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Emerging Trends in Electronic Engineering for Future Intelligent Technologies

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ABSTRACT
The evolution of electronic engineering is moving from traditional circuit based systems to intelligent, interconnected, adaptive and autonomous systems. The key emerging trends in the future of intelligent electronic systems, such as AI-enabled hardware, edge AI, TinyML, in-memory and neuromorphic computing, advanced semiconductor technologies, smart sensors, IoT architectures and next-gen wireless communications, are explored in this review. Specific attention to intelligent power electronics, integration of renewable energy, energy harvesting, flexible and wearable electronics and sustainable electronic design. The growing use of these technologies in autonomous transportation, robotics, smart manufacturing, human–machine interaction, and intelligent infrastructure is also featured. Despite the significant technological advances, issues of energy consumption, thermal management, miniaturization, heterogeneous integration, reliability, cybersecurity, interoperability and electronic waste remain as challenges for wide-spread implementation. Going forward, ultra-low power architectures, energy autonomous devices, energy efficient AI accelerators, sustainable materials and integrated sensing-computing-communication platforms are likely to be a key focus. These innovations will combine to create an intelligent technology base that is fundamental to the efficient, secure, sustainable and human-centric nature of the intelligent technology.

Keywords: Electronic Engineering, Intelligent Technologies, Artificial Intelligence, Smart Electronics, Emerging Technologies

INTRODUCTION

The world of electronic engineering is changing radically as traditional circuits are becoming intelligent, interconnected, adaptive and increasingly autonomous technology platforms. Semiconductor devices, embedded computing, Artificial Intelligence (AI), sensing technologies, wireless communication, power electronics, and the intelligent control have pushed the boundaries of traditional control technologies. The role of electronic systems is no longer just to acquire, process, transmit or control an electrical signal, but to interpret information, learn from the operating conditions, optimise their behaviour and dynamically interact with users and their environments. The shift has created electronic engineering as a pivotal technological enabler for a smart infrastructure, autonomous machines, connected healthcare, advanced manufacturing, intelligent transportation and energy efficient digital ecosystems. AI has become increasingly prevalent in Electrical and Electronic engineering, especially in the creation of intelligent systems that monitor, predict, optimize, and make decisions (Sundararajan et al., 2025). AI has thus become one of the main drivers transforming modern engineering.

Currently, machine and deep learning, computer vision and intelligent optimization techniques are integrated in engineering systems for enhancing automation, operational accuracy, reliability and responsiveness (Palazzo et al., 2025). Concurrently, this technologic change is impacting the knowledge and skills demanded of future electronic engineers. The rapid changes in technologies demand professional and educational institutions to foster multi-disciplinary abilities, current engineering methods and better linkages between education, research and technological innovation (Haba, 2025). In the context of electrical engineering, AI has started to find its use in power systems, control, fault detection and diagnosis, management of renewable energy resources, electronic design, and predictive maintenance, while challenges such as computational power, data quality, interpretability, and integration persist (Nguyen & Kittur, 2025). The development of smart computing architectures is another example of the shift from traditional electronic processing to the more advanced computing paradigms.

Intelligent computing systems integrate the latest advances in algorithms, hardware architecture, data processing and adaptive computational mechanisms to solve complex problems that cannot be efficiently solved by existing methods and solutions (Zhu et al., 2023). These developments are related to specialized AI accelerators, edge computing, neuromorphic and in-memory computing, and high-speed semiconductor technologies. The purpose of these methods is to enhance the computational capability and reduce latency and energy consumption, particularly in the case of resource constrained smart devices. They are also applicable to autonomous systems, where intelligent electronics need to be integrated with sensing, perception, processing, control and physical interaction. The convergence is even more evident in the field of intelligent robotics, as robotic systems are increasingly relying on AI, cutting-edge sensors, embedded processors, and adaptive control systems to execute complex tasks with increased autonomy and environmental awareness (Licardo et al., 2024).

The other large aspect of the future intelligent electronics is connectivity. Advances in the fields of artificial intelligence, Internet of Things (IoT) and advanced wireless communication are making distributed electronic systems with numerous interacting devices that collect data, communicate, and make coordinated decisions increasingly possible. For example, in a smart grid system, AI, IoT, and 5G can be used to monitor electrical grid usage in real-time, optimize energy consumption, predict demand, and increase the flexibility and responsiveness of the electrical grid (Esenogho et al., 2022). Wireless sensor networks (WSN) are another important field where this is the case, providing sensing and communication in industrial monitoring, environmental observation, health, agriculture, smart cities and other intelligent applications. Network architectures, energy management, communication protocols and sensor capabilities are all evolving and offer great promise in next generation intelligent systems (Trigka & Dritsas, 2025).

Electronic engineering is also shifting towards more miniaturized, wearable, flexible and integrated technologies that are closely coupled with human activities. The wearable electronic devices showcase the integration of microfluidics, smart sensing, flexible materials, and miniaturized components to deliver continuous and personalized monitoring solutions (Apoorva et al., 2024). The developments are significant for biomedical monitoring and human–machine interfaces, but also have applications in sports and in occupational safety, environmental sensing, and personalized intelligent services. At the same time, new technologies are reshaping the way engineering knowledge is created, produced, and used.At the same time, new technologies are changing the process of knowledge creation, production and usage in engineering. New technology-driven learning environments, such as digital platforms, AI-supported learning environments, immersive technologies, and others, have new opportunities for preparing learners to be part of the technological changes occurring in the world, with challenges relating to the infrastructure, accessibility, implementation, and digital competence (Almufarreh & Arshad, 2023).

