Review Article

How Blockchain Technology Can Address Circularity and Trace Emission in the Energy Sector

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This paper outlines the European perspective on circularity in the energy sector and details how blockchain could support it. Moreover, while the need for raw materials and e-fuels is increasing (due to the economic, industrial, and societal ecological transformation to slow down the pace of climate change), their supply becomes more and more risky. Therefore, technologies to support tracing and certification are in the spotlight.

To achieve resilience to new threats, Europe is focusing on circularity in all fields. Circularity requires the tracing of substances and devices, food, and products, to retrieve and recycle as much as possible. Besides the need to limit the exploitation of the planet's resources and thus stay within the planetary boundaries, circularity is tightly connected to strategic dependencies on highly unstable or politically distant countries. This issue is further aggravated by the Russia-Ukraine crisis. Digital technologies, like Distributed Ledger Technologies, can well support the implementation of circularity in many fields. The paper identifies challenges and proposes potential solutions related to the implementation of circularity. It also explores the application of circularity principles in the energy sector, with a focus on energy communities. Energy communities involve local stakeholders coming together to generate, consume, and manage renewable energy collectively. Overall, the paper provides insights into the European perspective on ecological transition, highlighting the importance of systemic transformation, resilience, and circularity in addressing climate change and achieving sustainability goals. It explores the role of digital technologies, such as Distributed Ledger Technologies (DLTs), in supporting circular practices and discusses specific applications in the energy sector.

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1. Introduction

Notwithstanding the different definitions of circular economy, there is a generalized consensus on identifying it with the idea of closing and, as far as possible, extending materials loops, instead of deteriorating and wasting them. A circular economy is also based on the well-known concept of the Doughnut economy [1]. According to the latter, the social and planetary boundaries (in the doughnut) are a simple visualization of the dual condition, social and ecological, that underpin collective human well-being. It is claimed that natural resources and effects on climate must not be overshot to over-satisfy human needs. The two things must stay in equilibrium, and the economy, as well as industry and society, should be redesigned to meet this challenge. The circular economy holds great potential for sustainable development. By applying its basic concepts, such as reducing waste, closing the loop on raw materials, and adopting innovative business models, several positive outcomes can be achieved [2][3][4].

1. Waste reduction: The circular economy aims to minimize waste generation by designing products and processes that prioritize durability, repairability, and recycling. Instead of following the traditional linear “take-make-dispose” model, materials and products are kept in use for as long as possible, reducing the amount of waste that ends up in landfills or incineration facilities.
2. Raw materials circle closure: The circular economy promotes the recycling and reuse of materials, allowing them to be looped back into the production process. This reduces the need for extracting and processing virgin resources, which often have significant environmental impacts. By closing the loop on raw materials, the circular economy conserves resources and decreases the pressure on ecosystems.
3. Innovative business models: The circular economy encourages the development of new business models that prioritize sustainable practices. These models can include product-as-a-service, sharing platforms, and collaborative consumption, among others. By shifting from a focus on selling products to providing services or access to products, companies can extend the lifespan of their offerings and generate value from them even after their initial use.

By implementing the principles of the circular economy, environmental benefits can be realized, including reduced greenhouse gas emissions, energy savings, and preservation of natural resources, with a positive impact on climate change. Moreover, it can drive economic growth by fostering innovation, creating new jobs, and generating economic opportunities in sectors such as recycling, remanufacturing, and repair.

Some examples of how a circular economy could impact climate change are listed below:

- Each ton of recycled plastics (instead of incineration) allows us to cut the emissions equivalent to the yearly emissions of a car.
- A reduction in the extraction of raw materials by 28%, potentially in place by 2050 through resource efficiency policies, can bring a reduction of the relevant emissions by 63%, bringing an economic growth of 1.5% of GDP worldwide.
- The emissions related to the production of materials were (in 2015) equal to 23% of total worldwide emissions and larger than those that can be referred to agriculture, forestry, and land use.

