Guide to good practices

Sustainable Blockchain and AI

Financiado por la Unión Europea
NextGenerationEU

MINISTERIO
PARA LA TRANSFORMACIÓN DIGITAL
Y DE LA FUNCIÓN PÚBLICA

Plan de Recuperación, Transformación y Resiliencia

ENIA Estrategia Nacional de Inteligencia Artificial

España | digital 2026

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1. Intersection between blockchain and artificial intelligence

The combination of blockchain and artificial intelligence (AI) can transform the way resources are managed, processes are optimized, and sustainability is promoted in various sectors. These technologies, when integrated, offer innovative solutions to address environmental and social challenges, from traceability in value chains to the creation of digital circular economies. Blockchain, with its ability to provide a decentralized, secure, and transparent infrastructure, is positioned as a key tool for recording and verifying data immutably. For its part, AI, with its ability to analyze large volumes of data and generate predictions, complements blockchain by optimizing processes and providing insights that improve decision-making.

Blockchain makes it possible to record each stage of the supply chain, ensuring transparency and data integrity, while AI analyzes this information to identify patterns and optimize processes. This is especially relevant in sectors such as agriculture, energy and waste management, where traceability of products and resources is essential to ensure sustainable practices. Projects funded by the European Union have demonstrated how these technologies can be integrated to improve traceability and sustainability in key sectors, promoting the circular economy and reducing the environmental impact of human activities.

Blockchain networks, especially those based on consensus mechanisms such as Proof of Work (PoW), are known for their high energy consumption. However, AI can be used to optimize these processes, significantly reducing energy consumption. Advanced AI algorithms can dynamically manage network nodes, adjusting the necessary resources in real-time and minimizing environmental impact.
Resource management and efficiency benefit from the integration of blockchain and AI. Tokenization, enabled by blockchain, can transform the way sustainable behaviors are incentivized. Tokens can be used to reward responsible energy consumption, recycling materials, or adopting sustainable practices. These systems, combined with AI, make it possible to analyze the impact of these initiatives and adjust strategies to maximize their effectiveness.

Blockchain can also act as an immutable record of ESG (environmental, social, and governance) metrics, providing a reliable basis for environmental impact auditing. AI, on the other hand, can interpret this data and anticipate patterns of impact, allowing organizations to make informed and proactive decisions. These technologies can be used to ensure transparency and accountability in environmental management.

Creating digital circular economies is another promising area. Blockchain and AI are facilitating the creation of green markets, where carbon credits, energy certificates, and other sustainability-related assets can be exchanged. Blockchain ensures the transparency and traceability of these transactions, while AI optimizes processes and analyzes the impact of these initiatives. These technologies not only seek to reduce the environmental impact of human activities, but also to promote transparency and accountability in resource management.

2. Environmental impact

The environmental impact of emerging technologies, such as blockchain and artificial intelligence (AI), has generated growing interest due to their high energy consumption and associated carbon emissions. These technologies, while critical to innovation and digital transformation, present significant challenges in terms of sustainability. From resource-intensive consensus mechanisms such as Proof-of-Work (PoW) to training AI models that require advanced computational infrastructures, their energy-intensive use raises questions about their environmental viability. In addition, the data centers and distributed networks that support these technologies contribute significantly to the overall carbon footprint. In this section, three key aspects will be analyzed: the energy consumption of blockchain and AI, the comparison of consensus protocols from an energy efficiency perspective, and the carbon footprint of the infrastructures that support them, proposing strategies and recommendations to mitigate their environmental impact.

2.1. Energy consumption

The energy consumption associated with emerging technologies such as blockchain, and artificial intelligence (AI) has generated significant debate in the field of sustainability. Both technologies, although they promise disruptive advances in multiple sectors, present significant challenges in terms of energy efficiency and environmental footprint. This section analyzes the energy impact of these technologies, highlighting the consensus mechanisms in blockchain and the processes of training AI models, as well as their points of intersection.

The Proof-of-Work (PoW) consensus mechanism, used by networks such as Bitcoin, has come under fire due to its high energy consumption. PoW requires participating nodes to solve complex mathematical problems to validate transactions and add blocks to the chain, a process that consumes large amounts of electricity. According to the European Blockchain Observatory, Bitcoin's energy consumption exceeds that of some small countries, raising serious concerns about its sustainability.

In addition to PoW, there are other consensus protocols that exhibit significant variations in their energy consumption. These include:

- **Proof-of-Stake (PoS):** Reduces energy consumption by eliminating the need for intensive calculations, instead using nodes' stake based on the number of tokens they hold.
- **Proof-of-Authority (PoA):** Uses pre-validated nodes to ensure network security, which decreases the use of computational resources.
- **Delegated Proof-of-Stake (DPoS):** Similar to PoS, but with delegated nodes representing network participants.
- **Proof-of-Space-Time (PoST):** Combines storage and time as resources to validate transactions, being more energy efficient.

- **Hybrid Consensus Mechanisms**: Combine various approaches to optimize energy consumption and grid security.

These protocols will be evaluated in the next section to determine their energy efficiency and their suitability for different use cases.

In response to criticism of PoW, mechanisms such as PoS have proven to be more energy efficient. For example, Ethereum's transition from PoW to PoS resulted in a 99.95% decrease in its energy footprint [Ethereum Merge Trend Report, European Blockchain Observatory]. However, these alternative mechanisms also present challenges. Although they are more efficient in terms of energy consumption, they can compromise decentralization and grid security. For example, PoS could favor nodes with greater financial resources, while PoA relies on a limited number of trusted validators, which could lead to centralization risks.

Training artificial intelligence models, especially large language models (LLMs) such as GPT, requires a significant amount of computational and energy resources. According to the OECD, training an AI model can consume as much energy as a small city uses for several days. This power consumption is mainly due to the need to process large volumes of data and perform complex calculations on specialized hardware, such as GPUs, TPUs, and ASICs.

Despite these challenges, both technologies have the potential to contribute to sustainability. Blockchain can be used to boost the production and consumption of renewable energies (GreenLedger, the blockchain bet on renewables – BLOCKCHAIN SERVICES), while AI can optimize the use of resources, reduce waste and save energy. These synergies represent an opportunity to develop technological solutions that are both innovative and sustainable.