This advances makes the adoption of future intelligent technologies significant engineering challenges. With greater computation needs come higher energy needs and thermal-management needs, and scaling devices continues to be a challenge in terms of fabrication, reliability, integration, etc. Cyber security, privacy, interoperability and standardization issues are also a challenge posed by connected intelligent systems. Furthermore, rapid innovation has increasingly to be complemented by the need for sustainability, which encompasses the responsible use of materials, energy-efficient running of equipment, the reuse of electronics and electronic-waste reduction. In order to solve these coupled problems, one has to look at electronic engineering beyond the single-dose technological advancement and go towards the integrated architectures where sensing, computation, communication, power management and intelligence work together.

In this context, this review explores some of the major emerging trends that are shaping up the future of electronic engineering and their impact on intelligent technologies of the future. Specifics are highlighted on the use of intelligent computing hardware, AI-powered electronics, the latest in semiconductor technology, smart sensors, IoT systems, next generation communications, intelligent power electronics, flexible and sustainable electronics and the growing use sectors. The review addresses these technological aspects bringing to light how their interaction can influence more and more independent, efficient,

connected and human centred electronic systems. The objectives of this study are as follows:
To examine emerging electronic engineering technologies enabling intelligent, adaptive, interconnected, and energy-efficient future systems
To explore the integration of artificial intelligence, advanced computing, sensing, communication, and electronic technologies
To identify major technological challenges, application opportunities, and future directions for next-generation intelligent electronic systems

2. EVOLUTION OF ARCHITECTURES OF ELECTRONIC ENGINEERING AND INTELLIGENT SYSTEMS

2.1 Conventional to Intelligent Electronics Transition

The evolution of electronic systems was from analog circuits to digital platforms, embedded systems and intelligence electronic architectures. Analog electronics was the first to offer continuous signal processing, but digital technologies provided programmable and reliable information processing. Later, embedded systems integrated processors, memory, sensing and control functions into application-specific devices (Cavus, 2025). These capabilities are exploited in modern smart electronics, which integrate sensing, computation, communication, and automated decision-making into a single architecture. The shift is evident in the use of connected sensors, wearable devices, intelligent monitoring, and data-driven clinical support systems for cardiovascular management (Ullah et al., 2023). Electronics are thus more and more used as responsive than passive processing devices.

2.2 High-density integration and miniaturization

Integrated circuits have continued to get better and better, and more computing power has been crammed into smaller and smaller electronic platforms. Higher transistor densities, improved fabrication processes and sophisticated packaging techniques enable System-on-Chip architectures integrating processors, memory, communication interfaces and specialized accelerators. Heterogeneous integration also includes integration of components manufactured with different technologies. Chiplet architectures are modular alternatives to monolithic semiconductor architectures. Such miniaturization allows for small intelligent devices with large processing and connectivity needs. IoT-enabled smart-city systems depend on integrated sensing, communication, and AI capabilities to efficiently process distributed information (Alahi et al., 2023). Such developments are improving the scalability and functionality across intelligent electronic architectures.

2.3 Hardware/Software Co-Design

Intelligent electronic systems must be high performance, energy efficient and adaptable to particular applications. So, hardware-software co-design is a necessity for these systems. This approach does not focus on the separate design of hardware and software, but optimizes the overall system performance by the synchronization of the processor architectures, memory, sensors, communication components and intelligent algorithms. Reconfigurable platforms enable the possibility to adapt computational resources on-the-fly according to operational needs, whereas dedicated hardware accelerators improve the execution of resource demanding intelligent algorithms. The deployment of smart gas sensing technologies demonstrates the importance of integrating advanced sensing hardware with computational techniques for better selectivity, sensitivity and intelligent understanding of the sensor responses (Zong et al., 2025). This combination enables the creation of responsive architectures for intelligent real world applications.

2.4 Intelligence Embedded

Embedded intelligence involves inserting the computational and decision-making ability directly into electronic devices so that information can be processed near the point of creation rather than relying solely on centralized computing infrastructure. Modern embedded processors can evaluate sensor inputs, recognize patterns, run control algorithms and generate real-time responses with lower communication latency. This ability allows autonomous devices to adapt their functioning to the environmental conditions and application requirements. Smart technologies are increasingly supporting sustainability-oriented applications thru digital monitoring, intelligent information processing, and technology-supported management approaches (Zhang & Deng, 2024). Embedded intelligence is therefore an important foundation for autonomous electronics capable of localized, responsive and context-aware decisions (Table 1) (Figure 1).

Table 1. Evolution of Intelligent Electronic Architectures

Technology Stage	Key Feature	Intelligent Capability	Application	Reference

Embedded electronics	Integrated processing	Real-time control	Smart devices	Ullah et al. (2023)
Smart sensors	Sensing and processing	Adaptive monitoring	Smart systems	Zong et al. (2025)
IoT architectures	Connected devices	Distributed intelligence	Smart cities	Alahi et al. (2023)
Intelligent electronics	Hardware–software integration	Autonomous decisions	Sustainable systems	Zhang & Deng (2024)