Raw materials extraction and production also impact water usage, as 90% of water stress comes from this activity worldwide. In addition to environmental reasons, the limitation of planetary resource exploitation also comes as an effect of the analysis of strategic dependencies that emerged as an issue during the COVID-19 crisis. The shortage of raw materials and manufactured components and systems has created big problems in the European supply chain in many industrial fields.

From the "Revised Industrial Strategy" [5] (after COVID-19) of the EU, it emerges that of 5,200 products imported into the EU, 137 products (6% of the total value of goods imported into the EU) are placed in sensitive ecosystems on which the EU is highly dependent - mostly in the industrial and pharmaceutical sectors as well as other products necessary for green and digital transformation.

A 52% share of the EU imports' value of these 137 products comes from China, 11% from Vietnam, and 3% from Russia. Lithium-Ion batteries, as an example, are produced mostly in China (66% of global production).

As far as raw materials supply is concerned, the situation is also dramatic. A share of 98% of rare earths and borates, used to manufacture magnets for electrical motors and memories for electronics, comes from China (and import is subjected to restrictions) and Turkey. Silicon (used for chip manufacturing and ICT products as well as Li-Ion batteries) is largely imported under restrictions from China. Platinum, used to manufacture electrolyzers, is almost fully imported from South Africa.

The recently proposed Net Zero Industry Act [6] aims at addressing several core drivers of net-zero technology manufacturing investments. In fact, Europe is a net importer of net-zero energy technologies, with the majority of solar PV modules, fuel cells, and around one-fourth of electric vehicles and batteries coming from China. The trade balance is getting worse, and EU companies are dealing with growing energy and input costs in other industries where the EU industry is still dominant, such as wind turbines and heat pumps. Additionally, in the domain of carbon capture and storage, the scarcity of CO_2 storage sites is now impeding the development of a CCS value chain in the EU. A key technology to support such a value chain in the EU and for delivering a fast transition in hard-to-abate industrial sectors is CCUS, for which also tracing CO_2 amounts (emissions, capture, and injection) is crucial for net-zero industrial activity.

The Raw Materials Act [7], through the proposal of a regulation, sets some minimum thresholds in terms of domestic extraction, processing, and recycling along the strategic raw material supply chain while aiming to diversify EU supply by 2030:

- *At least 10% of the EU's annual consumption for extraction*
- *At least 40% of the EU's annual consumption for processing*
- *At least 15% of the EU's annual consumption for recycling*
- *Not more than 65% of the Union's annual consumption of each strategic raw material at any relevant stage of processing from a single third country*

The Annual progress report on EU clean energy competitiveness as regards clean energy technologies [8] points to six key technologies that are expected to be enabling for several targets towards climate neutrality and the achievement of the EU's 2030 and 2050 energy mix: offshore renewables (wind and ocean), photovoltaic technology, green hydrogen, batteries, and smart grid technologies. As already mentioned, in the solar photovoltaic industry, the EU is no longer covering market shares in the upstream value chain (for example, solar photovoltaic cells and modules manufacturing). Important market opportunities exist in the parts of the value chain in which higher-value manufacturing and specialization are essential. Europe is thus aiming at strengthening internal supply chains, putting in place research, development, and industrial value of human resources and educational systems, and strategically aiming at resilient industrial development. A strong partnership with the United States makes the action plan even stronger (Energy Catalyst Fund [9]).

Blockchain technology [10], [11] has been identified as one of the possible technological solutions to fully implement circularity while overcoming barriers. The authors of [12] set out the main issues and research gaps still appearing in the application of blockchain to a circular economy. The Blockchain (BC) is a recent technology that is increasingly getting popular due to a large number of application fields and the outcomes it promises [10][11]. The Communication "Digital Compass: The European Way for the Digital Decade" outlines the digital ambitions in Europe as four clear and objective targets for the next decade:

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- a digitally skilled population and highly skilled digital professionals;
- secure and sustainable digital infrastructures;
- digital transformation of businesses;
- digitization of public services.