The energy consumption of blockchain and artificial intelligence poses significant challenges to global sustainability. While more efficient consensus mechanisms and energy optimisation strategies are being developed, it is critical to continue researching and adopting measures that promote sustainable practices. Collaboration between international organizations and entities that use these technologies will be key to ensuring that these technologies can be developed responsibly and with a reduced environmental impact.

2.2. Consensus Protocol Comparison

Energy consumption per transaction

Energy consumption per transaction is a key metric for assessing the sustainability of consensus protocols on the blockchain. This dimension not only reflects the operational efficiency of each protocol, but also its environmental impact and feasibility for large-scale applications. Next, the energy consumption of the main consensus mechanisms is analyzed, highlighting their differences and the implications for sustainability.

Proof-of-Work (PoW)

Proof-of-Work (PoW) is the most well-known and widely used consensus protocol, especially on networks like Bitcoin and Ethereum before their transition to Proof-of-Stake (PoS). PoW requires participating nodes to solve complex mathematical problems to validate transactions and add blocks to the chain. This process, known as mining, consumes large amounts of energy due to the need to perform intensive calculations on specialized hardware, such as ASICs.

According to the European Blockchain Observatory, Bitcoin's energy consumption is estimated at approximately 707 kWh per transaction, which is equivalent to the average consumption of a European household over several weeks [Energy Efficiency of Blockchain Technologies]. This high energy consumption is due to competition among miners to solve mathematical problems, which generates redundancy in the use of computational resources. In addition, the European Central Bank (ECB) points out that the environmental impact of PoW is one of the main factors limiting its adoption in sustainable applications [Mining the Environment, ECB].

Proof-of-Stake (PoS)

Proof-of-Stake (PoS) eliminates the need for intensive calculations by basing block validation on the amount of cryptocurrency a node owns and is willing to "stake." This approach significantly reduces energy consumption, as it does not require competition between nodes to solve mathematical problems. According to the European Blockchain Observatory, Ethereum's transition from PoW to PoS resulted in a 99.95% decrease in its energy footprint, reducing consumption per transaction to less than 0.05 kWh [Ethereum Merge Trend Report, European Blockchain Observatory].

Although PoS is much more energy-efficient than PoW, it faces criticism related to centralization, as nodes with greater financial resources have an inherent advantage in the validation process. However, from a sustainability perspective, PoS is a much more viable option for enterprise applications and private networks [Impact of PoW-Based Blockchain, MDPI].

Delegated Proof-of-Stake (DPoS)

Delegated Proof-of-Stake (DPoS) is a variant of PoS that delegates block validation to a small set of representative nodes. This approach optimizes performance and reduces power consumption, as only a limited number of nodes actively participate in the consensus process. According to studies by SpringerOpen, the energy consumption per transaction in DPoS-based networks is significantly lower than in PoW, although it depends on the number of delegated nodes and the frequency of validation [Evolution of Blockchain Consensus Algorithms, SpringerOpen].

However, DPoS also faces criticism related to decentralization, as the delegation of nodes can concentrate power in a small group of participants. This limits their adoption in public networks where decentralization is a critical requirement.

Proof-of-Authority (PoA)

Proof-of-Authority (PoA) uses pre-validated nodes to ensure network security, which decreases the use of computational resources and, therefore, energy consumption. This protocol is particularly suitable for private and enterprise networks, where decentralization is not a fundamental requirement. According to the International Monetary Fund (IMF), the energy consumption per transaction in PoA-based networks is one of the lowest among consensus protocols, making it an ideal choice for sustainable applications [Blockchain Consensus Mechanisms, FMI].

However, PoA faces criticism related to centralization and trust in pre-selected validators, which may limit its adoption on public networks.

Emerging protocols: Proof-of-History (PoH)

Proof-of-History (PoH) and directed acyclic graph (DAG)-based protocols represent innovative approaches to improving energy efficiency and scalability. PoH uses cryptographic timestamps to validate transactions, reducing the need for intensive calculations and optimizing energy consumption. According to studies by MDPI, the energy consumption per transaction in PoH-based networks is comparable to that of PoS, although its adoption is still limited.

Latency and scalability

Latency and scalability are critical dimensions for assessing the viability of consensus protocols on blockchain, especially in enterprise and public applications that require high throughput and capacity to handle large volumes of transactions. While latency measures the time required to validate and confirm a transaction, scalability assesses the network's ability to process an increasing number of transactions without compromising its performance. The main consensus mechanisms are discussed below in terms of these dimensions.

Proof-of-Work (PoW)

On Proof-of-Work (PoW)-based networks, such as Bitcoin, the average time to validate a block is approximately 10 minutes, limiting the network's ability to process transactions in real-time. However, there are variants and optimizations of PoW that have managed to significantly reduce this latency, through adjustments in difficulty, shorter block time or hybrid approaches.

As for synchronization between nodes, this process is inherent to any blockchain network; however, in PoW systems it can generate some temporary inefficiency due to the need to propagate and validate new blocks on a global scale, especially when temporary forks or orphan blocks arise that must be resolved to reach consensus.

On the other hand, competition between miners – where multiple participants simultaneously seek to solve the same cryptographic problem – reinforces the security and decentralization of the system, although it introduces a certain redundancy in the use of computational resources. This design implies that only one of the miners will effectively leverage their work to add the block, which, while an essential feature of the model, can limit efficiency and scalability in scenarios that demand high transactional capacity.

Proof-of-Stake (PoS)

Proof-of-Stake (PoS) significantly improves latency and scalability compared to PoW. By eliminating the need for intensive calculations, PoS allows blocks to be validated in seconds, reducing latency and improving the network's ability to process transactions in real-time. According to the European Blockchain Observatory, Ethereum's transition from PoW to PoS resulted in a noticeable improvement in network latency and scalability.

However, the scalability of PoS depends on the number of participating nodes and the efficiency of the consensus algorithm. PoS faces challenges related to centralization, which can limit its ability to handle large volumes of transactions on public networks.

Delegated Proof-of-Stake (DPoS)

Delegated Proof-of-Stake (DPoS) optimizes latency and scalability by delegating block validation to a small set of representative nodes. This approach allows blocks to be validated in seconds and handle a higher volume of transactions compared to PoW and PoS. According to Springer Open: Evolution of blockchain consensus algorithms: a review on the latest milestones of blockchain consensus algorithms , DPoS is one of the most scalable protocols, with the capacity to process thousands of transactions per second on enterprise networks.