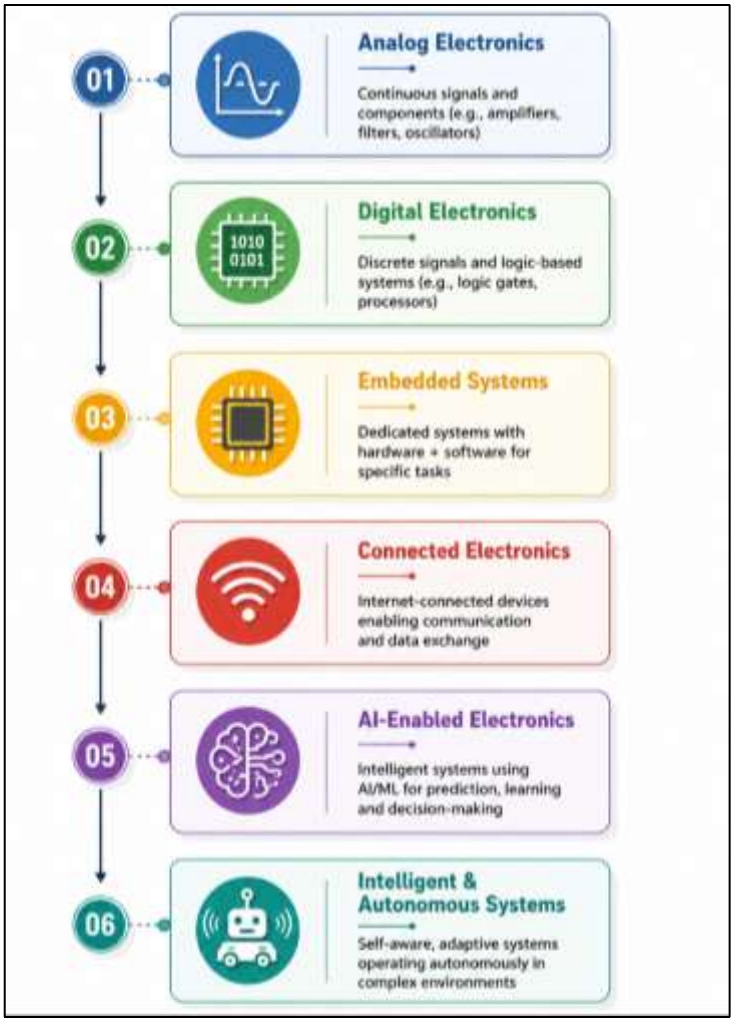

Figure 1. Evolution of Electronic Engineering Toward Intelligent Systems

3.EMERGING COMPUTING HARDWARE AND ARTIFICIAL INTELLIGENCE

3.1 Electronic Systems Enabled by AI

Electronic systems enabled by AI combine machine learning algorithms with sensors, processors, communication interfaces, and control components to enable intelligent functionality (Dimitriadou & Lanitis, 2023). This combination enables electronic devices to recognize patterns, predict operating conditions, optimize performance and detect abnormalities without continuous human intervention. With intelligent control, system parameters can be adjusted dynamically, predictive algorithms can detect faults early and plan maintenance. Intelligent processing and connected technologies have already transformed organizational processes thru automation, analytics and adaptive digital capabilities (Agarwal et al., 2024). Hence, the integration of AI is moving the operation of electronic systems from rule-based operation to more and more responsive, predictive, and context-aware technological platforms.

3.2 TinyML and Edge AI

Edge AI and TinyML allow machine learning algorithms to run on resource-constrained electronic devices, rather than continuously sending data to centralized cloud infrastructure. Processing on the device reduces communication latency, improves responsiveness, reduces bandwidth requirements and can improve data privacy. TinyML is all about microcontrollers and low-power processors so you can do smart inference even when memory and energy are scarce. Similarly, requirements are relevant in connected systems deployed remotely, where energy-efficient communication technologies enable distributed sensing and ongoing surveillance of agricultural environments (Pagano et al., 2022). These capabilities make localized intelligence more practical for wearable electronics, industrial monitoring, autonomous sensors, agriculture, and other real-time applications.

3.3 Neuromorphic Computing

Neuromorphic computing is a branch of computing that aims to mimic the fundamental features of biological neural processing in electronic architectures inspired by the brain. Neuromorphic systems, unlike conventional computing architectures, focus on event-driven computing, parallelism and localized computation, which could result in substantial improvements in energy efficiency for smart applications. Spiking neural networks encode information in the form of discrete events, similar to the activity of biological neurons, while special neuromorphic processors directly implement these mechanisms in hardware. Computing architectures for data-centric AI approaches are more and more required to efficiently process complex healthcare information and support intelligent diagnostic applications (Khang et al., 2023). Thus, neuromorphic technologies hold great promise for future autonomous sensors, robotics, biomedical devices, and adaptive edge-intelligence systems.

3.4 Near-Memory and In-Memory Computing

Conventional computing architectures suffer from performance and energy limitations because data needs to be shuffled back and forth between separate processors and memory units. These bottlenecks are tackled by in-memory and near-memory computing, which perform computational operations inside memory arrays or close to the stored data. These architectures can reduce the data transfer, latency, and energy consumption making them attractive for data intensive intelligent applications. Robotic medical platforms, including advanced wireless capsule technologies, are reflective of the increasing demand for miniature systems that can integrate sensing, processing, communication and autonomous operation with severe physical constraints (Cao et al., 2024). Memory-centric computing could therefore enhance future intelligent electronics with resource constraints that require fast local processing.

3.5 New Semiconductor Technologies

Traditional silicon electronics faces performance, power and scaling limits that are critical to overcome with novel semiconductor technologies. Wide bandgap materials such as gallium nitride and silicon carbide are advantageous for high power, high frequency and high temperature applications, and two dimensional materials are promising for very compact next generation devices. Also, beyond-CMOS concepts explore alternative switching and computing mechanisms for the future electronic architectures. Advanced semiconductor platforms will be of particular importance for intelligent sensing applications that require compactness, reliability, efficiency and integrated processing. The adoption of precision agriculture greatly relies on sophisticated smart sensors that enable constant environmental monitoring and data-informed agricultural management (Aarif KO et al., 2025) (Table 2) (Figure 2).