Within these targets, the blockchain application is recognized as one of the key enabling technologies, especially for the digital transformation of businesses. In this area, cross-border and cross-business cooperation will allow a more effective implementation of circularity.

However, some challenges remain, as the use of blockchain technology to implement circularity will (like other applications) rely on cyber-physical interaction. Therefore, it is necessary to manage the verification of the information/data/measures that are to be placed on a blockchain. Another important issue concerns the possibility of achieving trust between network participants simply through technology.

To this end, this article describes some relevant applications of circularity in the energy sector and discusses the challenges in these areas.

Section 2 introduces blockchain technology and the main advantages of using it.

Section 3 describes how this technology can be used for supply chain and circular economy applications.

To conclude, Section 4 describes the concept of circularity in the energy sector, also showing blockchain applications for energy services delivery and Energy Community management.

2. Blockchain technology

Since 1990, blockchain has been the technology first used in Bitcoin and cryptocurrency transactions. It is one of the Distributed Ledger Technologies (DLT), characterized by immutability, cryptography, and authoritative consensus. A blockchain platform is composed of a chain of blocks of transactions that update synchronously across the network of machines that are part of the platform and that are validated by the participants. The latter can run 'nodes' of the blockchain, showing different possibilities to execute operations and keep the information about all transactions immutably. The blocks of transactions are arranged chronologically, and each block is uniquely connected to the previous one. A cryptographic hash of the content of the last block of the chain is generated and saved in each new block, so that each block is connected to all previous blocks. The main benefits of blockchain technology are listed below [13][14]:

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- Blockchain is Decentralized: New transactions are copied to all the nodes of the network, ensuring transparency and data integrity.
- Data in blockchain are immutable: Data saved are immutable, thus preventing fraud, as the change of data in a given block would require changing all blocks upstream, which becomes computationally unfeasible.
- Data in the blockchain is shared: Sharing of information provides transparency and higher security.
- Reduced cost of transactions: The middleman is often eliminated in many transactions as no longer needed. This causes a cost reduction.
- Selective data disclosure: It is possible to share sensitive data in a selective way across the platform, according to the privileges of each user.

The above-cited positive aspects must be counterbalanced with some negative features, namely energy consumption and scalability. As the technology is distributed and decentralized, the time for data propagation across all the network nodes and their validation is strictly related to the number of nodes of the blockchain platform, the bandwidth of the telecommunication infrastructure, and the storage capacity.

3. Blockchain technology for supply chain and circularity

Although blockchain technology is often linked to cryptocurrencies, its decentralized structure, high level of data immutability, and adaptability make it potentially useful in a variety of other use cases [15].

Blockchain technology has gained considerable attention for its potential applications in supply chain management and promoting circularity. Blockchain offers a transparent, secure, and decentralized system for recording and verifying transactions, which can be useful in improving the traceability, transparency, and efficiency of supply chains.

As an immutable and transparent record of transactions, each participant in the supply chain can register and verify the movement of goods and raw materials from provisioning to production to distribution. This ensures that every step is documented, and the origin of products can be easily traced. This helps combat counterfeiting, verify authenticity, and ensure compliance with ethical and sustainability standards.

With a view to reducing waste and promoting the reuse, recycling, and restoration of resources, the same concept can be applied to circularity.

In fact, by tracking the production, use, and waste phases, it is possible to identify and monitor where waste or inefficiencies occur and to identify potential opportunities for improvement. Tracking product life cycles can facilitate the adoption of circularity-based business models, such as product leasing, refurbishment, and recycling.

The use of smart contracts can automate various aspects of supply chain management, including procurement, payments, and compliance. Smart contracts are self-executing agreements that trigger predefined actions once certain conditions are met. They eliminate the need for intermediaries, reduce costs, and increase efficiency. For example, a smart contract can automatically release payment to a supplier once the goods have been delivered and verified.

Blockchain can enable more affordable and efficient supply chain financing options. By digitizing and tokenizing assets, companies can prove ownership, track the flow of assets, and establish creditworthiness. This data transparency reduces risk for lenders, making it easier for suppliers and manufacturers to obtain financing. This, in turn, enables more fluid operations, promotes growth, and supports sustainability initiatives.