However, reliance on a limited number of validators can compromise network decentralization and security, especially in public applications where transparency and trust are critical.

Proof-of-Authority (PoA)

Proof-of-Authority (PoA) is one of the most efficient protocols in terms of latency and scalability. By using pre-validated nodes to ensure network security, PoA eliminates the need for intensive calculations and synchronization between nodes, significantly reducing latency. According to the International Monetary Fund (IMF), PoA is ideal for enterprise applications and private networks that require high performance and capacity to handle large volumes of transactions.

However, PoA faces criticism related to centralization and trust in pre-selected validators, which may limit its adoption on public networks.

Emerging Protocols: Proof-of-History (PoH) and DAG

Proof-of-History (PoH) and Directed Acyclic Graph (DAG)-based protocols represent innovative approaches to improving latency and scalability. PoH uses cryptographic timestamps to validate transactions, reducing the need for intensive calculations and optimizing latency. According to studies by MDPI, PoH is capable of processing thousands of transactions per second, making it a promising option for enterprise applications and public networks.

On the other hand, DAG protocols eliminate the need for blocks and allow parallel transactions, which improves scalability and reduces latency. According to Springer Open: Evolution of blockchain consensus algorithms: a review on the latest milestones of blockchain consensus algorithms, DAG is one of the most scalable protocols, with the capacity to handle millions of transactions per second on distributed networks. However, its technical complexity and lack of widespread adoption limit its impact on today's market.

Security and decentralization

Security and decentralization are fundamental pillars of consensus protocols on blockchain. Security ensures transaction integrity and resilience to attacks, while decentralization ensures that control of the network does not fall to a small group of participants, promoting transparency and trust. However, each consensus protocol exhibits unique characteristics that affect these dimensions, influencing its adoption and viability for different use cases.

Proof-of-Work (PoW)

Proof-of-Work (PoW) is widely recognized as one of the most secure protocols due to its 51% attack resistance. In this type of attack, a malicious actor would need to control more than half of the network's computational power to alter transactions or manipulate blocks. The high security of PoW is due to competition among miners and the inherent difficulty of the mathematical calculations required to validate blocks.

Proof-of-Stake (PoS)

Proof-of-Stake (PoS) offers a more energy-efficient alternative to PoW, but it faces challenges related to security and decentralization. Although PoS eliminates the need for intensive calculations, its security depends on the amount of cryptocurrency that nodes own and are willing to "stake." This creates an incentive for nodes to act honestly, as any malicious behavior could result in the loss of their assets.

However, PoS faces centralization risks, as nodes with greater financial resources have an inherent advantage in the validation process. According to studies by MDPI, this concentration of power can limit transparency and trust in public networks, although it is less problematic in private and business networks.

Delegated Proof-of-Stake (DPoS)

Delegated Proof-of-Stake (DPoS) optimizes power efficiency and scalability by delegating block validation to a small set of representative nodes. This approach improves security by reducing the number of nodes actively participating in the consensus process, minimizing the risk of attacks. However, DPoS faces significant criticism in terms of decentralization, as the delegation of nodes can concentrate power in a small group of participants.

In public networks, this concentration of power can compromise transparency and trust, limiting the adoption of DPoS in applications where decentralization is a critical requirement.

Proof-of-Authority (PoA)

Proof-of-Authority (PoA) uses pre-validated nodes to ensure network security, eliminating the need for intensive calculations and improving energy efficiency. This protocol is particularly suitable for private and enterprise networks, where decentralization is not a fundamental requirement. According to the International Monetary Fund (IMF), PoA offers high security by relying on reliable validators, but it faces criticism related to centralization and trust in pre-selected validators.

On public networks, reliance on pre-selected validators can limit transparency and trust, restricting PoA adoption in applications where decentralization is essential.

Emerging protocols: Proof-of-History (PoH)

Proof-of-History (PoH) and directed acyclic graph (DAG)-based protocols represent innovative approaches to improving security and decentralization. PoH uses cryptographic timestamps to validate transactions, reducing the need for intensive calculations and optimizing security. According to MDPI studies, PoH offers high resistance to attacks, but faces challenges related to decentralization due to its reliance on trusted nodes.

Feasibility for sustainable use cases

The viability of consensus protocols for sustainable use cases depends on their ability to minimize environmental impact and align with the Sustainable Development Goals (SDGs). PoS and PoA are better suited for sustainable applications due to their lower energy consumption. In addition, hybrid protocols that combine Byzantine fault tolerance (BFT) and DAG offer innovative solutions to improve power efficiency and scalability, making them ideal for enterprise applications and private networks.

Protocol comparison table

Protocol	Pros	Disadvantages
Proof-of-Work (PoW)	• High security and 51% resistance to attacks. • Robust decentralization in public networks • Broad technology adoption and maturity	• Extremely high energy consumption • Low scalability due to the need for intensive computation
Proof-of-Work (PoS)	• Lower power consumption compared to PoW. • Better scalability and lower latency.	• Centralization risks due to the advantage of nodes with greater financial resources.

	• Suitable for enterprise applications and private networks.	• Reliance on the amount of cryptocurrency staked to ensure security. • Vulnerability to "nothing at stake" attacks if additional security measures are not implemented.
Delegated Proof-of-Work (DPoS)	• High energy efficiency and scalability. • Fast block validation, ideal for enterprise applications. • Ability to handle thousands of transactions per second.	• Reliance on a limited number of validators, compromising decentralization. • Risk of concentration of power in delegated nodes. • Less transparency in public networks.
Proof-of-Authority (PoA)	• Low latency and power consumption. • High security in private and business networks. • Ideal for applications where decentralization is not critical.	• Centralization due to reliance on pre-selected validators. • Limited adoption on public networks due to lack of decentralization. • Trust in pre-selected validators, which can lead to manipulation risks.
Proof-of-History (PoH)	• High energy efficiency and ability to process thousands of transactions per second. • Latency optimization using cryptographic timestamps. • Promising for enterprise applications and public networks.	• Lower adoption and lack of extensive studies on its environmental impact. • Reliance on trusted nodes, which can limit decentralization. • Technical complexity in its implementation.
DAG (Directed Acyclic Graph)	• Almost unlimited scalability by enabling parallel transactions. • High decentralization by distributing control across multiple nodes. • Ideal for applications that require high performance and capacity.	• Technical complexity and lower adoption in today's market. • Security risks on public networks due to the lack of traditional blocks. • Lower technological maturity compared to other protocols.