Table 2. Emerging AI and Computing Hardware

Technology	Core Feature	Major Advantage	Application	Reference
AI-enabled electronics	Machine learning	Adaptive operation	Intelligent control	Agarwal et al. (2024)
Edge AI/TinyML	On-device AI	Low latency	Edge devices	Pagano et al. (2022)
Neuromorphic computing	Brain-inspired processing	Energy efficiency	Intelligent systems	Khang et al. (2023)
Memory-centric computing	Localized computation	Reduced data movement	Embedded systems	Cao et al. (2024)
Smart sensing hardware	Integrated intelligence	Real-time analysis	Precision agriculture	Aarif KO et al. (2025)

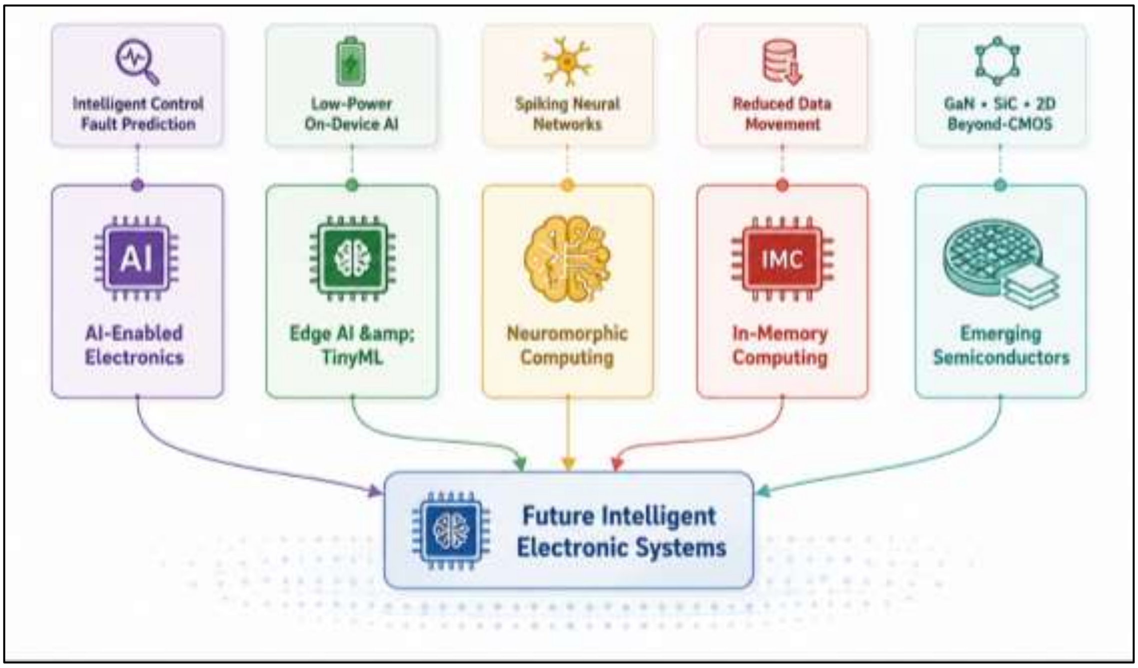

Figure 2. AI and Emerging Computing Hardware Ecosystem

4. INTELLIGENT SENSORS, IOT, AND CONNECTED ELECTRONIC SYSTEMS

Intelligent sensors, Internet of Things (IoT) platforms and connected electronic systems are emerging as key components of future intelligent technologies thru the integration of sensing, computation, communication and automated decision making in distributed environments. Smart sensors are increasingly embedded with self-calibration, signal conditioning, processing and intelligent algorithms, enabling devices to interpret measurements locally rather than being simply data acquisition components. The integration of nanoscale technologies with AI further demonstrates the potential of highly sensitive intelligent sensing platforms for complex applications such as cancer prediction, screening, and detection (Chugh et al., 2024). MEMS and NEMS technologies build on these capabilities with miniaturized mechanical and electronic structures to enable compact, energy-efficient microsystems and nanosystems for environmental, biomedical, industrial and consumer applications. Meanwhile, flexible sensing materials have contributed to the advancement of wearable sensors, electronic skin, and conformal monitoring devices, which can continuously interact with the human body and its surrounding environment. Such sensing technologies are interconnected thru embedded architectures for device-to-device communication, remote monitoring and distributed intelligence in IoT electronics. For example, connected transportation represents an important example in which emerging vehicle-to-everything architectures integrate vehicles, infrastructure, communication networks, and intelligent services to improve efficiency and support greener mobility ecosystems (Aldhanhani et al., 2024). Cloud-connected intelligent architectures also enable the integration of sensor information with sophisticated computation models. An example of how connected sensing with cloud processing can enable automated analysis of the environment is neural-network-based vehicle-emission monitoring (Anusha et al., 2024). However, large sensor datasets are continuously transferred to centralized servers, which can lead to increased latency, bandwidth consumption and communication energy requirements. Edge and fog computing overcome these limitations by moving computing resources closer to the sensors and connected devices, allowing for faster localized processing and more responsive decision-making. Such real-time connected technologies are also influencing educational institutions, facilitating mobile and digitally mediated interactions that support increasingly technology-rich learning environments (Alam, 2023). In addition, multi-sensor integration and sensor fusion combine heterogeneous information from visual, acoustic, environmental, biomedical, motion and other sensing modalities to generate more comprehensive representations of operating conditions. AI-assisted fusion algorithms can relate these inputs to each other, reduce uncertainty, and generate context-aware interpretations. Intelligent sensors, miniaturized sensing platforms, wearable electronics, IoT connectivity, edge processing, and sensor fusion, collectively, constitute a common technological infrastructure for responsive, interconnected, and more autonomous electronic systems (Table 3) (Figure 3).