Finally, it enables the tracking and verification of supply chain sustainability. By recording relevant data, such as carbon emissions, water use, or fair-trade practices on the blockchain, companies can provide transparent proof of their sustainability efforts. This increases consumers′ trust and allows them to make informed choices based on verified information.

Overall, blockchain technology has the potential to transform supply chains by improving transparency, traceability, and trust.

The EU communication on Circular Economy [16] claims that the circular economy can strengthen the EU's industrial base and foster business creation and entrepreneurship among SMEs.

According to the communication, a closer relationship with end users, the sharing economy, and the massive use of digital technologies, among which are the Internet of Things, big data, blockchain, and artificial intelligence, will accelerate the pervasive implementation of circularity in the economy but also push the dematerialization of the economy, making Europe less dependent on raw materials.

Both the circular economy and blockchain technology have emerged separately, with separate bodies of literature. Many papers have clearly expressed the wide potential application of blockchain technology in circular supply chains for different products [17][18]. Many conditions need to be met to implement a circular economy first and then mainstream the application of blockchain to the circular economy, overcoming challenges. One of these is the existence of an ICT infrastructure for information sharing and platforms for collaboration among the different actors. This digital infrastructure is the base on which a circular economy can be implemented, since sharing information transparently is key to supporting different resource and material flows. Such a digital infrastructure could be provided to all actors by blockchain technology, thus allowing smooth Business-to-Business interactions.

By setting a shared information infrastructure on a blockchain platform, the technology can enable the sourcing of verifiable data inputs and support resource efficiency.

The blockchain can also support the recovery of raw materials, in particular tracking the refurbishing and recycling from manufacturers and consumers, following material and resource flows across various countries and supply chains, and finally consumption steps.

4. CO2 Circularity in the energy sector

Energy industries represent, on a global level, the source of 13.8 $GtCO_2$ in 2018, of which 72.5% is linked to production from coal, 22.5% from gas, and the remaining 5% from oil [19]. These industries, even if they suffered from reduced production in 2020 due to the COVID-19 pandemic, which affected the demand for oil and coal to a greater extent than other energy sources, are on the way to fully recovering the pre-pandemic demand. In Europe, GHG emissions created by energy industries in 2019 were 988 $MtCO_2eq$. A share of 98% of these is related to CO_2 alone. The reduction observed since 2018 of 11.1% is caused by the reduction in the use of fossil fuels in favor of renewable energies. In 2019, the consumption of fossil primary energy in Europe was 1,065 Mtoe (-14.7% when compared to 2018), while renewable energy was 250 Mtoe (+4.6%) [20].

In Europe, these companies are subjected to the Emissions Trading System, which is about to be revised. The new Emission Trading System, ETS, envisaged as one of the actuation measures from the ‘Fit for 55’ package under the green deal, is expected to include the buildings sector and the transport sector.

The EU ETS operates on the 'cap and trade' concept. Starting from the total amount of GHG that can be emitted by the installations located in each member state, a cap is set on it. The cap is reduced over time so that total emissions fall. Within this cap, installations can purchase or receive emissions ‘allowances’, which they can trade with one another as needed. Therefore, if a given installation has X allowances but should achieve more, it can buy them from another more virtuous installation in the EU. Conversely, if an installation reduces its emissions, it can keep the spare allowances to cover its future needs or, as already,

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sell them to another installation that is short of allowances. The limit on the total number of allowances available ensures that they have a value.

After each year, an installation must surrender enough allowances to cover fully its emissions; otherwise, heavy fines are imposed by the EU Commission.

Trading brings flexibility that ensures emissions are cut where it costs least to do so. A robust carbon price also promotes investment in innovative, low-carbon technologies. The certification of emissions reduction is currently referred to aircraft and industrial installations and is done by means of monitoring and reporting plans. As the ETS will involve car and building owners, probably, the monitoring will need more detailed and pervasive reporting, as this will significantly impact the prices of goods with higher GHG emissions.