2.3. Carbon footprint of data centers and distributed networks

The carbon footprint of data centers and distributed networks in the blockchain space represents a significant challenge to global sustainability. These infrastructures, which are essential for the operation of decentralized networks, are responsible for high energy consumption and greenhouse gas (GHG) emissions. However, there are strategies and guidelines that can be adopted to mitigate its environmental impact and move towards a more sustainable model.

Adoption of efficient consensus mechanisms

Prioritizing the use of algorithms such as Proof-of-Stake (PoS) and Proof-of-Authority (PoA) in blockchain networks is one of the most effective strategies for reducing one's carbon footprint. PoS eliminates the need for intensive calculations by basing block validation on the amount of cryptocurrency a node owns and is willing to "stake." This approach significantly reduces energy consumption, as evidenced in Ethereum's transition from Proof-of-Work (PoW) to PoS, which resulted in a 99.95% decrease in its energy footprint. PoA, on the other hand, uses pre-validated nodes to ensure network security, which decreases the use of computational resources and, therefore, energy consumption and carbon footprint.

Sustainable infrastructure design

Implementing advanced technologies in data centers can significantly improve their energy efficiency. These technologies include liquid cooling, which reduces the energy consumption associated with cooling equipment, and heat reuse, which allows the heat generated by servers to be used for other uses. These measures are essential to reduce the carbon footprint of data centers that support blockchain networks.

Sustainability certification

Blockchain can be used to certify the use of renewable energy and ensure transparency in data center operations. For example, blockchain networks can record and verify the origin of energy used in data centers, ensuring that it comes from renewable sources. These certifications can encourage the adoption of sustainable practices in the ICT sector and increase confidence in distributed network operations.

Distributed Network Optimization

Optimizing distributed networks is a key aspect of reducing the carbon footprint in the blockchain space. These networks, which rely on distributed nodes to validate transactions and maintain security, present significant challenges in terms of energy consumption and sustainability. Traditional blockchain networks, such as PoW-based ones, are highly compute-intensive due to the need for complex mathematical calculations to validate transactions. This approach creates redundancy in the use of computational resources, as multiple nodes compete simultaneously to solve the same problems. According to the OECD, this redundancy is one of the main factors contributing to the high energy consumption of blockchain networks.

To address this challenge, more efficient consensus algorithms, such as PoS and PoA, are being adopted. In addition to these algorithms, hybrid and emerging protocols are gaining relevance as solutions to optimize distributed networks. Algorithms based on directed acyclic graphs (DAGs) eliminate the need for blocks and enable parallel transactions, improving scalability and reducing redundancy in the use of computational resources. DAG protocols are capable of handling millions of transactions per second, making them a promising option for enterprise applications and public networks. However, its technical complexity and lack of widespread adoption limit its impact on today's market.

Another strategy to optimize distributed networks is the implementation of federated learning techniques in the field of blockchain. Federated learning allows artificial intelligence models to be trained in a distributed manner, minimizing data transfer between nodes and reducing associated energy consumption. This technique, combined with efficient consensus algorithms, can significantly improve the sustainability of blockchain networks.

From a carbon footprint perspective, the optimization of distributed networks also includes the migration to sustainable infrastructures. Powering blockchain nodes with renewable energy sources, such as solar and wind, is a key strategy for reducing greenhouse gas (GHG) emissions. According to the European Commission, this transition is essential to achieve carbon neutrality in the near future. In addition, technologies such as liquid cooling and heat reuse are being implemented to improve the energy efficiency of the nodes and data centers that support blockchain networks.

3. Distributed AI Model Execution

3.1. Federated learning on blockchain

Federated learning (FL) is an emerging technique in the field of artificial intelligence (AI) that allows machine learning models to be trained without the need to centralize data. Instead of transferring large volumes of information to a central server, the data remains on local devices, and only model updates are shared. Not only does this methodology improve data privacy and security, but it also has significant implications in terms of sustainability and energy efficiency. When combined with blockchain, federated learning takes on a new level of transparency, traceability, and decentralization, making it a promising solution for addressing the environmental and ethical challenges of digital technologies.

What it is and why it matters in sustainability

Federated learning is based on the idea of distributing AI model training across multiple nodes, such as mobile devices, sensors, or local servers. Each node trains the model using its own data and sends only the updated parameters to the central server or a distributed network, rather than the original data. This approach has two key benefits from a sustainability perspective:

1. **Reduced power consumption**: By avoiding the massive transfer of data to centralized data centers, bandwidth usage and energy associated with communications are minimized. This is especially relevant in applications involving large volumes of data, such as medical imaging or industrial sensor data.
2. **Improved privacy**: By keeping data at its source, the risk of privacy breaches is reduced, which is crucial in sectors such as healthcare, finance, and education. This also eliminates the need for costly additional security mechanisms to protect data in transit.

In terms of sustainability, federated learning contributes to reducing reliance on large data centers, which are responsible for a significant portion of the technology sector's carbon emissions. According to the OECD's report on the environmental impact of AI, decentralized technologies such as federated learning have the potential to decrease the carbon footprint associated with big data processing.

How it integrates with blockchain

Integrating blockchain with federated learning adds a layer of trust and transparency to the distributed training process. Blockchain acts as an immutable, decentralized ledger where model updates and contributions from each node are stored. This allows the training process to be audited and ensures that the data and models have not been tampered with.

In addition, blockchain can be used to implement incentive schemes that reward nodes that contribute efficiently and sustainably to model training. For example, nodes that use renewable energy or optimize the use of computational resources could receive tokens as a reward. This approach not only encourages participation in the system but also aligns economic incentives with sustainability goals.

A case study of this integration is the "Fedchain" project ([2308.15095] FedChain: An Efficient and Secure Consensus Protocol based on Proof of Useful Federated Learning for Blockchain), which uses blockchain to manage federated learning in sustainable irrigation systems. In this project, blockchain ensures the traceability of model updates and facilitates collaboration between multiple stakeholders, such as farmers, researchers, and local governments.

Benefits in a green key

The combination of federated learning and blockchain offers several benefits from an environmental perspective:

- **Reduced reliance on large data centers**: By distributing processing across local nodes, the need for centralized infrastructures, which are typically energy-intensive, is reduced.
- **Energy savings in communications and storage**: By minimizing data transfer and using blockchain only to record updates, the use of resources is optimized.

