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Edge Computing: Enabling Opportunities for Industry 4.0 and Addressing the Green Problem

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***Abstract*:** The convergence of Edge Computing and Industry 4.0 holds immense potential for revolutionizing industrial processes and systems, enabling enhanced real-time data processing, reduced latency, and improved scalability. This article explores the opportunities that Edge Computing presents in the context of Industry 4.0, highlighting applications such as smart manufacturing, predictive maintenance, supply chain optimization, and AI-driven insights. However, as technological advancements surge, environmental concerns regarding energy consumption and carbon footprint intensify—the "Green Problem." This paper delves into the environmental implications of Edge Computing and Industry 4.0, and proposes strategies to address these challenges, including energy-efficient processing, reduced data transmission, and localized data management. Furthermore, this article discusses the challenges and considerations associated with the adoption of Edge Computing in Industry 4.0, encompassing security, standardization, and workforce training. Through case studies and examples, the potential of Edge Computing in driving sustainable practices and shaping the future of industry is illuminated. Finally, the article presents a forward-looking perspective on the trajectory of Edge Computing and its transformative impact, underscoring the importance of a holistic approach that balances technological innovation with ecological sustainability.

Keywords: *Edge Computing; Industry 4.0; Convergence; Green problem*

1. Introduction

The combination of Edge Computing and Industry 4.0 emerges as a compelling narrative in the age of technological acceleration, promising extraordinary efficiencies, real-time insights, and disruptive innovations. This convergence of sophisticated computing paradigms with the fourth industrial revolution has the potential to change industries, boost economic growth, and reshape our interactions with technology. As we embrace this era of interconnection, it becomes critical not only to celebrate the promises, but also to traverse the complicated terrain of obstacles and considerations that comes with this incredible convergence.

This article looks into this dynamic interaction, exposing the intricate web of possibilities, environmental worries, security issues, standardization roadblocks, and labour readiness.

A thorough examination of edge computing, a paradigm that brings processing and data storage closer to the location where data is generated, paves the way for real-time insights and improved security, kicks off the voyage. The fourth industrial revolution, Industry 4.0, then takes center stage as the backdrop for the convergence, characterized by the integration of modern technologies across the value chain.

The synergy between Edge Computing and Industry 4.0 is explored through a series of compelling case studies that demonstrate how smart manufacturing, predictive maintenance, supply chain optimization, the Industrial Internet of Things (IIoT), and AI-driven applications leverage this alliance to usher in a new era of operational excellence and efficiency. Despite the promise, the "green problem"—an environmental concern—looms large.

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1.1. Understanding Edge Computing

Edge computing is a distributed computing paradigm that brings computation and data storage closer to the gadgets and sensors that produce and use data. By processing data more closely to its source at the network's edge, edge computing aims to reduce the latency, bandwidth, and security issues that come with centralized cloud computing. [1].

Real-time insights and analytics are one of the most significant benefits of edge computing. By processing data at the edge, organizations can quickly analyze it and make decisions based on the findings. Real-time information is especially helpful in industrial settings where it can increase operational efficiency and decrease downtime [2].

Edge computing also has the ability to increase security and privacy. Edge computing processes data at the edge of the network, reducing the risk of data breaches and cyberattacks. Additionally, edge computing can be used to support applications that require data privacy, such as those in the financial and healthcare sectors [3].

Edge computing is a concept that is similar to fog computing and cloudlets. Fog computing is a distributed computing paradigm that extends cloud computing to the network edge.

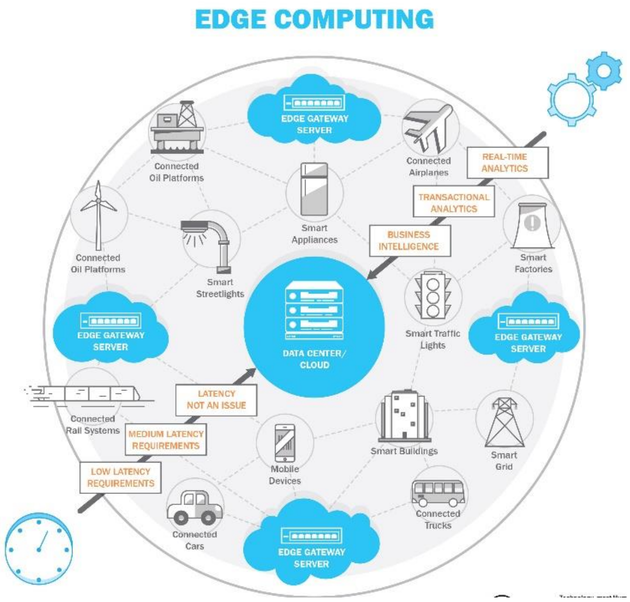

Figure 1. The datacentre ecosystem is changing as a result of IoT, effective data distribution and edge computing [100]

1.2. Industry 4.0: A Brief Overview

Modern technologies are being incorporated into the manufacturing process as part of the fourth industrial revolution, also referred to as Industry 4.0.

Businesses utilizing more than 1200 technological advancements—often categorized into nine key information-related (software) and operational-related (hardware) technological components—make up Industry 4.0. These components include the use of big data, the Internet of Things, cloud computing, cyber security, simulation, and horizontal and vertical integration. There is also X-reality, which includes virtual, augmented, and reduced reality [4].

Production, logistics, warehousing, buying, selling, and administration are just a few stages of the value chain that can use Industry 4.0 technology. Due to these factors, the adoption or rejection of at least one Industry 4.0 technology is frequently used to gauge the phenomenon or the desire to adopt Industry 4.0 principles [5].

2. Convergence of Edge Computing and Industry 4.0

The technology sector is very interested in the merging of edge computing and industry 4.0. One of the foundations of Industry 4.0, Edge Computing is an extension of the Cloud. They work together to provide a specialized process experience that is especially required in remote locations where connectivity is scarce or non-existent when configured in complementary waysm [6].

Edge computing provides enough processing power to choose the input data and equips sensors and machinery with enough calculations. It enables a system to recognize crucial data, processes the data using real-time algorithms, and removes the majority of errors from the procedure1. Businesses can increase the efficiency of their equipment by using smart sensors, and by integrating them into older equipment, the systems can operate in harsh environments [7].