With the advent of Carbon Capture and Use technologies, CO2 could be captured to synthesize new e-fuels also by green hydrogen.

4.1. Blockchain in EU ETS

The authors of [21] report that several fraudulent activities are already running in the field of ETS trading, and this phenomenon may scale as the number of involved entities grows. Several papers propose blockchain technology to overcome fraud and provide transparency to ETS monitoring and reporting. The architecture is depicted in Figure 3.

In the figure, the blockchain system deploys its action in 3 steps. The first is the delivery or emission of allowances from the EU to each participant in the ETS, considering the established cap per year and the already decided linear decreasing trend (4.2% per year). The second step concerns the trading of allowances among companies involved in the ETS. The new ETS, referring to buildings and transport, will entitle fuel suppliers to keep emissions related to the use of their fuel in that sector (i.e., transport or building heating) lower than a given cap. Such a burden will be shifted to end users, as the price of the fuels will increase, thus incentivizing the decarbonization of fuels (i.e., blue to green hydrogen; methane or biomethane) from fuel suppliers.

Finally, in the third step, the audit of the balance of emissions is carried out. This is probably the most challenging part of the application of blockchain technology to cyber-physical systems. Indeed, legacy devices typically do not provide direct information available on the blockchain; rather, data are collected on proprietary cloud systems and then delivered to the blockchain.