- **Greater decentralization of computational resources**: By leveraging edge devices, such as sensors and IoT devices, the load on centralized infrastructures is reduced and a more equitable use of technological resources is promoted.

These benefits are aligned with the objectives of the European Green Deal, which seeks to reduce carbon emissions in all sectors, including digital technology.

Challenges to consider

Despite its advantages, implementing federated learning on blockchain faces several challenges:

- **Technical complexity and initial cost**: Setting up distributed and decentralized systems requires significant investment in infrastructure and know-how.
- **Energy consumption of the blockchain itself**: If efficient consensus protocols, such as Proof of Stake (PoS), are not used, the energy consumption of the blockchain could counteract the benefits of federated learning.
- **Coordination in heterogeneous environments**: The diversity of devices and networks can make it difficult to synchronize and make the system efficient.

These challenges underscore the importance of carefully designing solutions and selecting use cases where the benefits outweigh the costs and associated complexities.

Best Practices

To maximize benefits and minimize challenges, the following good practices are recommended:

- **Prioritize energy-efficient consensus protocols**: Use blockchain with mechanisms such as PoS or Delegated Proof of Stake (DPoS) to reduce energy consumption.
- **Use blockchain only for traceability**: Avoid storing heavy datasets on the blockchain and limit its use to recording updates and metadata.
- **Design sustainable incentive schemes**: Align economic rewards with the reduction of the carbon footprint, incentivizing the use of renewable energy and the optimization of resources.
- **Select use cases with direct impact**: Prioritize applications in sectors such as health, energy, and sustainable agriculture, where the social and environmental benefits are evident.

3.2. Distributed Infrastructure and Edge Computing

Edge computing is a computing architecture that allows data to be processed close to where it is generated, such as in sensors, mobile devices or gateways, instead of sending it to be centralized data centers or the cloud. This decentralized approach reduces latency, optimizes bandwidth usage, and lowers the power consumption associated with data transport. In the context of blockchain, edge computing is perfectly complemented by distributed networks, as both paradigms promote decentralization and efficiency in the use of resources. In addition, their integration has a significant impact on sustainability, by reducing the carbon footprint of technological infrastructures.

Edge computing is especially relevant in a world where the volume of data generated by connected devices, such as those of the Internet of Things (IoT), is growing exponentially. According to the European Union's Digital Strategy, the transition to edge computing architectures is essential to reduce reliance on large data centers and to enable more sustainable and efficient applications (European Commission, 2022). This approach not only optimizes data processing, but also makes it possible to leverage existing devices, such as mobile phones and sensors, instead of relying exclusively on dedicated infrastructures.

The relationship between edge computing and blockchain is particularly interesting from a sustainability point of view. Blockchain can act as a layer of trust that coordinates distributed devices at the edge, validating their contributions and ensuring the integrity of the data processed. For example, in an edge computing system, devices can process data locally and send only the relevant results to the blockchain, where they are immutably recorded. This not only reduces the volume of data that needs to be transferred but also ensures traceability and transparency of the system.

From a sustainability perspective, edge computing offers several key benefits. First, it reduces the need to use large data centers, which are energy-intensive and responsible for a significant portion of the technology sector's carbon emissions. According to the World Economic Forum (This is the current state of the global data center 'gold rush' | World Economic Forum), data centers account for approximately 1% of global energy consumption. Second, by processing data locally, bandwidth usage is optimized and energy consumption associated with communications is minimized. This is especially important in applications that generate large volumes of data, such as video surveillance systems or industrial sensors. Finally, edge computing makes it possible to leverage existing devices, such as mobile phones and sensors, rather than relying exclusively on dedicated infrastructure, reducing the environmental impact associated with manufacturing and transporting new equipment.

Blockchain plays a crucial role in coordinating distributed devices at the edge. By acting as a reliable and transparent ledger, blockchain can validate the inputs of each node and ensure that the processed data is authentic and has not been tampered with. In addition, smart contracts can be used to orchestrate artificial intelligence (AI) tasks at the edge, such as resource allocation or task scheduling.

Another important benefit of blockchain and edge computing integration is the ability to auditable record the energy consumption or green contributions of each node. This makes it possible to implement incentive schemes that reward nodes that operate sustainably, such as those that use renewable energy or optimize the use of computational resources. This approach not only encourages sustainability, but also aligns economic incentives with environmental goals, creating a more balanced and efficient system.

However, implementing edge computing and blockchain in distributed environments is not without its challenges. One of the main challenges is the complexity of managing heterogeneous systems, where devices can vary significantly in terms of processing capacity, power consumption, and connectivity. In addition, there is a risk that the overhead of blockchain, in terms of energy consumption and storage capacity, will outweigh the benefits of edge computing if not designed properly. For example, the use of energy-intensive consensus protocols, such as Proof of Work (PoW), could counteract the energy savings achieved through local data processing. For this reason, it is critical to select low-power consensus protocols, such as Proof of Stake (PoS) or Delegated Proof of Stake (DPoS), that are more energy-efficient.

Another major challenge is the need to standardize energy consumption and carbon footprint measurements in distributed environments. Without clear standards, it can be difficult to assess the environmental impact of edge computing and blockchain systems, limiting the ability to optimize their design and operation.

To maximize benefits and minimize challenges, several good sustainable design practices are recommended. First, it's important to minimize the weight of AI models running at the edge, using approaches such as lightweight machine learning (tinyML). This not only reduces the power consumption of the devices but also improves their performance and extends their lifespan. Second, low-power blockchain protocols should be selected to coordinate nodes, prioritizing those that are energy-efficient. Finally, it is crucial to use energy-efficient hardware at the edge, such as low-power sensors and optimized microchips, which reduce the environmental impact of the system as a whole.

In conclusion, the integration of edge computing and blockchain represents a unique opportunity to develop more sustainable and efficient technological systems. By processing data locally and using blockchain as a layer of trust, these technologies can significantly reduce the carbon footprint of digital infrastructures, while improving transparency and traceability. However, to fully realize its potential, it is essential to address technical challenges and adopt good sustainable design practices that prioritize energy efficiency and reduce environmental impact.