Edge computing provides sensors and machinery with enough computation and processing power to choose input data. Important data can be found, real-time algorithms can be applied to the data, and most process errors can be removed. When integrated into legacy equipment, smart sensors can help businesses make the most of their machinery and enable the systems to operate in challenging conditions [7].

The convergence of Edge Computing and Industry 4.0 is critical for several reasons [8] [9]:

- Interoperability: Edge computing enables systems to communicate with one another directly, bypassing upstream, more sophisticated or intelligent systems like an enterprise resource planning (ERP) system.
- Inclusive: The edge computing system is comprised of both physical and digital identities.
- Data Processing: Edge computing provides enough processing power to choose the input data and equips sensors and machinery with enough calculations. The majority of the errors are removed from the process by using real-time algorithms to process the data.
- Intelligent Edge: Advanced connectivity, portable processing power, and artificial intelligence (AI) are all components of the intelligent edge, which is situated close to data-generating and data-using devices2. It is an evolution and convergence of trends in telecommunications, automated manufacturing, utility management, industrial monitoring, and cloud computing.
- Cloud Capabilities: Remote operations' performance may be greatly enhanced by the intelligent edge's ability to bring cloud capabilities to those operations.

Industry 4.0, which incorporates numerous technological advancements, significantly alters how businesses run. In these circumstances, edge computing is especially helpful because it also presents unique challenges [10][11][12]:

- Data Volume: Traditional data center infrastructures have a hard time keeping up with the exponential growth in data production and the number of internet-connected devices. This volume of data places a heavy burden on the internet, clogging it up and causing disruption.
- Real-Time Processing: For optimal production, Industry 4.0 needs real-time data processing, which is impossible with conventional cloud computing due to latency problems.
- Data Sensitivity: Technology advancement has led to growing worries about the ownership, management, and privacy of data and intellectual property. Many businesses are hesitant to give developers of third-party solutions access to their data.
- Interoperability: There is a lack of separation between protocols, components, products, and systems.

According to [11][13], Edge computing addresses these challenges effectively:

- Reduced Latency: By processing and analyzing data closer to the point where it is created, edge computing reduces latency. Latency is greatly decreased because data does not have to travel across a network to a cloud or data center to be processed.
- Bandwidth Saving: By processing data locally, edge computing reduces the amount of data that needs to be sent over the network, saving bandwidth.
- Data Security: Edge computing reduces the amount of data that needs to be sent over the network by processing data locally, saving bandwidth.
- Interoperability: Systems can communicate with other systems using edge computing without passing through upstream, more knowledgeable or sophisticated systems.

With its capabilities well-aligned with those of Industry 4.0, edge computing is an essential tool for overcoming the special difficulties presented by this industrial revolution.

2.1. Enhanced Real-Time Data Processing

Improved real-time data processing is a crucial aspect of edge computing and Industry 4.0 convergence. The improvement in real-time data processing within Industry 4.0 is the main force behind the convergence of edge computing and this technology. Combining edge computing with Industry 4.0 technologies like the Internet of Things significantly enhances real-time data processing capabilities [14]. Real-time application and decision-making in smart manufacturing processes are thus made possible. Real-time data processing is the timely collection, analysis, and use of data for prompt decision-making and action. Processing real-time data is essential in industries that depend on timely information and decisions, such as manufacturing, logistics, and energy [15]. Convergence between Industry 4.0 and edge computing creates both new opportunities and challenges for better real-time data processing. These challenges can be lessened by designing suitable architectures for data acquisition, communication, and processing. Many factors, such as latency, data volume and bandwidth, computing power, data protection, and IT security, have an impact on the data processing method that is chosen [14].

One way to enhance real-time data processing in the Industry 4.0 and edge computing convergence is to use edge devices. Edge devices are computing devices located closer to the source of data generation, such as sensors and Internet of Things (IoT) devices. These edge devices have the ability to filter, aggregate, and analyse data at the edge of the network [16].

According to Shao, et al. 2022 [17], the use of edge devices for data processing in the convergence of edge computing and Industry 4.0 offers several advantages. Firstly, it reduces latency by processing data closer to the source, enabling real-time insights and actions. Secondly, it reduces the frequency and real-time requirements of communication to core devices, as local processing at the edge reduces the amount of data that needs to be transmitted to the cloud or data centres.

The volume and velocity of real-time data can be effectively managed by utilizing edge devices for data processing, which improves decision-making and resource utilization. Additionally, by supplying more computational power and storage capabilities, the incorporation of cloud-based computing into the architecture can improve real-time data processing in the convergence of edge computing and Industry 4.0 [18].

Some case studies from Meyer 2022 [19] highlight the tangible benefits of edge computing in various industries. Companies like Xocean and MartinCSI have successfully leveraged edge technologies, such as MQTT and robust cellular connectivity, to revolutionize their operations. Xocean, an Irish company utilizing uncrewed surface vessels for ocean data collection, exemplifies the transformative power of edge computing. By embedding lightweight, cost-effective computers on their vessels and efficiently transmitting data via MQTT over cellular networks, they've achieved real-time data management, thanks to a confluence of advanced technologies. For a client in the oil and gas industry, MartinCSI, a system integration company, implemented an edge project. The goal of this project is to gather data from 40 service trucks, including crucial operational parameters and maintenance data, and send it wirelessly to the cloud and mobile devices. Their ability to create reliable applications with the help of cloud-based technologies and open, secure standards has provided their clients with immediate advantages and value. By demonstrating how cutting-edge technology and the cloud are making it more and more appealing for businesses to take advantage of real-time data processing and analytics, edge computing adoption has proven to be a game-changer in both situations.

2.2. Improved Latency and Bandwidth Efficiency

The improvement in bandwidth and latency efficiency is one of the main advantages of edge computing and Industry 4.0 convergence. Traditional cloud computing involves sending data to far-off data centers for processing, which increases outbound traffic's delays and costs. On the other hand, edge computing enables data to be processed at the edge of the network, where it is generated [16]. Data flows are processed locally in real-time, which reduces latency and delays in information processing. Quick feedback is made possible, and unnecessary data transmission delays are reduced. Concerns about the privacy of data processed in the public cloud are allayed by edge computing, which also improves real-time data processing while lowering latency and bandwidth usage [20]. Edge computing eliminates the need to send sensitive data to a distant cloud server where privacy and security risks could occur by ensuring that sensitive data is processed locally. Additionally, the fusion of edge computing and Industry 4.0 enables improved real-time data processing by utilizing cutting-edge analytics methods. These techniques can be applied at the edge to instantly analyze and comprehend incoming data, similar to machine learning algorithms [21]. As a result, there is less need for human intervention and autonomous systems are made possible, allowing for real-time decision-making and rapid response to urgent situations.