Table 3. Intelligent Sensors and Connected Electronic Systems

Technology	Primary Function	Key Benefit	Application	Reference
Smart sensors	Intelligent sensing	Real-time monitoring	Smart environments	Chugh et al. (2024)
IoT electronics	Device connectivity	Distributed operation	Connected systems	Aldhanhani et al. (2024)
Cloud-enabled sensing	Remote processing	Advanced analytics	Emission monitoring	Anusha et al. (2024)
Edge computing	Local processing	Reduced latency	Intelligent IoT	Alam (2023)
Sensor fusion	Multi-source integration	Improved decisions	Autonomous systems	Chugh et al. (2024)

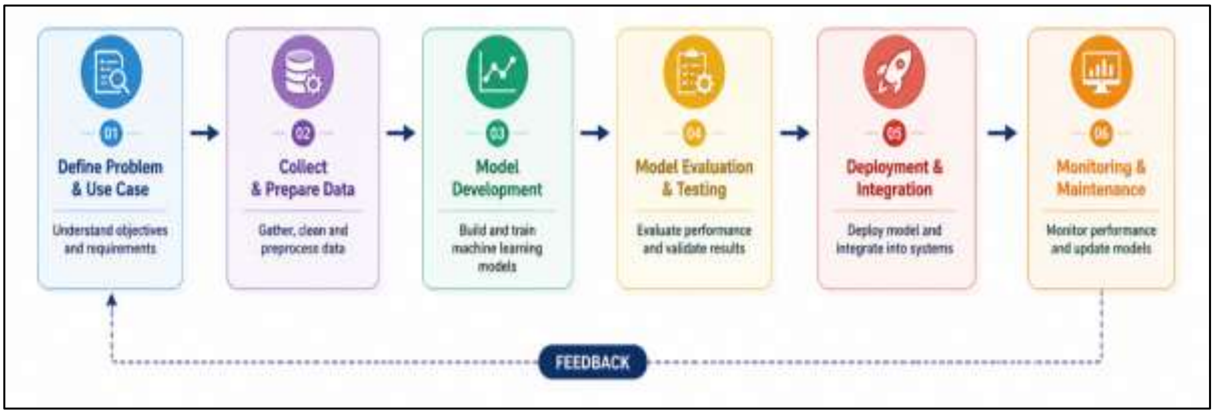

Figure 3. Connected Intelligent Electronics Architecture

5. NEXT-GENERATION COMMUNICATION TECHNOLOGIES FOR INTELLIGENT ELECTRONICS

Next-generation communication technologies are at the core of intelligent electronics, offering high-speed, reliable, low-latency and energy-efficient connectivity among more and more distributed electronic systems. 5G to 6G transition is expected to be enhanced in terms of ultra-reliable communication and the incorporation of artificial intelligence directly into the network management, resource allocation, and adaptive connectivity. The capabilities are especially relevant to smart grids that are based on machine learning, renewable energy integration, storage systems and communication infrastructure to enable intelligent energy management and grid transformation (Kiasari et al., 2024). Millimeter-wave and terahertz electronics promise to provide much larger bandwidths for high capacity wireless communication beyond traditional frequency bands. However, propagation losses, hardware complexity, and energy consumption remain significant technical challenges. An alternative emerging approach comes from reconfigurable intelligent surfaces that electronically steer electromagnetic-wave propagation and enable wireless environments to adapt dynamically their signal reflection, coverage and interference as communication requirements change. These advances can facilitate highly-connected industrial environments where communication, sensing, automation, robotics and data processing are important enabling technologies for intelligent manufacturing and automotive smart factories (Lee et al., 2023). The convergence is further enhanced by integrated sensing and communication, allowing common electronic and wireless infrastructures to simultaneously sense the environment and transmit data. The technology has the potential to improve spectral and hardware efficiency for autonomous vehicles, robotics, smart infrastructure and context-aware environments. Reliable connectivity is also important when considering wearable diagnostic technologies, where continuous acquisition and interpretation of physiological information can help with early disease detection and biomarker monitoring (Haghayegh et al., 2024). However, the communication capabilities of future intelligent devices need to be preserved under stringent power budgets, in particular, in IoT nodes, wearable systems and remotely deployed sensors. Hence, low-power wireless protocols, optimized transceivers, duty-cycling strategies and efficient network architectures are crucial to increase operational lifetime. The advances in the battery technologies can improve the energy autonomy of the connected electronics by improving the storage performance and the potential for the future mobile and intelligent devices, according to Itani and De Bernardinis (2023). The wireless power transfer system further reduces reliance on traditional wired charging and delivers power to hard-to-reach or continuously operating connected devices (Alabsi et al., 2024). 6G, high-frequency electronics, intelligent surfaces, integrated sensing and communication, and low-power connectivity to create the communication ecosystem required for scalable, responsive and autonomous intelligent electronic systems (Table 4).