3.3. Designing Low-Impact AI Solutions on Blockchain

Designing low-impact artificial intelligence (AI) solutions on blockchain is an approach that combines resource optimization, environmental sustainability, and energy efficiency. This expanded section explores key principles, best practices, and practical examples that illustrate how these technologies can be integrated responsibly and effectively.

Low-impact principles in AI

Designing lighter and more efficient AI models is essential to reduce energy consumption and carbon footprint. This is achieved through advanced optimization techniques and the use of specialized hardware.

- **Compact and optimized models**: Techniques such as pruning and quantization can reduce the size and complexity of AI models. For example, pruning eliminates unnecessary connections in neural networks, while quantization reduces the accuracy of weights and activations, decreasing energy consumption without significantly compromising model accuracy. Frameworks such as TensorFlow Lite and PyTorch Mobile are specifically designed to deploy lightweight models on edge devices.
- **Avoid unnecessary intensive training**: Complex algorithms should be used only when they provide clear and justified value. For example, in climate prediction applications, where social and environmental benefits outweigh energy costs, the use of advanced models may be justified. However, in simpler tasks, lightweight models are preferable.
- **Efficient hardware**: Using optimized hardware, such as microchips designed specifically for machine learning tasks (e.g., Google Edge TPU or NVIDIA Jetson Nano), can significantly reduce power consumption compared to traditional GPUs.

Practical example: In wearable medical devices, compressed AI models enable real-time diagnostics without sending data to the cloud, reducing power consumption and improving privacy.

Smart use of blockchain

Blockchain can be a powerful tool to ensure transparency and traceability, but its implementation must be carefully designed to minimize its environmental impact.

- **Efficient storage**: Instead of storing entire datasets on the blockchain, it is recommended to record only hashes or references to the data. This significantly reduces space and energy consumption, as the entire data is stored off-chain.

By **storing the data outside the blockchain** and recording only the *hashes* or references:

1. **Impact on consumption and efficiency**
    - **Lower energy and storage consumption**: the blockchain stores only one cryptographic identifier (hash), which weighs a few bytes instead of gigabytes or terabytes.
    - **Lower environmental footprint**: By reducing compute operations and chain size, you avoid replicating heavy information across all nodes.
    - **Increased scalability**: The blockchain can grow more slowly and remain operational at reasonable costs.

2. **Impact on safety and traceability**
    - The complete data remains in external repositories (distributed databases, cloud storage, IPFS, etc.), but its **integrity is guaranteed** by the hash recorded on the blockchain.
    - This ensures that even if the data is not on-chain, its authenticity can be verified at any time.
3. **Comparison of storing them on-chain**
    - **On-chain**: each node must keep an exact copy of the data → maximum security, but very high energy and storage consumption, as well as low efficiency.
    - **Off-chain**: redundancy and environmental impact are drastically reduced, although external systems are relied on for data availability.
4. **Case with Distributed Data (Federated Learning – FL)**
    - In **federated learning**, data remains locally on each node (e.g., hospitals, mobiles, or enterprises), and only trained models or gradients are shared.
    - The blockchain can store **hashes of partial models or updates**, not datasets.
    - Advantages:
        - Respect data privacy and sovereignty.
        - The traceability of contributions remains in the blockchain (which node trained, when, with which version).
        - Lower environmental impact, as there is no need to replicate the entire datasets either on blockchain or in a centralized repository.

- **Trust and audit layer**:
  Blockchain should be used primarily as a trust layer to ensure the integrity of data and transactions. For example, in supply chains, blockchain can record the hashes of product certificates of authenticity, while the complete data is stored on external servers.

The use of blockchain as a **trust and auditing layer** can be considered **sustainable** if it is designed with certain principles in mind:

1. **Minimization of consumption in the chain**
    - Instead of storing all the data, the blockchain only records *cryptographic proofs* (hashes, digital signatures, "proofs"), which weigh very little.
    - This avoids replicating heavy information on each node and reduces both storage and compute.

2. **Use of more efficient consensus mechanisms**
    - Instead of *Proof of Work* (very expensive in terms of energy), *Proof of Stake* or lighter variants (*Proof of Authority*, *Delegated PoS*) can be used.
    - These alternatives drastically reduce the energy expenditure of the network without losing security.
3. **Sustainable auditing in practice**
    - The blockchain functions as an **immutable record of references** (e.g., hash of a certificate of authenticity).
    - The complete data is stored on servers, distributed to repositories or systems such as IPFS, which can be energy optimized and with sustainability policies (e.g. green data centers).
    - The direct environmental impact of the blockchain is limited to saving and validating small entries, not massive datasets.
4. **Scalability and traceability without excess resources**
    - Every transaction on the blockchain acts as a **verifiable timestamp**.
    - This allows the audit to be transparent and verifiable without the need for multiple actors to keep complete duplicates of documents.

- **Sustainable consensus protocols**: Prototails such as Proof of Stake (PoS), Proof of Authority (PoA), and Directed Acyclic Graphs (DAG) are more sustainable alternatives to traditional Proof of Work (PoW). These protocols reduce energy consumption by eliminating the need for intensive calculations to validate transactions.

Practical example: In food traceability projects, blockchain records only the hashes of origin and transport data, while the full details are stored in external databases.

Eco-efficient design in AI-Blockchain integration

The integration of AI and blockchain must be optimized to minimize energy consumption and maximize efficiency.

- **Minimize on-chain transactions**:
  Grouping multiple transactions into a single one (batching) reduces the total number of operations in the chain, reducing energy consumption.
- **Outsource intensive calculations**:
  Complex calculations must be performed outside of the blockchain (off-chain computing), using the chain only to record key results or verifications. Frameworks like Chainlink and TrueBit allow you to implement this approach efficiently.

- **Using green nodes**: Deploying nodes powered by renewable energy sources, such as solar panels or wind turbines, can reduce the carbon footprint of the grid. Additionally, green nodes can receive additional incentives in the form of tokens to encourage adoption.

Practical example: In energy microgrids, demand forecasting models run locally on edge nodes, while blockchain records energy transactions between users.

Good practices in the life cycle

To ensure sustainability throughout the lifecycle of AI and blockchain solutions, the following practices should be adopted:

- **Energy consumption monitoring**: Tools such as Green Algorithms and Carbontracker allow you to assess the environmental impact during model training, validation, and deployment.
- **Environmental metrics**: Establishing indicators such as carbon footprint, Power Usage Effectiveness (PUE) and computational efficiency allows you to measure and optimize environmental impact.
- **Sustainable scalability**: Design systems that can grow in number of users without exponentially increasing energy consumption. This can be achieved by adopting distributed architectures and optimizing computational resources.