Improved operational efficiency in real-time data processing is another benefit of edge computing and Industry 4.0 convergence. Edge computing speeds up the transfer of data from devices to the cloud and back by bringing data processing closer to the source [22].

While edge computing offers significant benefits in terms of latency and bandwidth efficiency, there are also challenges and limitations to consider [23][24][25][26][27]:

- Hardware Limitations: Compact and powerful edge devices are required to handle complex analysis. The amount that latency can be reduced may be constrained by the difficulty of achieving this balance.

- Network management: Traffic on edge networks needs to be effectively managed and organized in order to use less bandwidth. This necessitates the use of complex network management tools and techniques, which can be difficult to implement.

- Security and privacy: Edge computing may increase security and privacy by processing and storing data closer to the end users, but it also introduces new vulnerabilities. Making sure there are reliable security measures in place is a difficult task.

- Interoperability: It can be challenging to ensure seamless interoperability between various systems and devices given the growth of IoT devices.

- Quality of Service (QoS): Maintaining a high QoS is necessary for real-time applications. However, doing so in an edge computing environment can be challenging because of things like hardware limitations and network congestion.

- Scalability: Scaling up the edge computing infrastructure to keep up with the exponential increase in network-connected devices is a significant challenge.

The necessity of ongoing edge computing research and development is highlighted by these challenges. Despite these challenges, edge computing offers the chance to improve bandwidth and latency efficiency in a variety of applications.

2.3. Scalability and Decentralization

Another advantage of the convergence of edge computing and Industry 4.0 in enhancing real-time data processing is scalability and decentralization. Edge computing shifts storage and computation load from centralized data centers to distributed edge nodes. More edge nodes can be added to handle increasing data volumes and processing demands, allowing for greater scalability [28]. On the other hand, decentralization reduces the dependency on a single centralized infrastructure, enhancing fault tolerance and resilience. On the other hand, decentralization lessens reliance on a single centralized infrastructure, enhancing fault tolerance and resilience. In the context of edge computing and Industry 4.0, this shift towards scalability and decentralization is crucial for a number of reasons. The first benefit of scalability is that it enables companies to manage the exponential growth in data produced by Industry 4.0 technologies. This is especially crucial in light of predictions that by 2025, 75% of businesses will be using edge computing to process data [29]. Industry 4.0 depends on this move toward scalability and decentralization because it enables organizations to manage the exponential growth in data produced by cutting-edge technologies like the Internet of Things and automation systems. Additionally, decentralization and scalability are crucial for ensuring effective and trustworthy data processing. The processing of data occurs at or close to the source, reducing latency and bandwidth usage, thanks to the distribution of the computational load and storage to edge nodes.

One case study that exemplifies the advantages of scalability and decentralization in the context of edge computing and Industry 4.0 is the deployment of edge servers in a smart manufacturing facility. By implementing edge servers at various points within the manufacturing facility, data can be processed and analysed in real-time, enabling immediate decision-making and action. This decentralized approach allows for faster response times and reduces the reliance on a single centralized system, enhancing fault tolerance and resilience in the event of system failures or network problems. The manufacturing facility can easily add more edge servers to handle growing data loads as they expand their operations or incorporate more Industry 4.0 technologies, demonstrating the scalability of edge server [30][31]. Decentralized data processing at this smart manufacturing facility also increases fault tolerance while ensuring continuous operations. If one edge server has an issue or fails, the other edge servers can seamlessly take over, preventing costly downtime and production pauses.

3. Opportunities and Applications of Edge Computing in Industry 4.0

There are many opportunities for the use of edge computing in Industry 4.0, which is characterized by the integration of smart technologies into manufacturing processes.

3.1 Smart Manufacturing and Predictive Maintenance

Edge computing is essential to Industry 4.0 in two key areas: smart manufacturing and predictive maintenance. Manufacturers can achieve real-time analytics and insights by processing data directly at the edge of the network, allowing them to optimize production processes and find problems before they result in downtime [32]. For example, by leveraging edge computing, manufacturers can analyze sensor data from production equipment in real time to identify patterns and anomalies that may indicate the need for maintenance or potential failures. This enables proactive maintenance strategies, minimizing downtime and increasing overall equipment effectiveness [33].

According to Bike Xie (Vice President, Engineering, Kneron), edge computing enables manufacturers to make flexible decisions about whether data may be discarded immediately after processing in order to save bandwidth use and remove time gaps. Manufacturers can move some data to the cloud if latency and bandwidth are not a problem, or process data quickly at the edge if data transmission to the cloud is a bottleneck. In addition to saving bandwidth and money, processing data closer to its intended use also makes it safer since it happens straight away [34].

3.2 Supply Chain Optimization

Another area where edge computing has significant opportunities and applications in Industry 4.0 is supply chain optimization. Edge computing enables businesses to gather and process data in real-time from various supply chain nodes. This enhances the performance of the supply chain overall by reducing inefficiencies and enabling more accurate and timely decision-making [20]. For example, edge computing can enable real-time tracking and monitoring of inventory levels, transportation routes, and delivery schedules. This real-time data processing and analysis at the edge enables organizations to quickly identify bottlenecks, anticipate disruptions, and optimize logistics [35].

Edge computing has been crucial in addressing supply chain disruptions, especially those brought on by the COVID-19 pandemic. A prime example of how edge computing can transform supply chain management is the shipping giant Maersk's APM Terminals division. The port of the future is being created, complete with private 5G, AI-enhanced IoT devices, and a strong edge computing foundation. With this change, Maersk hopes to improve the effectiveness, standard, and visibility of the container ships it employs for transoceanic cargo transportation [36]. Edge offers real-time computation processing, including computer vision and real-time computation of decision-making algorithms says Gavin Laybourne, global CIO of Maersk's APM Terminals business. He sends data back to the cloud where he can tolerate a processing delay of 5 to 10 milliseconds [36]. It shows that edge computing can enable faster decision-making and more efficient operations, thereby increasing supply chain resilience. It is important to remember that a successful implementation requires careful planning and management to overcome potential obstacles such as security issues and interoperability issues.