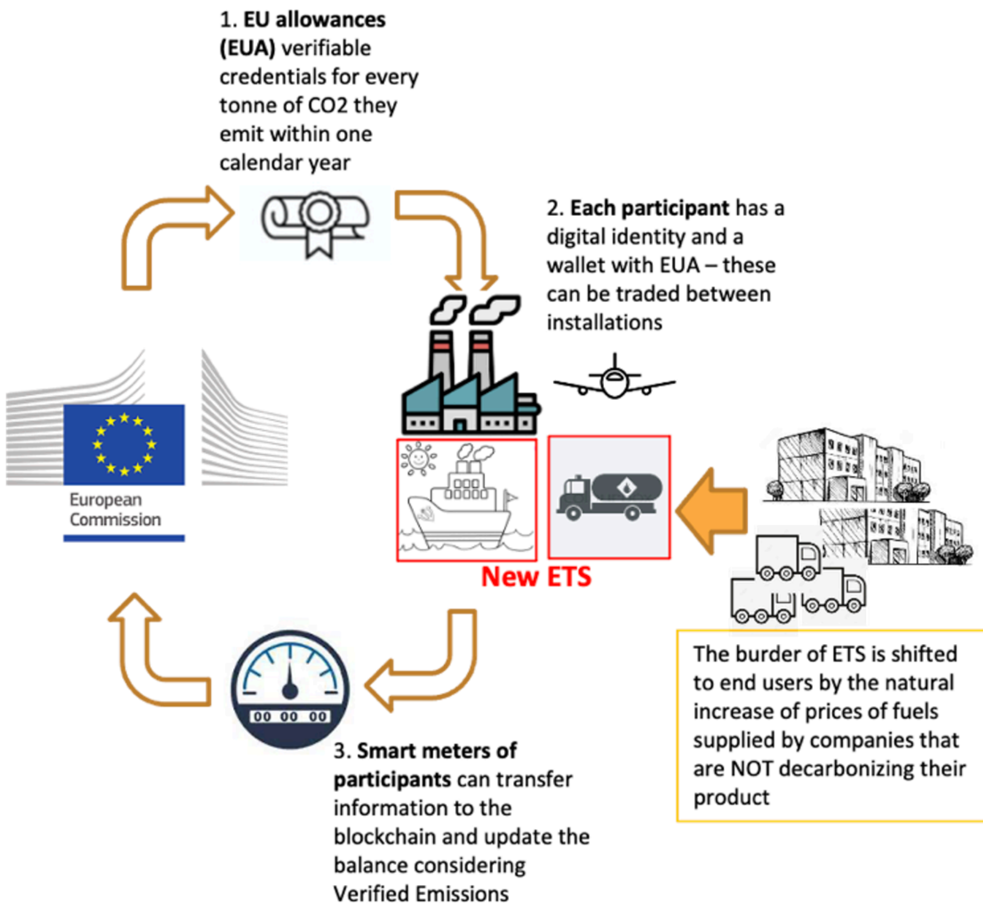

Figure 3. *Use of blockchain for EU ETS.*

Another sector in which blockchain could be used for circularity in energy is the supply chain management of manufactured products for which raw materials or production phases are not embedded in the EU industrial system.

4.2. Blockchain in raw materials tracing

Raw materials may be tracked throughout their worldwide supply chains by fusing blockchain with physical tracking systems. While blockchain converts these events into the digital realm with an immutable record, physical tracking technologies allow for the observation of raw material movement within the physical world. This study explores if and how the combination of several physical tracking technologies makes the supply chains for raw materials more visible. It also gives a taxonomy of these technologies [22]. The potential of blockchain to facilitate supply chain transparency is gaining more and more attention from academics and industry professionals [23][24][25][26]. The idea seems to be that bringing blockchain technology to supply chain participants will immediately improve the environment for supply chain transparency. The usefulness of utilizing blockchain technology, however, depends not just on the architecture design but also on the caliber of data it is able to store in an immutable, or tamper-proof, manner.

One strategy for producing useful, reliable data is to track the movement of materials using physical tracking technology and then input this data. The project Minespider is conducting the analysis as part of a research initiative that is being sponsored by the EU [27].

Using go-ethereum [28] nodes and a proof-of-authority consensus method, Minespider created a public, permissioned blockchain that links supply chain data and documents by encrypting them in linked, digital certificates (also known as "product passports"). Everyone can access the public blockchain in Minespider's version of a public-permissioned blockchain, but only nodes that have been accredited to the consortium are allowed to seal blocks. A vote is held if a new sealer asks for accreditation; if the new account receives more than 50% of the votes, it is accredited. Minespider offers manual users frontend applications, templates, and APIs for process automation. In the sense that input data of any format can be incorporated into a product passport, encrypted in an immutable manner on the blockchain, and transferred along a supply chain, Minespider is data agnostic. Examples of this might be PDFs, pictures, videos, and other types of documentation. It may also accept data generated by physical trackers in any format. Product passports come with a unique QR code that can be scanned using common scanning equipment (like a smartphone) to grant access to the passport's associated public data and to request authorization to access secured data. These QR codes can be laser printed directly onto the materials or printed on paper and attached to packages. Additionally, product passports offer a chain of custody and proof of provenance along a supply chain. In this manner, the Minespider infrastructure can support a circular economy by bridging gaps brought about by the fusion of various sources or stages of production.

4.3. Blockchain in certification of energy services delivery

As an example, Li-Ion batteries are critical devices for which the use phase must be monitored for possible second-life use in grid applications. The conditions in which they operate are critical to delay ageing mechanisms. The BLORIN project implements a blockchain platform for managing energy services certification and supply chain management for electric vehicles' batteries [29]. The project

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indeed refers to Demand Response (DR) and Vehicle to Grid (V2G) services certification and remuneration. It was observed from the literature that V2G services can be responsible for the premature ageing of Lithium-Ion batteries.

For this reason, one part of the BLORIN blockchain was devoted to monitoring the ageing status of the vehicle's battery. The platform collects data from the vehicle in real time and provides them with data analytics tools to extrapolate ageing speed and suggest to the owner how to behave. The BloRin ecosystem is composed of several interconnected actors from the energy market. These are Distribution System Operators (DSOs), end-users, energy service companies, car manufacturers, and insurance companies, as depicted in Figure 4.