Practical example: In urban mobility systems, route optimization algorithms process data on edge devices, while blockchain records only key results, such as avoided emissions.

Practical examples

1. **Traceability in sustainable supply chains**:
   AI certifies the origin and authenticity of products, while blockchain records only the hashes of the certificates, ensuring traceability with minimal resource consumption.
2. **Energy prediction in microgrids**:
   AI models predict energy demand locally, and blockchain audits energy transactions between users, ensuring transparency and efficiency.
3. **Sustainable urban mobility**: Green algorithms process data on edge devices to optimize routes and reduce emissions, while blockchain records key sustainability metrics.

Checklist Guide (DOs & DON'Ts)

DOs:

- Use compact and optimized models.
- Adopt energy-efficient consensus protocols.

- Measure and report environmental impact in each phase of the life cycle.
- Prioritize the use of nodes powered by renewable energy.

DON'Ts:

- Store heavy data on the blockchain.
- Training complex models without a clear justification of their social or environmental value.
- Ignoring the environmental impact of on-chain transactions.

4. Recommendations

Sustainability at the intersection of blockchain and artificial intelligence (AI) requires a comprehensive approach that encompasses technical, environmental, regulatory, and application aspects. These recommendations are designed to guide developers, regulators, and users toward implementing responsible and sustainable solutions.

4.1. Technical recommendations

1. **Selecting Efficient Consensus Protocols**
   Consensus protocols are at the core of blockchain networks, as they determine how transactions are validated and the integrity of the network is ensured. However, their environmental impact varies significantly.
   - **Proof of Work (PoW):** Although it is the most well-known protocol used by Bitcoin, its energy consumption is extremely high due to the need to solve complex computational problems.
     - **Impact**: Bitcoin consumes approximately 127 TWh per year, comparable to the energy consumption of countries such as Norway.
   - **Proof of Stake (PoS):** This protocol eliminates the need for intensive calculations, reducing energy consumption by more than 99%. Ethereum, by migrating from PoW to PoS, achieved this significant savings.
2. **Minimizing data and transactions on blockchain**
   Reducing the size of transactions and data stored on blockchain can significantly decrease energy consumption.
   - **Recommended techniques**:
     - **Off-chain storage**: Saving large data off-chain and only storing references on the blockchain.
     - **Data compression**: Reduce the size of data before storing it.

- **Example**: zk-SNARKs, a zero-knowledge proofing technology, enables lighter and more efficient transactions.

4.2. Sustainability recommendations and good green practices

1. **Migration to renewable-powered infrastructures**
   Blockchain data centers and nodes must use renewable energy sources to reduce their carbon footprint.
   - **Strategies**:
     - Power purchase agreements (PPAs) with renewable energy suppliers.
     - Installation of solar panels and wind turbines in own facilities.
   - **Example**: Google and Microsoft already operate 100% renewable data centers, setting a standard for the industry.

2. **Inclusion of environmental metrics**
   It is crucial to measure and report on the environmental impact of technologies.

   - **Key metrics**:
     - **Carbon footprint**: CO2 emissions generated by the infrastructure.
     - **Power Usage Effectiveness (PUE):** The ratio of the total energy consumed by a data center to the energy used by its IT team.
     - **Energy efficiency**: The ratio between the useful work performed and the energy consumed.
   - **Applicable standards**: ISO 14001 on environmental management.

3. **Incentives for nodes and participants**
   Implement reward mechanisms for nodes that use renewable energy or reduce their environmental impact.

   - **Example**: Networks like Chia incentivize the use of efficient storage instead of intensive mining.

4. **Promoting digital circular economies**
   Encouraging the reuse of hardware and the optimization of digital resources can reduce environmental impact.

   - **Use case**: Blockchain hardware recycling projects in the EU.

4.3. Regulatory and governance recommendations

1. **Alignment with international regulations and standards**
   Solutions must comply with frameworks such as the Sustainable Development Goals (SDGs), the EU Taxonomy, and the CSRD.
   - **Example**: The EU Taxonomy classifies sustainable activities, including blockchain and AI.
2. **Transparency and traceability in environmental reporting**
   Blockchain can be used to record and verify environmental data, improving transparency.
   - **Use case**: Carbon traceability projects in the EU.
3. **Establishing ethical frameworks**
   It is critical to develop ethical principles for the use of blockchain and AI, ensuring that these technologies do not compromise sustainability.
   - **Applicable rules**: EU Ethical Guidelines for AI.

5. Blockchain and AI Examples

5.1. Energy and sustainability

Smart grids

Smart grids are advanced systems that integrate digital technologies, such as IoT sensors, artificial intelligence (AI), and blockchain, to efficiently manage energy generation, distribution, and consumption. These networks enable two-way communication between energy suppliers and consumers, optimizing resource use and reducing waste.

Practical example:
In Germany, the "Enerchain" project uses blockchain to record renewable energy transactions between producers and consumers. AI, on the other hand, analyzes consumption patterns in real time to adjust power distribution, avoiding overloads and maximizing efficiency. This approach also allows consumers to sell the surplus energy generated by solar panels or wind turbines directly to other users, eliminating intermediaries.
Expected Benefits:

- Reduction of energy losses in distribution.
- Greater transparency in the origin of the energy consumption.
- Promotion of the use of renewable energies.
  Challenges:

- Ensure interoperability between different blockchain systems.
- Protect the privacy of consumer data.

Community Microgrids and Federated Learning

Microgrids are local power grids that can operate independently or connected to the main grid. These networks allow communities to generate, store and share energy autonomously. Federated learning, an AI technique that trains models without sharing sensitive data, can balance production and demand in these microgrids.

Practical example:
In the Netherlands, the "Powerpeers" project allows households to share locally generated renewable energy. Consumption and generation data are processed locally using edge computing, while federated learning optimizes the energy balance without compromising user privacy.
Expected Benefits:

- Reduced reliance on core networks.
- Increased energy resilience in local communities.
- Optimization of the use of energy resources.

Challenges:

- Scalability of microgrids at the regional or national level.
- Local regulations that limit energy exchange.