3.3 Industrial Internet of Things (IIOT)

The Industrial Internet of Things is a key component of Industry 4.0, and edge computing plays a crucial role in enabling its implementation. Edge computing lowers the latency involved in sending data to a central cloud or data centre for processing by moving computing power closer to the devices and sensors in an industrial IoT setup [16]. This enables data processing, analysis, and decision-making in real-time at the network's edge. For instance, edge computing can enable real-time monitoring and control of IoT devices like sensors, actuators, and production machinery in a manufacturing environment, enabling quicker response times and more effective operations [37].

Edge computing implementation for the Industrial Internet of Things (IIoT) does indeed come with its own set of difficulties. Ensuring interoperability between various IoT platforms and devices is one of the major challenges. The proliferation of IoT devices makes it difficult to guarantee seamless interoperability between various systems and devices [38].

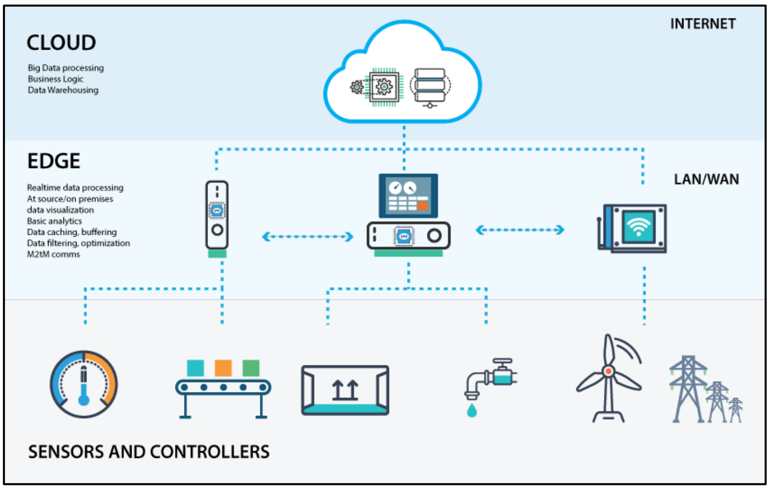

Figure 2. Cloud and Edge computing – complementary technologies powering IIoT [97]

The Industrial Internet of Things (IIoT) edge computing implementation presents unique difficulties. Getting different IoT platforms and devices to work together seamlessly is one of the main challenges. As IoT devices multiply, it can be difficult to guarantee seamless interoperability between various systems and devices [39].

3.4 AI and Machine Learning at the Edge

AI and machine learning are transforming industries across the board, and edge computing offers exciting opportunities for their implementation in Industry 4.0.

According to Glockmann (2021) Rittal's Smart Factory, data is generated by over 100 machines. That's up to 18 terabytes a day. After being gathered, the data can only be evaluated if it is examined by artificial intelligence (AI). And humans have a significant impact on this: The plants only develop into machine learning (ML) learning systems and later intelligent systems with humans acting as systematic trainers [40].

Edge computing allows businesses to directly deploy AI and machine learning algorithms at the network's edge, where data is generated. This eliminates the need to transfer substantial amounts of data to a centralized data center or cloud and enables real-time data analysis and decision-making. Edge computing enables quicker and more efficient AI and machine learning applications because data processing is done locally [41].

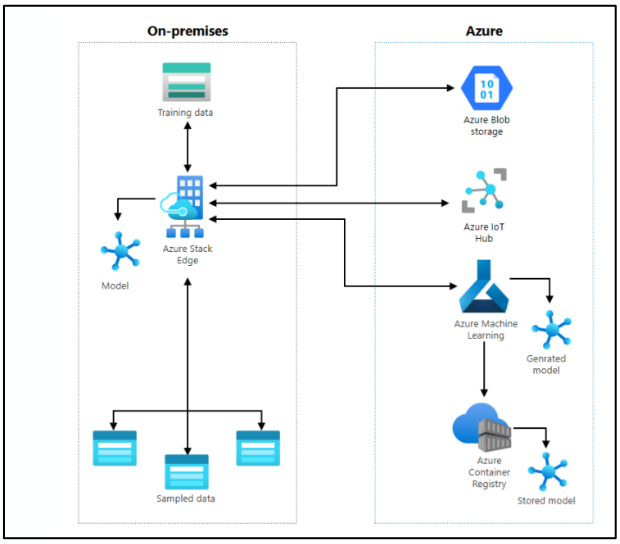

Figure 3. Illustrates how to use Azure Stack Edge to extend rapid machine learning inference from the cloud to on-premises or edge scenarios [98]

This is especially advantageous for low latency applications like real-time manufacturing quality control or autonomous vehicles. Edge computing also addresses issues with data security and privacy. The widespread use of edge computing in Industry 4.0 opens up a number of opportunities and applications in a variety of industries. Numerous edge computing opportunities and applications are provided by Industry 4.0, which has the potential to revolutionize a wide range of industries [16].

For example, edge computing enables real-time equipment monitoring in smart manufacturing and predictive maintenance, enabling early issue detection and proactive maintenance. This can greatly cut down on downtime and boost overall operational effectiveness. Edge computing enables real-time tracking and monitoring of inventory, shipments, and logistics in supply chain optimization. Edge computing improves visibility and enables quick decision-making for supply chain operations optimization while minimizing disruptions. Edge computing is crucial in the context of the Industrial Internet of Things for enabling real-time communication and data analysis between IoT devices like sensors and actuators [42]. This makes it easier to control and manage IoT devices in real-time, which boosts productivity, lowers costs, and increases efficiency [43].

4. Environmental Concerns and the Green Problem

One crucial factor comes into play as the digital world develops and technologies like edge computing converge with the Industrial Revolution: the effects of these innovations on the environment. While the convergence of Edge Computing and Industry 4.0 offers transformative potential, it also introduces a number of environmental issues commonly referred to as the "green problem" [44]. Below we will discuss the main environmental challenges associated with this convergence and strategies to address them from different authors and sources [45][46][47][48][49][50][51]:

1. Energy Consumption: An enormous increase in energy consumption is caused by the expanding use of Edge Computing devices, which need electricity for computation and data processing. This is particularly clear in industrial settings where a large number of edge devices are dispersed throughout buildings. Concerns about the sustainability of energy sources and the possibility of increased greenhouse gas emissions are brought up by the rising demand for energy.

