the mining industry: Insights and ethical considerations for multi-objective optimization". *The Extractive Industries and Society*, Volume 17, 2024, 101440, ISSN 2214 790X. Available <https://doi.org/10.1016/j.exis.2024.101440>
- [18] Yoon K. -S., Oh J. H., Lee H. J., Kim J. Y. and Cho I. K., "Wide-band Magnetic Induction Wireless Communications in Challenging Underground Environments: A Current-Driven Scheme," in *IEEE Internet of Things Journal*, vol. 12, no. 13, pp. 24929-24943, July 1, 2025. <https://doi.org/10.1109/JIOT.2025.3557019>
- [19] Hund K., La Porta, D., Fabregas T., Laing T.; Drexhage, J. Minerals for Climate Action: "The Mineral Intensity of the Clean Energy Transition", *World Bank Report*, 2020.
- [20] Topol E., "High-performance medicine: the convergence of human and artificial intelligence". *Nature Medicine*, vol. 25, pp. 44-56, 2019. <https://doi.org/10.1038/s41591-018-0300-7>

- [21] Bhowmick, A., Hazarika, S. M.: "An insight into assistive technology for the visually impaired and blind people: State-of-the-art and future trends". *IEEE Reviews in Biomedical Engineering* 10, 195-207 (2017).
- [22] Reyes-Cruz, G., Fischer, J. E., Reeves, S.: "Demonstrating interaction: The case of assistive technology". *ACM Transactions on Computer-Human Interaction* 29(5), 1-37 (2022).
- [23] Polus M., Keikosrokiani P., Uusimaa J., Komulainen-Ebrahim J., Annunen J., Khan S., and Walrus M., "The role of digital care pathway for epilepsy on patients' treatment burden: clinicians' perspective". In *Nordic Conference on Digital Health and Wireless Solutions* (pp. 257-268). 2024. Cham, Switzerland. Springer Nature.
- [24] El-Taher, F. E.-Z., Taha, A., Courtney, J., McKeever, S.: "A systematic review of urban navigation systems for visually impaired people". *Sensors* 21(9), 3103 (2021). <https://doi.org/10.3390/s21093103>
- [25] Buchholz, M., Holmgren, K., Ferm, U.: "Remote communication for people with disabilities: Support persons' views on benefits, challenges, and suggestions for technology development". *Technology and Disability* 32(2), 69-80 (2020).
- [26] Chaudary, B. S., Pohjolainen S., Aziz S., Arhippainen., Pulli P., "Teleguidance-based remote navigation assistance for visually impaired and blind people: Usability and user experience". *Virtual Reality* 27(1), 141-158 (2023). <https://doi.org/10.1007/s10055-021-00536-z>
- [27] Almeida, L., Menezes, P., Dias, J.: "Telepresence social robotics towards co-presence: A review". *Applied Sciences* 12(11), 5557 (2022). <https://doi.org/10.3390/app12115557>
- [28] Niemelä, M., Van Aerschot, L., Tammela, A., Aaltonen, I., Lammi, H.: "Towards ethical guidelines for using telepresence robots in residential care". *International Journal of Social Robotics* 13(3), 431-439 (2021). <https://doi.org/10.1007/s12369-019-00529-8>
- [29] Shneiderman, B.: "Human-Centered AI". Oxford University Press, Oxford (2022).
- [30] European Union: "General Data Protection Regulation (GDPR)", Regulation (EU) 2016/679.
- [31] Shahid, H. F., Islam, J., Ahmad, I., & Harjula, E. (2025, July). Optimizing resource-aware service orchestration in edge-cloud continuum. In *2025 IEEE Intelligent Mobile Computing* (pp. 44-50). IEEE.
- [32] Chaudary B., Pulli P., Harjula E. (2026). "A Human-AI Digital Health Architecture for Scalable Visually Impaired People (VIP) Navigation". *Nordic Conference on Digital Health and Wireless Solutions*. Oulu, Finland. June 2026.
- [33] Han S., Pool J., Tran J., and Dally W., "Edge AI: Machine learning for mobile and IoT devices," *IEEE Micro*, vol. 40, no. 6, pp. 22-29, 2020.
- [34] Kamruzzaman, M. M.: "New opportunities, challenges, and applications of edge-AI for connected healthcare in smart cities". In: *Proceedings of the IEEE Globecom Workshops* (2021).
- [35] Rahmani, A. M., et al.: "Exploiting smart e-health gateways at the edge of healthcare Internet of Things". *Future Generation Computer Systems* 78, 641-658 (2018). <https://doi.org/10.1016/j.future.2017.02.014>
- [36] Rancea, A., Anghel, I., Cioara, T.: "Edge computing in healthcare: Innovations, opportunities, and challenges". *Future Internet* 16(9), 329 (2024).
- [37] Floridi, L., et al.: "AI4People—An ethical framework for a good AI society". *Minds and Machines* 28, 689-707 (2018). <https://doi.org/10.1007/s11023-018-9482-5>
- [38] Amershi, S., et al.: "Guidelines for Human-AI interaction". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM (2019). <https://doi.org/10.1145/3290605.3300233>
- [39] Okamura, K., Yamada, S.: "Adaptive trust calibration for human-AI collaboration". *PLOS ONE* 15(2), e0229132 (2020). <https://doi.org/10.1371/journal.pone.0229132>
- [40] Samavati, F. C., Abadi, A. R. G., & Samavati, F. C. (2025). "Assistive Technologies for the Visually Impaired: A Review". *Cureus Journals*, 2(1).
- [41] Velázquez R., "Wearable assistive devices for the blind". *Robotics and Autonomous Systems*, vol. 62, no. 12, pp. 1708-1718, 2014.
- [42] Borenstein J., Ulrich I., "The GuideCane: A computerized travel aid for the active guidance of blind pedestrians". *Proc. IEEE ICRA*, 1997.
- [43] Real, S., and Araujo, A., "Navigation systems for the blind and visually impaired: Past work, challenges, and open problems". *Sensors*, 19(15) 2019, 3404. <https://doi.org/10.3390/s19153404>
- [44] Herbst, J. F. "NdFeB permanent magnets: Applications and supply chain consideration". *Journal of Magnetism and Magnetic Materials*, 2014.
- [45] Kim H., "Advances in tactile display technologies for visually impaired users". *IEEE Transactions on Haptics*, 2019.
- [46] Keskinen T., "Keliber Lithium Project Pre-Feasibility Study". Sweco Industry Oy, Helsinki, Finland. 2016, 215 p. Available: <https://www.scribd.com/document/460023984/keliber-oy-pre-feasibility-study-final-2016-14-03-pdf>
- [47] Johnson C. A., Clavijo A., Lorca M., and Andrade M. O., "Bringing the state back in the lithium triangle: An institutional analysis of resource nationalism in Chile, Argentina, and Bolivia." *The Extractive Industries and Society*, Volume 20, 2024, 101534, ISSN 2214-790X, Available: <https://doi.org/10.1016/j.exis.2024.101534>
- [48] Coherent Market Insights, "Geopolitical factors affecting platinum mining and trade." Available: <https://www.coherentmarketinsights.com/blog/energy/geopolitical-factors-affecting-platinum-mining-and-trade-2810>
- [49] Center for Strategic and International Studies (CSIS), "Greenland rare earths and Arctic security." Available: <https://www.csis.org/analysis/greenland-rare-earths-and-arctic-security>