5.2. Green supply chain

Traceability of the origin of sustainable raw materials

Traceability in supply chains is essential to ensure that products meet sustainability standards. Blockchain makes it possible to record every stage of a product's life cycle, from the extraction of raw materials to its distribution, providing an immutable and transparent record.

Practical example:
In the food industry, the IBM Food Trust project uses blockchain to track the origin of ingredients in food products. For example, consumers can scan a QR code on a coffee package to verify that the beans come from certified sustainable crops.
Expected Benefits:

- Increased consumer confidence in sustainable products.
- Reduction of fraud in sustainability certifications.

- Improved efficiency of audits and regulatory controls.
  Challenges:
- Initial blockchain implementation costs.
- Need for standardization in the data recorded.

Logistics optimization with AI

AI can analyze real-time and historical data to identify inefficiencies in the supply chain, optimizing transportation routes, reducing delivery times, and minimizing carbon emissions.

Practical example: In France, the company "Geodis" uses AI to predict delivery delays due to adverse weather conditions. This allows transport routes to be adjusted and shipments to be consolidated, reducing fuel consumption and CO2 emissions.
Expected Benefits:

- Reduced operating costs.
- Reduction of the carbon footprint in transport.
- Improved customer satisfaction.
  Challenges:
- AI integration with existing logistics systems.
- Access to quality data to train AI models.

5.3. Agriculture and natural resource management

IoT sensors and edge computing

IoT sensors installed in agricultural fields collect data on moisture, temperature, soil quality, and other key parameters. This data is processed locally using edge computing, reducing latency and power consumption.

Practical example: In Spain, the "SmartAgriHubs" project uses IoT sensors to monitor irrigation in real time. Locally processed data allows water use to be adjusted according to the specific needs of each plot, reducing waste and improving sustainability.
Expected Benefits:

- More efficient use of natural resources such as water and fertilizers.
- Increase in agricultural productivity.
- Reducing the environmental impact of agriculture.
  Challenges:
- Installation and maintenance costs of IoT sensors.

- Connectivity in rural areas.

Blockchain for certifications

Blockchain registers certifications related to the efficient use of resources, such as water and fertilizers, ensuring transparency and trust in agricultural products.

Practical example: In Italy, the "Wine Blockchain" project certifies that vineyards comply with organic farming standards. This facilitates the export of wines to international markets that demand high standards of sustainability.
Expected Benefits:

- Access to international markets with high sustainability standards.
- Reduction of fraud in agricultural certifications.
- Improvement in the reputation of producers.
  Challenges:
- Education and training of farmers in the use of blockchain.
- Local regulations on digital certifications.

5.4. Smart cities and mobility

Traffic and air quality management with AI

In smart cities, urban sensors equipped with lightweight AI collect real-time data on traffic flow, air quality, and other key indicators. This data is processed locally using edge computing, which allows quick decisions to be made and reduces traffic congestion and pollutant emissions.

Practical example: In Copenhagen, Denmark, an AI-based traffic management system has been implemented that adjusts traffic lights in real-time based on traffic flow. In addition, sensors distributed throughout the city monitor air quality, providing data that helps identify areas with high levels of pollution. This data is used to design sustainable mobility policies, such as the creation of low emission zones.
Expected Benefits:

- Reduction of traffic congestion.
- Improvement in urban air quality.
- Optimization of public and private transport.
  Challenges:
- Ensure the privacy of the data collected by the sensors.
- Integrate AI systems with existing urban infrastructure.

Transparency in mobility data with blockchain

Blockchain can ensure the integrity and transparency of data related to urban mobility, such as the use of shared bicycles, electric vehicles, and public transportation. This builds citizen trust and facilitates the implementation of data-driven policies.

Practical example: In Estonia, blockchain is used to record the use of electric vehicles and charging stations. Citizens can access this information to verify the environmental impact of their mobility decisions. In addition, the collected data is used to optimize the location of new charging stations.
Expected Benefits:

- Increased confidence in urban mobility data.
- Promotion of the use of sustainable transport.
- Transparency in the implementation of public policies.
  Challenges:
- Initial blockchain implementation costs.
- Need for standardization in mobility data.

5.5. Health and sensitive data

Federated Learning and Blockchain

Federated learning allows AI models to be trained using data distributed across different healthcare institutions, without the need to centralize medical records. Blockchain ensures the integrity and privacy of this data, providing an immutable record of transactions made during model training.

Practical example: The European project "MELLODDY" uses federated learning and blockchain to develop predictive models in oncology. Clinical data remains in participating hospitals, but models are trained collectively, ensuring patient privacy.
Expected Benefits:

- Protection of the privacy of clinical data.
- Collaboration between health institutions without sharing sensitive data.
- Development of more robust and representative AI models.
  Challenges:
- Technical complexity in the implementation of federated learning.
- Strict regulations on the use of health data.

Reduced energy costs associated with data transport and duplication

The use of blockchain and federated learning reduces the need to transfer large volumes of data between institutions, decreasing the energy costs associated with data transport and information duplication.

Practical example:
In a pilot project in Germany, hospitals and laboratories use blockchain to record access to clinical data and federated learning to train diagnostic models. This eliminates the need to transfer data between institutions, significantly reducing energy consumption.
Expected Benefits:

- Reduction of the carbon footprint in the health sector.
- Greater efficiency in the use of technological resources.
- Compliance with privacy regulations such as GDPR.
  Challenges:
- Need for advanced technological infrastructure.
- Resistance to change in traditional institutions.

5.6. Sustainable finance

Tokenization of carbon credits

Tokenizing carbon credits using blockchain allows digital assets to be created that represent a specific amount of offset carbon emissions. These tokens can be traded on digital markets, facilitating investment in sustainable projects.

Practical example: In Sweden, the "Chooose" platform uses blockchain to tokenize carbon credits generated by reforestation and renewable energy projects. Companies can acquire these tokens to offset their emissions, while blockchain records ensure transparency and traceability of transactions.
Expected Benefits:

- Greater transparency in carbon credit trading.
- Access to global markets for sustainable projects.
- Encouraging investment in climate change mitigation initiatives.
  Challenges:
- Inconsistent regulations on carbon credits in different countries.
- Need for global standards for tokenization.

AI to verify compliance with ESG criteria

AI can analyze large volumes of financial and non-financial data to verify in real time compliance with environmental, social, and governance (ESG) criteria in investments.

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