2. Data Center Energy Demand: The proliferation of smaller data centers or edge nodes is a potential side effect of edge computing, which reduces the need for centralized cloud data processing. While decentralization can increase efficiency, it also forces energy-intensive operations in these distributed data centers, necessitating careful management to prevent excessive energy consumption.

3. Device Proliferation: A wide range of IoT gadgets, sensors, and edge servers are now available thanks to the growth of edge computing. Concerns about electronic waste and resource depletion are exacerbated by the

production, use, and eventual disposal of these devices. It becomes crucial to strike a balance between technological innovation, responsible production, and end-of-life management.

4. Heat Generation: During operation, Edge Computing devices generate heat. In densely deployed scenarios, insufficient heat dissipation mechanisms can increase cooling energy consumption, creating a self-perpetuating energy consumption loop.

5. Carbon Emissions: Increased energy consumption, particularly when derived from nonrenewable sources, directly correlates with increased carbon emissions. The environmental footprint of Edge Computing implementations is directly influenced by the energy sources and energy efficiency strategies used.

6. Resource Usage: Raw materials are required for the production of edge devices and their supporting infrastructure. Unsustainable extraction and utilization of these resources can contribute to environmental degradation and ecological imbalances.

7. E-Waste Management: Devices can quickly become obsolete as Edge Computing technologies evolve, necessitating their replacement. Inadequate e-waste management and disposal practices can pollute the environment and pose health risks.

8. Eco-Footprint of Device Lifecycle: The environmental impact of edge devices is influenced by every stage of their lifecycle, including production, use, and eventual disposal. The ecological impact must be reduced at every stage, which calls for a comprehensive strategy.

9. Infrastructure Overhead: Additional resources are needed to set up the networking, power, and cooling systems necessary for Edge Computing infrastructure. It is essential to plan and run this infrastructure with a sustainability angle.

10. Network Overhead: Localized communication between edge nodes can still use energy and resources, even though edge computing reduces data transmission to centralized clouds. It is crucial to strike a balance between the advantages of distributed processing and effective network usage.

In order to address the environmental issues raised by the fusion of Industry 4.0 and Edge Computing, a proactive approach is required. This entails implementing regulations that encourage energy-efficient hardware and infrastructure, embracing renewable energy sources, responsibly managing e-waste, utilizing sustainable manufacturing processes, and performing thorough assessments throughout the lifespan process. By acknowledging and proactively addressing these environmental concerns, we can use the integration of edge computing within Industry 4.0 as a catalyst for sustainable technological growth that benefits both the affected industries and the environment [52][53].

The spread of edge computing and IIoT technologies has raised significant environmental concerns. The estimated annual energy consumption of data centers, which are crucial to these technologies, is 200 terawatt hours (TWh), which is greater than the total energy consumption of some nations. They contribute an estimated 2% of the world's total CO2 emissions [54].

A more sustainable solution, though, may be provided by edge computing. The fundamental tenet of edge computing is that you store your data close to your infrastructure so that you don't constantly send massive data packets across the internet and consume bandwidth. Edge computing is now more highly optimized for resource efficiency thanks to this distinction, which also makes it possible for businesses to utilize their current hardware and infrastructure. Additionally, when companies want to expand their edge computing capabilities, they can more precisely select goods and services that go along with their sustainability objectives. These include adhering to the circular economy's tenets and ensuring that the products they buy were not produced in a way that would harm the environment [54][55]. This highlights the potential for edge computing and IIoT to contribute to more sustainable solutions while also highlighting the scope and urgency of the environmental challenges posed by these technologies.

5. Addressing the Green Problem with Edge Computing

It's crucial to keep an eye on the environment in the rapidly evolving world of technology, where innovation, efficiency, and speed rule supreme. Although Industry 4.0 and edge computing promise a promising future, they also cause environmental concerns. As the energy footprint of these technologies increases, solutions must be integrated into every aspect of their use. The "Green Problem" is the challenge of balancing technological development with ecological sustainability [56].

5.1 Energy-Efficient Data Processing

One essential element of using edge computing to address the "Green Problem" is energy-efficient data processing. The traditional approach of centralized data processing in cloud computing frequently leads to high energy use and carbon emissions. Edge computing eliminates the need for extensive data transmission by enabling data processing and analysis to occur closer to the point of data collection [57].

Localized processing allows for more efficient use of computing resources and requires less power for data transmission. Furthermore, edge computing enables data processing with smaller, more power-efficient hardware. These green data processing techniques improve the responsiveness and performance of the system as a whole while reducing the environmental impact of digital infrastructure [58][59].

The application of the Energy-efficient Data Processing (EDaP) protocol in edge-based IoT networks serves as an illustration of energy-efficient data processing in edge computing. In the protocol described by Idress and Jawad (2023) [60], data is gathered by sensor devices and then encoded using either the proposed Modified Run Length Encoding (MRLE) or the Huffman Encoding (HE). This procedure cuts down on the amount of data that must be transmitted, saving energy. The EDaP protocol also employs a sensor node scheduling algorithm at the edge gateway level to create the best sensor schedule for carrying out the monitoring mission in the upcoming time frame. Clustering techniques are used to schedule the sensor nodes according to the spatial correlation between the data they have gathered. This strategy lengthens the life of the network by reducing unnecessary sensed readings and communications overhead [60].

5.2 Reducing Data Transmission Overhead

The daily generation and processing of enormous amounts of information in the Big Data era has led to an increase in the amount of energy used to transmit this data across networks. With its promise of lessening data transmission overhead, edge computing appears as a potential solution to this problem [56]. Edge computing moves data processing and analysis capabilities closer to the edge of the network, where data is generated and collected, rather than relying on centralized servers for these tasks. Edge computing reduces energy consumption by processing and analyzing data close to where it is generated, eliminating the need for extensive data transfers.