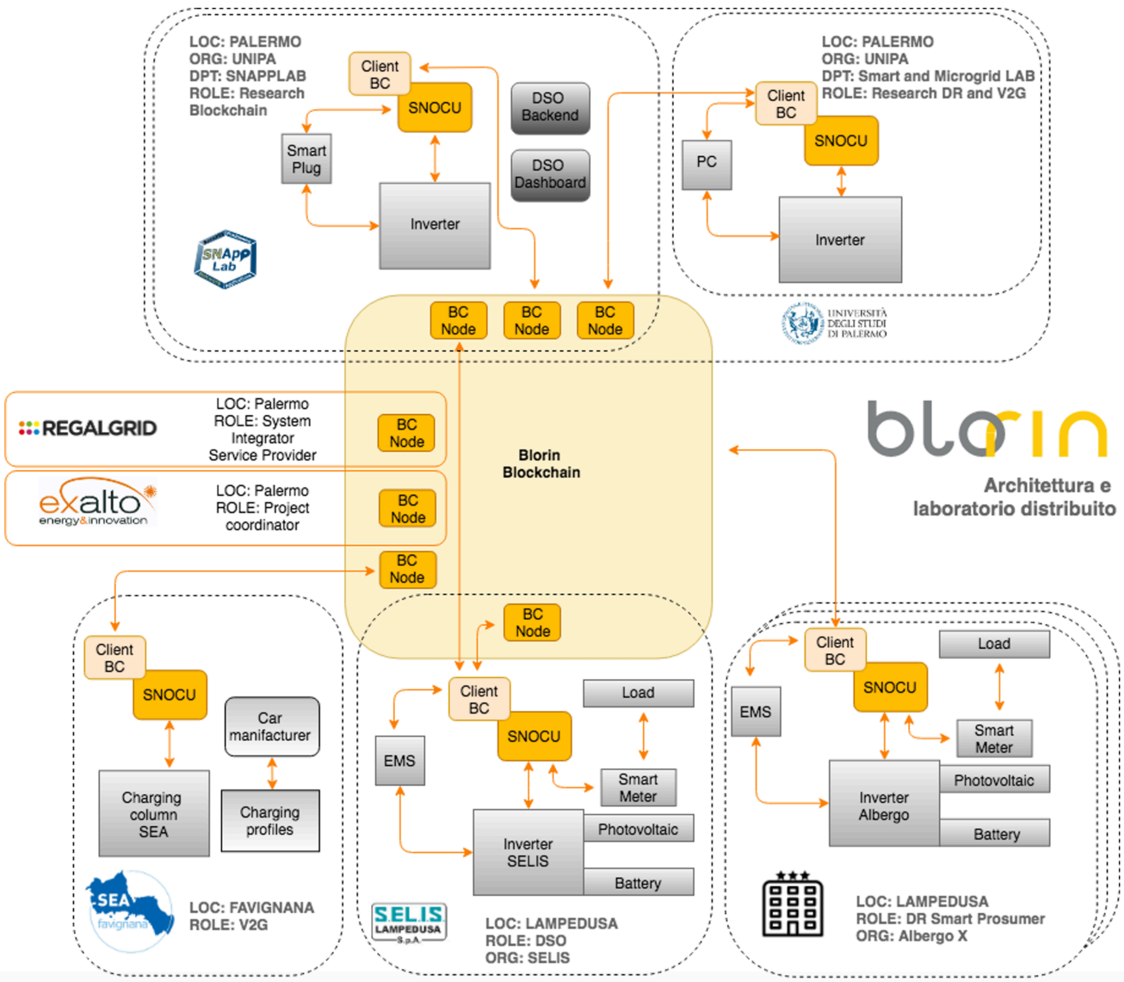

Figure 4. *The Blorin ecosystem based on blockchain technology.*

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The BLORIN ecosystem is based on Hyperledger Fabric 2.0, and the smart contracts devoted to V2G management are integrated with the monitoring of the battery health status.

Hyperledger Fabric 2.0, differently from other blockchains, allows the use of smart contracts, called "chaincodes", written in a general-purpose programming language such as Go, Java, or Node.js.

Smart contracts are programs that implement transaction logic that processes the data that can be retrieved from the blocks. Such smart contracts also allow the users to interact with the ledger (read/write).