- [50] Dijkstra, R., King, M., Lee, H. Sulfuric Acid Production in the Copper Industry—A Review with Future Insights. In: 12th International Copper Conference. COPR 2025. Springer, Cham. https://doi.org/10.1007/978-3-032-00102-3_4
- [51] IMDEA Materials Institute, “Global copper crisis: do we have alternatives?” Available: <https://materials.imdea.org/global-copper-crisis-do-we-have-alternatives/>
- [52] Batteries News, “Samsung’s silver solid-state battery closer to becoming mainstream.” Available: <https://batteriesnews.com/samsungs-silver-solid-state-battery-closer-to-becoming-mainstream/>
- [53] Cytera, C., “Gallium, Germanium, and China — The Minerals Inflaming the Global Chip War”. The Center for European Policy Analysis (CEPA). Available: <https://cepa.org/article/china-gallium-and-germanium-the-minerals-inflaming-the-global-chip-war/>
- [54] BIS Research, “Inside Europe’s supercapacitor revolution: breakthrough materials and 2025 market momentum.” Available: <https://bisresearch.com/insights/inside-europes-supercapacitor-revolution-breakthrough-materials-and-2025-market-momentum>
- [55] Mining SEE News, “Pakistan’s Reko-Diq copper project could anchor Europe’s electrification future/” Available: <https://www.miningsee.eu/pakistans-reko-diq-copper-project-could-anchor-europes-electrification-future/>
- [56] Mining SEE News, “Pakistan seeks UAE investment for five mineral projects, including major copper mining ventures”. Available: <https://www.miningsee.eu/pakistan-seeks-uae-investment-for-five-mineral-projects-including-major-copper-mining-ventures/>
- [57] M. S. Malkani, "Mineral Resources of Gilgit Baltistan and Azad Kashmir, Pakistan: An Update". Open Journal of Geology, Vol. 10 No. 6, 2020. Available: <https://doi.org/10.4236/ojg.2020.106030>
- [58] Modern Diplomacy, “China and Pakistan Shipping Pact Takes Shape”. Available: <https://moderndiplomacy.eu/2025/08/14/china-and-pakistan-shipping-pact-takes-shape/>
- [59] U.S. Geological Survey, National Minerals Information Center. “Pakistan: Mineral Industry Statistics and Information,” 2024 country overview and data release. U.S. Geological Survey, 2026. Available: <https://www.usgs.gov/centers/national-minerals-information-center/pakistan>
- [60] Geological Survey of Pakistan. “GSP Achievements: Saindak Copper-Gold Deposit and Reko Diq Copper-Gold Deposit.” Geological Survey of Pakistan. Available: <https://gsp.gov.pk/gsp-achievements/>
- [61] Barrick Mining Corporation. “Barrick Provides an Update on Reko Diq,” April 2, 2026. Available: <https://www.barrick.com/English/news/news-details/2026/barrick-provides-an-update-on-reko-diq/default.aspx>
- [62] Hevner, A. R., "A Three Cycle View of Design Science Research," Scandinavian Journal of Information Systems: Vol. 19: Iss. 2, Article 4. Available at: <https://aisel.aisnet.org/sjis/vol19/iss2/4>
- [63] U.S. Geological Survey. “USGS mineral commodity summaries 2025”. Available <https://pubs.usgs.gov/periodicals/mcs2025/mcs2025.pdf>

Biography



(2025 - present).

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