The energy savings realized by reduced data transmission in edge computing are illustrated by a number of case studies and research findings. A multiuser mobile-edge computing (MEC) system with a latency constraint is taken into consideration in a study by Xu (2019). Each user can partially offload the task to the MEC server for edge computing in order to satisfy the latency requirement and reduce energy consumption. Prior to transmission, data compression is used to reduce the size of the offloaded data. This method not only satisfies the latency requirement but also uses less energy [61].

Authors Li, et. al. (2022), in their study, the purpose is to solve the problems of high transmission rate and low delay in the deployment of mobile edge computing network, ensure the security and effectiveness of the Internet of things (IoT), and save resources. Dynamic power management is adopted to control the working state transition of Edge Data Center (EDC) servers [62].

5.3 Localized Processing and Data Storage

Another critical aspect of addressing the "Green Problem" with edge computing is localized processing and data storage. With edge computing, data can be processed and stored locally at the edge devices or in nearby edge servers. This localized approach reduces the need for extensive data transmission to centralized cloud servers, resulting in lower energy consumption. Reduced data transmission not only improves energy efficiency but also reduces the strain on network bandwidth, resulting in faster and more responsive data processing [63] [64]. Additionally, edge computing makes it possible to process data using smaller, more power-efficient devices. By using this strategy, digital infrastructure leaves a smaller carbon footprint and uses less energy. The processing tasks that were previously carried out in the cloud computing layer can now be offloaded to the edge processing layer thanks to edge computing. The computing load and energy consumption of the cloud computing layer are reduced by this offloading of processing tasks from the cloud computing layer to the edge processing layer [65]. The advantage of being physically close to the data sources and computing resources is another benefit of edge computing. When compared to transmitting tasks to the cloud computing layer, this proximity results in lower latency when sending tasks to the edge nodes. In terms of addressing the "Green Problem" of energy consumption in data processing, edge computing offers a number of advantages [66].

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There are several challenges to implementing localized processing and data storage in edge computing [67][68][69][70]:

- Data Consistency: It can be difficult to guarantee data consistency among distributed edge nodes. This is due to the fact that edge computing involves processing data across different devices, which, if not properly managed, can result in inconsistencies.
- Data Synchronization: The synchronization of data among various edge nodes can be challenging as well. This is especially crucial when multiple devices are using and modifying the same data.
- Hardware Limitations: Edge devices need to be compact yet powerful enough to handle complex analysis. This balance can be difficult to achieve and may limit the extent to which latency can be reduced.
- Network Management: The traffic on edge networks needs to be effectively managed and organized to lower bandwidth usage. This requires sophisticated network management strategies and technologies, which can be complex to implement.
- Security and Privacy: As data is processed and stored closer to the end users, edge computing may increase security and privacy but also creates new vulnerabilities. A significant challenge is putting in place reliable security measures.

Several approaches are being used to address these issues, including the use of sophisticated data management techniques, dependable security protocols, and the creation of more potent and manageable edge devices. The successful implementation of localized processing in edge computing depends on ongoing research and development in these fields.

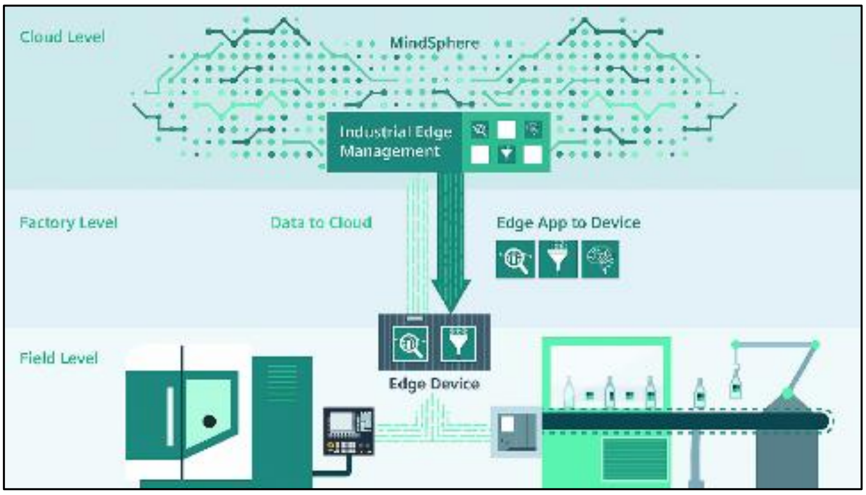

Figure 4. Data processing in edge computing systems is primarily done locally rather than in the cloud [99]

6. Challenges and Considerations

It's critical to recognize the challenges that lie ahead as we embark on the exciting journey toward an industry 4.0 and edge computing powered future. We must face the complexities that arise even as we embrace the promises of increased efficiency, real-time insights, and sustainable innovation. The increasing demand for IoT connectivity and intelligent edge computing is one of the major obstacles [71]. The need for IoT connectivity and intelligent edge computing is being driven by the rising demand for low-latency and real-time, automatic decision-making solutions. A major challenge is also posed by the exponential growth of data and network traffic. One of the main obstacles to the adoption of IoT connectivity and intelligent edge computing is the need to deal with the rapidly growing volume of data and network traffic. Creating a reliable IoT edge computing platform to support IoT devices is another challenge. IoT edge computing platforms must be developed because IoT devices themselves cannot be equipped with powerful processing and storage capabilities. In addition, protecting IoT networks' privacy and security is a related open research challenge.

6.1 Security and Privacy

The crucial issues of security and privacy come to the fore in the chaos of data exchange and digital transformation. These problems take on a new dimension with the introduction of edge computing and its decentralized architecture. The protection of sensitive information becomes more difficult and necessary as data is processed and stored closer to the source. Making sure AI components are physically secure is one of the biggest obstacles to security and privacy in edge computing [72]. AI integration with edge computing elevates the role of edge AI resources in network management and orchestration. However, these deployments often exist outside the central data infrastructure, residing in physically insecure premises [73]. As Edge Computing and Industry 4.0 intertwine, the fusion of innovation and security is essential for unlocking the true potential of this convergence [74].

According to AT&T Cybersecurity Insights Report – 2022 Securing the Edge, 81% of respondents in energy and utilities are most concerned about sniffing attacks against the radio access network (RAN) [77].