Table 4. Next-Generation Communication Technologies

Technology	Key Feature	Main Advantage	Application	Reference
5G/6G	High-speed networks	Low latency	Smart grids	Kiasari et al. (2024)
Smart connectivity	Connected electronics	Real-time communication	Smart factories	Lee et al. (2023)
Low-power wireless	Energy-efficient links	Extended operation	Wearables	Haghayegh et al. (2024)
Wireless power transfer	Contactless energy	Flexible charging	IoT devices	Alabsi et al. (2024)
Advanced batteries	Improved storage	Longer operation	Mobile electronics	Itani & De Bernardinis (2023)

6. INTELLIGENT POWER, FLEXIBLE, AND SUSTAINABLE ELECTRONICS

6.1 Power Semiconductor Devices, Advanced

Advanced power semiconductor devices are providing better efficiency, switching performance and thermal capabilities to modern power-electronic systems (Aloqaily et al., 2022). Gallium nitride and silicon carbide are wide-bandgap materials that can operate at higher voltages, frequencies and temperatures than many conventional silicon devices, enabling compact converters with lower energy losses. These features are useful for electric transportation, renewable energy interfaces, industrial systems and autonomous platforms that require efficient power conversion. For example, collaborative unmanned aerial vehicles rely on advanced communication and control architectures that operate under severe energy and hardware constraints (Javaid et al., 2023). Thus, high-performance power semiconductors are able to make electronic platforms lighter, more efficient and ever more autonomous.

6.2 AI-Driven Power Electronics

Artificial intelligence is being increasingly integrated into power-electronic systems to improve energy management, operational control, condition monitoring and fault diagnosis. Machine learning algorithms can evaluate electrical and operational parameters, detect abnormal behavior, predict component degradation and optimize control strategies according to changing loads and environmental conditions . These adaptive capabilities are particularly important for connected electronic environments consisting of heterogeneous devices with diverse energy requirements. Healthcare IoT highlights the increasing reliance of interconnected intelligent devices on robust processing, communication, security and resource management for their continued operation (Kumar et al., 2023). AI-enabled power management can therefore enhance reliability, efficiency and responsiveness in increasingly complex intelligent electronic infrastructures.

6.3 Smart Grids and Power Electronics for Renewable Energy

Smart grids integrate power electronics, communication networks, smart sensors, automated control and data analysis to improve the integration and management of distributed renewable-energy resources. Smart monitoring allows constant tracking of generation, consumption, storage and grid status, and smart management allows efficient energy distribution and demand management. Similar combinations of IoT and AI are enabling data-driven optimization of resources in smart agriculture, where connected devices help monitor and automate decision-making in the face of changing environmental conditions (Qazi et al., 2022). As renewable generation becomes more decentralized, smart electronic interfaces will be needed to coordinate variable resources, storage technologies, distributed loads, and responsive energy-management mechanisms.

6.4 Energy Harvesting and Self-Powered Electronics

Energy harvesting is a means of producing self-powered electronic systems by converting ambient solar, thermal, mechanical, vibrational or electromagnetic energy into usable electrical power. Such approaches can reduce the dependence on conventional batteries and increase the operational lifetime of remotely deployed sensors, wearable devices and IoT nodes. The issue of energy autonomy is especially important in smart environments where the number of always-on devices is growing. An example of distributed sensing and intelligent control for optimizing energy utilization and supporting sustainable operation of the building are IoT-based energy-management systems in smart buildings (Poyyamozhi et al., 2024). Integrating energy harvesting with ultra-low-power circuits will allow the creation of long-lived intelligent devices that require little maintenance.

6.5 Stretchable and Flexible Electronics

Flexible and stretchable electronics are based on the use of mechanically compliant materials and device structures that maintain their electronic functionality under bending, stretching and attachment to irregular surfaces. Such features enable conformable convergence by providing non-intrusive interfaces to continually gather information from users and physical environments.

6.6 Green and Sustainable Electronics

Energy efficient circuit design, environmentally friendly materials, longer product lifetimes and approaches to reduce electronic waste are discussed in Green and sustainable electronics. Such considerations are growing in importance with the proliferation of intelligent technologies in the workplace, infrastructure, consumer electronics, and in automated environments. The Fourth Industrial Revolution has led to an accelerated adoption of smart technologies, AI, robotics and algorithmic systems, resulting in significant technological and organizational transformations (Oosthuizen, 2022). Similarly, on the urban scale, the development of smart cities needs integrated technological systems, but must also consider sustainability, governance, infrastructure and long-term societal needs (Gracias et al., 2023). Hence, circular design and recyclable electronics will be critical for environmentally responsible intelligent technologies (Table 5) (Figure 4).

Table 5. Intelligent Power, Flexible, and Sustainable Electronics

Technology	Key Function	Main Benefit	Application	Reference
Intelligent power control	Adaptive management	Energy efficiency	Autonomous systems	Javaid et al. (2023)
Smart grids	Distributed management	Renewable integration	Energy networks	Qazi et al. (2022)
Energy management	IoT-based optimization	Reduced consumption	Smart buildings	Poyyamozhi et al. (2024)
Flexible electronics	Conformable devices	Wearability	Smart interfaces	Aloqaily et al. (2022)
Sustainable electronics	Green design	Reduced impact	Smart cities	Gracias et al. (2023)