There are a number of new techniques and technologies that can improve edge computing's security and privacy, including [78][79][80]:

- Secure Enclaves: A hardware-based security feature known as a secure enclave offers a secure setting for handling sensitive data. Even if the underlying system has been compromised, this technology can assist in securing data against unauthorized access or manipulation.
- Encryption Techniques: Data is encoded through the process of encryption to prevent unauthorized access. Edge computing can benefit from a number of encryption techniques, including homomorphic encryption, which enables processing of data while it is still encrypted.
- Blockchain Technology: Data can be shared and stored in a secure, decentralized manner thanks to blockchain technology. By offering a tamper-proof record of data transactions, this technology can be used to improve security and privacy in edge computing.
- Zero-Knowledge Proofs: A cryptographic technique called zero-knowledge proofs enables one party to demonstrate to another that they are in possession of specific information without actually disclosing that information. This technology enables data to be processed without disclosing sensitive information, enhancing privacy in edge computing.

These technologies and strategies are part of ongoing research and innovative approaches to enhance security and privacy in edge computing. They provide a glimpse into the future of edge computing, where security and privacy are key concerns.

6.2 Standardization and Interoperability

Development in a world with many different technologies may be slowed down by a lack of standardization and interoperability. As they are woven into the fabric of edge computing and industry 4.0, numerous platforms, gadgets, and protocols struggle for supremacy. The difficulty lies in ensuring that these components converse and cooperate effectively [75]. To enable an ecosystem where devices, systems, and services can easily integrate and cooperate, standardization and interoperability are essential [76]. It is necessary to work toward creating common frameworks, protocols, and interfaces that permit interoperability between various technologies in order to address this challenge. Additionally, industry stakeholders must work together to establish and uphold standards that encourage compatibility and dependability. There are a number of possible outcomes if the issues with standardization and interoperability in edge computing are not resolved. Ecosystems that are fragmented, things that are more complicated, and things that are harder to scale [81]. This emphasizes how crucial industry cooperation and standard-setting efforts are to making sure that edge computing systems can coexist and function effectively. A Joint Technical Committee (JTC 1) of the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) is responsible for standardizing information technology, including edge computing. To create and advance standards for edge computing, this committee collaborates with both internal and external standards development organizations. [82][26].

6.3 Skill Gaps and Workforce Training

The unstoppable advancement of technology frequently coexists with a growing skills and knowledge gap. The workforce must develop simultaneously in order to fully realize the transformative potential of Edge Computing and Industry 4.0. Bridging the chasm between current skill sets and those needed for these cutting-edge technologies is difficult. Effectively implementing and managing Edge Computing solutions becomes difficult without a knowledgeable and skilled workforce. To close this skill gap, organizations need to invest in thorough workforce training programs. These courses ought to cover both hard skills like problem-solving and soft skills like AI, IoT, and other edge computing-related technologies [56][83].

IBM is an illustration of a business that has put in place a thorough workforce training program in the fields of edge computing, IoT, and AI. A thorough AI and platform-based edge research strategy, supported by enterprise use cases and partnerships, has been released by IBM Research. With data, AI, and Kubernetes-based platform technologies, IBM is concentrating on developing a "edge in" rather than a "cloud out" position to scale hub and spoke deployments of edge applications1. In order to establish and grow its presence in this market, IBM has identified four key market entry points, which it believes will generate $200 billion in revenue by 2025 [84].

Another example is Microsoft, which offers an AI Edge Engineer [1] training program through Microsoft Learn. This program, which was created in collaboration with the University of Oxford, aims to model problems in the real world using machine learning and deep learning algorithms, and then to implement the model using cloud computing and artificial intelligence on edge devices. A feedback loop for the business process (digital transformation) is provided by the deployment to the edge. By building an industry-specific, self-learning ecosystem spanning the entire value chain, AI, cloud, and edge technologies deployed as containers in CICD mode have the potential to completely transform entire industries.

Udacity [2] offers an Intel® Edge AI for IoT Developers Nanodegree Program. The goal of this program is to guide the creation of cutting-edge Edge AI applications for the Internet of Things in the future. In order to expedite the development of high-performance computer vision & deep learning inference applications, it makes use of the Intel® Distribution of OpenVINO™ Toolkit.

7. Case Studies

In the era of Industry 4.0, where the fusion of manufacturing and technology is revolutionizing the production line, edge computing is a key enabler. Advanced automation, the Industrial Internet of Things (IIoT), and smart factories are enabling productivity and efficiency levels that have never before been possible.

7.1 Edge Computing Implementation in Smart Factories

According to Harmatos & Maliosz, (2021), they examined how an end-to-end solution that satisfies the needs of Industry 4.0 use cases may be provided through the integration of edge computing and a 5G-enabled industrial network. The integration of edge computing and 5G-enabled industrial networks to meet Industry 4.0 requirements is thoroughly examined in the paper. Key findings show various deployments of 3GPP NPN and edge computing, allowing interactions across various domains [85]. Edge computing benefits must be used effectively, especially in cases that are industry-specific, which calls for coordinated domain deployment and management. More integrated NPN and edge domains are needed for stricter use cases, taking into account technical, commercial ownership, and deployment model considerations, such as self-managed, IaaS, and PaaS.

Another paper from authors Lee, et. Al., (2019) highlighted the inefficiency of centralized platforms in the context of smart factories, which demand real-time processing and quick responses. Delays in data processing and congested communication channels are among the issues. The authors recommend using a distributed platform approach to address these problems. They present a distributed smart factory platform that makes use of edge computing technology, and they test it out in a smart factory setting. The OPC UA standard is proposed as a data exchange mechanism for machine-to-machine interaction among edge devices, and a communication protocol is also being developed to improve real-time data processing between edge devices [86].

Emerald 66 Enterprises (E66) set up shop in an empty denim processing plant in Seminole, Okla., U.S. In only three months, E66 had three automated packaging lines producing up to 1 million bottles of hand sanitizer a week in a cGMP-compliant facility. They used industrial edge computing to build an information management system at the same time that they scaled up production capabilities. They used an edge programmable industrial controller (EPIC) to establish a primary control network [87].

[1] https://learn.microsoft.com/en-us/training/paths/ai-edge-engineer/
[2] https://www.udacity.com/course/intel-edge-ai-for-iot-developers-nanodegree--nd131

NEC, a Japanese multinational company that provides information technology and network solutions introduced five cases of edge computing solutions. Two of the examples, the walkthrough face recognition system and the human behaviour analysis service, perform image processing such as face recognition at the edge layer, then perform actuation at local or behaviour analyses on the cloud. These solutions enable optimization of the quantity of data sent to the cloud system and its real-time actuation in the field. They not only collect sensor data in the edge layer installed in the field but also process and analyse such data. This procedure can avoid a concentration of processing operations in the cloud layer so that the IT resources of the cloud layer can be optimized and their availability improved [88].

7.2 Edge-driven Sustainability Solutions

By lowering energy use, optimizing resource use, enabling real-time monitoring, boosting data security, and supporting remote and autonomous operations, edge computing presents an exciting opportunity to improve sustainability. By utilizing the computational capabilities of edge devices, businesses can reduce the overall demand on centralized servers, resulting in lower resource consumption [89].

Edge-driven sustainability solutions are a new approach to sustainability that focuses on the use of edge computing and artificial intelligence technologies to reduce greenhouse gas emissions and improve energy efficiency. Some of the key benefits of edge-driven sustainability solutions include reduced energy consumption, improved efficiency, and increased transparency into operations and supply chains [90].

Author Minevich (2021), has write some examples of edge-driven sustainability solutions that can be used to reduce greenhouse gas emissions and improve energy efficiency [91]:

- Smart Grids - use edge computing and artificial intelligence technologies to optimize energy usage and reduce waste.
- Smart Buildings: Smart buildings use sensors and edge computing to optimize energy usage, reduce waste, and improve occupant comfort.
- Smart Agriculture - uses edge computing and artificial intelligence technologies to optimize crop yields, reduce water usage, and improve soil health.
- Smart Transportation - uses edge computing and artificial intelligence technologies to optimize traffic flow, reduce congestion, and improve fuel efficiency.
- Smart Waste Management - uses sensors and edge computing to optimize waste collection routes, reduce waste, and improve recycling rates.

Sustainability solutions have the potential to revolutionize the way we approach sustainability by enabling real-time computing and data analysis in places that would not normally be possible. By using these technologies, companies can reduce their energy consumption, improve their efficiency and increase the transparency of their operations and supply chains.

It can be difficult to implement cutting-edge sustainability solutions. Determine where to focus for greatest impact, how to put the right transformation engine in place, and how to finance the journey are the three main challenges that BCG [92] claims are preventing companies from undergoing a sustainability transformation. Because sustainability initiatives frequently cross multiple business units and functions, it can be challenging to decide where to concentrate for the biggest impact. Additionally, businesses might not have complete control over the levers of change, and cooperation along the entire value chain, from raw material suppliers to final consumers, is necessary for success.

Another difficulty is choosing and installing the appropriate transformation engine. Any kind of large-scale transformation is a complex program that needs significant funding and organized implementation efforts. Transformations toward sustainability are particularly challenging because they frequently call for novel technologies and procedures that employees might not be familiar with.

A challenge is also finding the money to travel. Major investments in new technologies, procedures, and infrastructure are necessary for sustainability transformations. Companies must create a detailed funding strategy for these projects and make sure their resource allocation is efficient [92].

Overall, implementing edge-driven sustainability solutions requires careful planning, collaboration across the entire value chain, and significant investment. However, by overcoming these challenges, companies can reduce their carbon footprint and improve energy efficiency.

8. The edge-driven factory of the future

The future of Edge-Driven Manufacturing is exciting, with many industry experts predicting that it will bring about significant changes. By bringing data-driven technologies like artificial intelligence and robotics closer to the point of production, edge computing has the potential to revolutionize manufacturing [93]. Manufacturers will be able to capture and analyse data at the edge for better insights and efficiency [94]. One way that edge computing can help the manufacturing sector is with intelligent sensors. These sensors can be installed throughout buildings to gather data, process it locally, and deliver insights on the production floor without the use of the cloud. As a result, manufacturers can make decisions in real time with little latency, quickly adapting to changes in their operations [95].

Applications for edge computing in manufacturing include spotting workplace dangers, spotting product flaws on assembly lines, and highlighting machine maintenance requirements. Automating these procedures and using AI to analyze the data generated by IoT sensors can improve the operational efficiency and productivity of manufacturers [95].

By 2025, 25% of supply chain decisions, according to Gartner, will be made via intelligent edge ecosystems. As a result, edges—physical locations where objects, people, and data connect—will become more crucial to the supply chain network [96]. Overall, edge computing's AI-driven operational efficiencies and productivity gains are poised to revolutionize the manufacturing industry. As manufacturers begin implementing these cutting-edge technologies and modernizing their processes, it's an exciting time for them.

9. Conclusion

Industry 4.0 and Edge Computing coming together represents a paradigm shift in how businesses use data-driven technologies and operate. Numerous opportunities and applications in a range of industries, such as supply chain optimization, smart manufacturing, and predictive maintenance, are made possible by this convergence. Real-time analytics, data-driven decisions, and increased operational effectiveness are all made possible for businesses. This transformation, however, raises environmental concerns known as the "green problem." Edge computing's environmental impact is influenced by factors such as energy consumption, data center energy demand, device proliferation, heat generation, carbon emissions, resource usage, e-waste management, the eco-footprint of device lifecycle, infrastructure overhead, and network overhead. To address these issues, energy-efficient data processing, reduced data transmission overhead, and localized processing and data storage are required.

Furthermore, concerns about security and privacy are paramount in the adoption of edge computing. Innovative technologies such as secure enclaves, encryption techniques, blockchain, and zero-knowledge proofs are critical in ensuring the confidentiality and integrity of sensitive data.

Despite these obstacles, the benefits of edge computing in Industry 4.0 are significant. It enables real-time decision-making, lowers latency, optimizes resource utilization, and improves transparency across supply chains and operations. Edge computing has already been adopted by companies such as IBM, Microsoft, and NEC to drive innovation and sustainability.

As we move forward, addressing standardization, interoperability, and workforce training challenges will be critical to realizing the full potential of edge computing. The convergence of Edge Computing and Industry 4.0, with the right strategies and solutions, has the potential to revolutionize industries, increase sustainability, and pave the way for a more efficient and data-driven future.

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