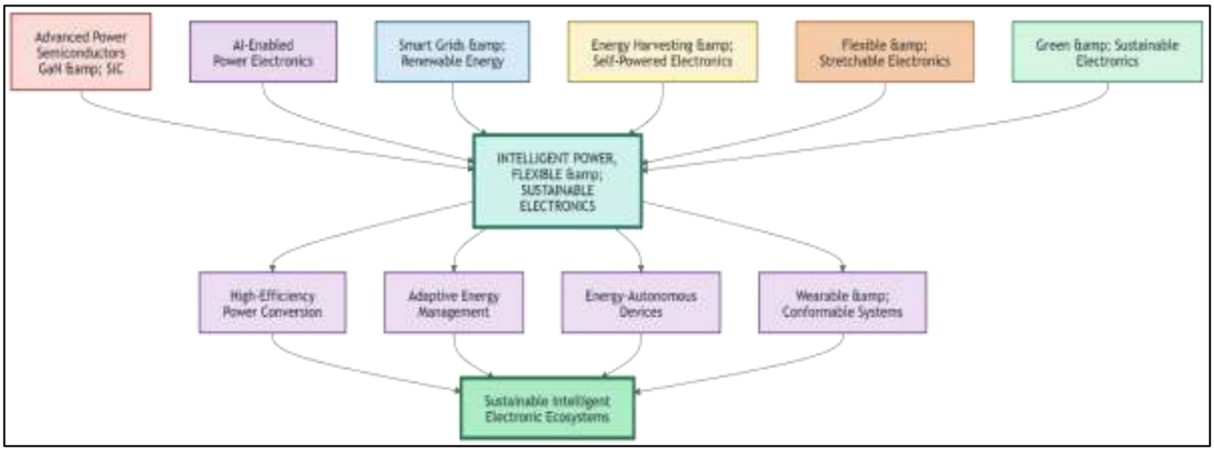

Figure 4. Intelligent Power, Flexible, and Sustainable Electronics Framework

7. APPLICATIONS OF EMERGING ELECTRONICS IN FUTURE INTELLIGENT TECHNOLOGIES

7.1 Intelligent Transportation and Autonomous Vehicles

Autonomous vehicles and intelligent transportation systems incorporate cameras, radar, LiDAR, positioning technologies, electronic control units, and embedded processors to sense the environment and make operational decisions in real time. To this end, sensor information must be processed quickly to support localization, obstacle recognition, trajectory planning and vehicle control under dynamic conditions (Almuhaya et al., 2022). Connected transportation also supports communication between vehicles, infrastructure and traffic management platforms. These capabilities demand reliable electronics with low processing latencies and high fault tolerance. Advanced manufacturing techniques such as rapidly evolving three-dimensional printing methods can further enable customized components, complex architectures and multidisciplinary engineering applications pertinent to advancing transportation technologies (Elhadad et al., 2023).

7.2 Robotics and Intelligent Automation

Nowadays, more and more sophisticated electronic systems with integrated smart sensors, actuators, embedded processors, communication modules and intelligent control algorithms are becoming significant in robotics. Sensors collect information about the location, force, proximity, movement and the surrounding environment, and actuators translate computational instructions into precise physical actions (Admass et al., 2024). Embedded intelligence enables robotic systems to interpret sensor data and alter behavior without constant external control. Similar principles can be found in smart-home systems. In these systems, sensors, controllers, communication networks and automated devices coordinate their activities based on environmental conditions and user requirements (Chakraborty et al., 2023). Further advances in embedded electronics will continue to drive advances in autonomous navigation, manipulation, collaborative robotics and intelligent automation.

7.3 Intelligent Manufacturing and Industry 4.0/5.0

Smart manufacturing combines industrial IoT, automation, intelligent sensors, data analytics, robotics and interconnected control systems to create responsive production environments. Industry 4.0 architectures focus on connectivity and cyber-physical integration, enabling production equipment to continuously communicate operational information and enable automated supervision (Folgado et al., 2024). Predictive-maintenance algorithms can use sensor measurements to identify abnormal equipment behavior prior to failures, reducing downtime and maintenance costs. Industry 5.0 further focuses on resilient, sustainable and human centric production by improving the collaboration between workers and intelligent machines. Thus emerging electronics provide the necessary sensing, processing, connectivity and control infrastructure for flexible and increasingly autonomous industrial production.

7.4 Smart Healthcare and Biomedical Electronics

Wearable electronics, biosensors, connected medical devices and embedded processing technologies for continuous physiological assessment and personalized healthcare support are increasingly becoming a part of intelligent healthcare . Wearable platforms can measure variables such as movement, temperature, cardiovascular signals and other biomarkers and communicate information to external monitoring systems . Progress in flexible and sustainable materials is also opening up opportunities for wearable technologies, like electronically functional fabrics and body-compatible sensing platforms (Hossain et al., 2024). Integrated intelligence can help to automatically interpret acquired signals, early detect abnormalities and monitor patients remotely. Future biomedical electronics will thus be expected to be more and more unobtrusive, personalized, networked and able to continuously assess health.

7.5 Intelligent Infrastructure & Smart Cities

Smart cities depend on networks of electronic infrastructure to monitor the environment, manage transportation, optimize energy use, deliver public services, and manage agriculture, buildings, and resources. Distributed sensor networks can continuously collect data about the environment and operating conditions, while IoT platforms can enable centralized or distributed analysis and responsive interventions. Smart sensors with IoT connectivity have demonstrated significant potential in precision agriculture by continuously monitoring and managing agricultural resources thru data-driven approaches (Mansoor et al., 2025). However, the adoption of intelligent infrastructure may differ significantly across geographical and socioeconomic contexts, especially with rural areas facing barriers regarding connectivity, cost, technical skills, availability of infrastructure, and institutional support (Alabdali et al., 2023).

7.6 Human-Machine Interactions

Smart interfaces are enabling human–machine interaction with electronic systems that understand physical actions, physiological signals, environmental context and user intent. More natural communication between humans and machines can be established by using flexible sensors, electronic skin, wearable interfaces, gesture recognition technologies and intelligent assistive devices. Context-aware electronics can also change system behavior based on user activities and environmental conditions, allowing for customized interaction. Smart-home technologies are an example of how integrated sensing, communication and automated control can be used to satisfy user requirements with connected devices (Chakraborty et al., 2023). Future interfaces will be more and more adaptive and unobtrusive, improving interactions with robots, healthcare devices, intelligent environments and assistive technologies (Table 6) (Figure 5).

Table 6. Applications of Emerging Electronics

Application	Enabling Electronics	Intelligent Function	Key Benefit	Reference
Transportation	Connected electronics	Real-time control	Safer mobility	Almuhaya et al. (2022)
Smart manufacturing	Industrial IoT	Predictive automation	Higher efficiency	Folgado et al. (2024)
Healthcare	Wearable electronics	Remote monitoring	Personalized care	Hossain et al. (2024)
Smart cities	IoT infrastructure	Resource management	Urban efficiency	Alabdali et al. (2023)
Precision agriculture	Smart sensors	Automated monitoring	Resource optimization	Mansoor et al. (2025)
Smart homes	Connected sensors	Automated control	Intelligent living	Chakraborty et al. (2023)

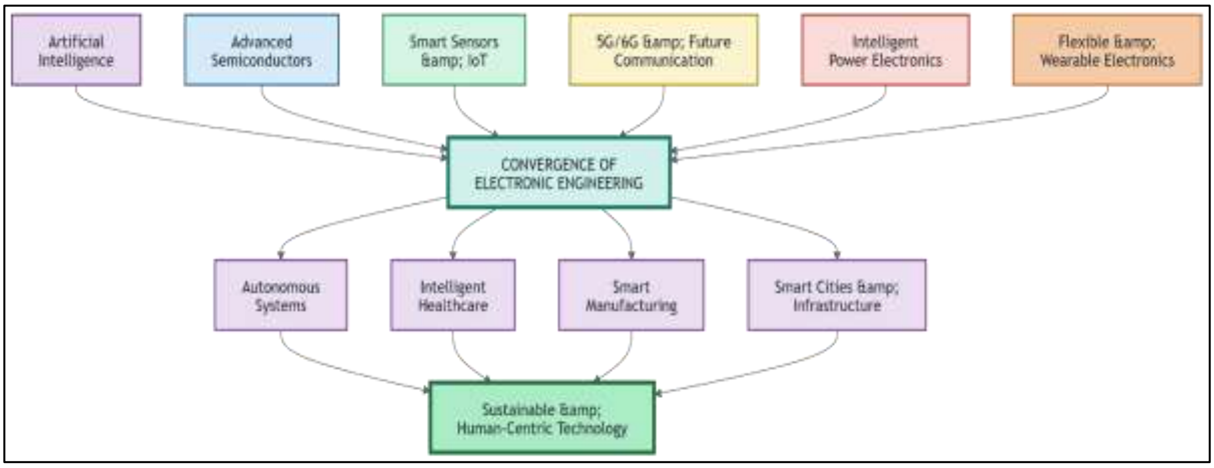

Figure 5. Convergence Framework for Future Intelligent Technologies

8. KEY CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Smart electronics are rapidly evolving and they are accompanied by an integrated technical, security and sustainability issues. The growing computational demands lead to increased power consumption and heat generation, requiring ultra-low-power circuit architectures and advanced thermal-management solutions. The scaling down of the devices is met by device scaling limitations, fabrication complexity and challenges with heterogeneous integration. Reliability is also crucial for future intelligent systems that have to be stable, fault-tolerant, self-diagnostic in the long term, particularly for autonomous and safety-critical applications. The growing connectivity create new cyber-security challenges and data-privacy challenges at the hardware level, which demand the ability to secure devices, communications and sensitive data. Interoperability is another challenge, since there are many different sensors, processors, communication technologies, and intelligent platforms that must be compatible with one another and share common standards and coordinated architectures. There are challenges in sustainable manufacturing – such as using sustainable materials, recycling and the increasing issue of e-waste. Future research needs must focus on energy autonomous electronics, next generation AI accelerators, and on neuromorphic and brain inspired computing and self-learning adaptive architectures. Sensing, computing, communications and control will converge more, facilitating integrated intelligent platforms. Human-centric design ought to make things more accessible and more interactive. In the end, the sustainable materials, circular manufacturing, secure architectures and energy efficient intelligence are essential for scalable future electronic ecosystems.

9. CONCLUSION

The transformation from the traditional circuit based technologies to the intelligent, adaptive, interconnected and increasingly autonomous systems is very significant for electronic engineering. This evolution is powered by convergence of Artificial Intelligence Hardware, advanced semiconductor devices, intelligent sensors, IoT platforms, next generation communication networks, intelligent power electronics and emerging computing architectures. All these advances are enabling electronic systems to be more efficient and functional in their ability to sense, process, communicate, optimize and make autonomous decisions in real time. The use of electronics in the new intelligent healthcare, autonomous transportation, robotics, smart manufacturing, wearable technologies, and connected infrastructure makes electronics an increasingly important part of future technology ecosystems. There are, however, significant challenges that must be solved to further progress such as computational energy consumption, thermal management, device miniaturization, heterogeneous integration, cyber-security, data privacy, reliability, interoperability and large-scale deployment. Furthermore, the use of resources, the production process and the disposal of used electronic components are of concern with regard to the utilization of sustainable development in technology development. Going forward, ultra-low power architectures, reliable and secure hardware, energy autonomous devices, sustainable materials and standard integration frameworks should be the next areas of interest for future developments. With these continued advances of sensing, computing, communication, control and artificial intelligence, more and more responsive and context-aware electronic platforms are expected, and eE is expected to be a key enabler in the design of sustainable, human-centric and intelligent technological systems.

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