In addition, because they are implemented on the Blockchain, they inherit some interesting properties from it:

1. Immutability: after creation, a Smart Contract can never be changed. No one can change the contract code, not even the creator of the contract itself;
2. The contract is distributed over the network and validated by the Blockchain. A single user cannot force the contract against the specified characteristics because other users on the blockchain would not approve it.

The Hyperledger Fabric blockchain is based on a particular architecture that logically arranges the nodes into different containers. The elementary network is shown in Figure 5. It consists of five main components: Peer, Orderer, Client, Smart Contract, and Ledger copy.

In this scheme, the "peer" is the basic element of the network, as it is the entity that keeps a copy of the ledger while hosting and running the smart contract for writing/reading data from the ledger.

Peer nodes are kept in operation by the members of the blockchain platform. An App Client is a code that is external to the blockchain. The latter is fundamental for calling the execution of a smart contract and thus activating reading or writing.

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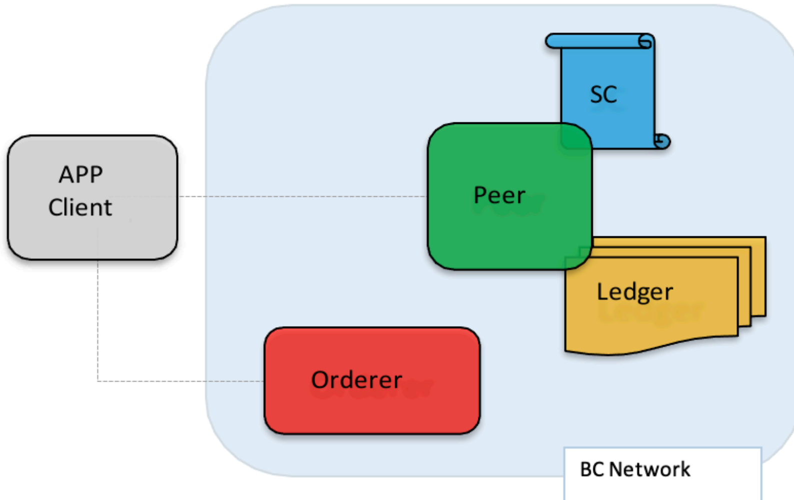

Figure 5. *Elementary Hyperledger fabric network.*

The App client also shows the members the outcome following a query or a “transaction proposal.” In the case of a transaction proposal, the new transaction is sent to the Orderer node, which oversees the consensus process. All members can be grouped into organizations, and organizations can be grouped into consortia. This architecture of relations allows the implementation of the most diverse interactions among nodes. The disclosure of data to different actors can be orchestrated using channels that provide visibility to different data depending on the role of the single actor.

The BLORIN blockchain platform is a tool developed for the provision of energy services, specifically DR and V2G. Using the blockchain, DR and V2G programs can be executed directly between the grid operator and users, unlike today where the aggregator mediates between the user and the grid operator. In this case, it is the exchange of an energy service: the TSO/DSO requests a reduction/increase in load, and users respond accordingly by reducing or increasing load. The transaction is not a direct energy exchange between two parties, but a request to provide a service, where users will then be remunerated if they respond appropriately. One of the main problems in the traditional provision of these services is the lack of transparency between the different parties involved, but through blockchain, it is possible to manage this problem while also encouraging disintermediation. With the BLORIN platform, it is possible to directly engage small prosumers in capacity and balancing markets by aggregating them into virtual load units that can be managed as needed.

On the island of Lampedusa, virtual user aggregation has been used to implement DR programs.

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DR makes it possible to manage or modulate the electrical load, allowing load shifting or reduction of peak consumption during certain periods; this service is useful for several reasons:

- Avoid costs for new generation capacity.
- Avoid the costs of installing new transmission or distribution capacity.
- Improve the efficiency of the generation system by reducing costs due to fuel consumption.
- Reduce the costs of ancillary services.
- Potential to reduce environmental impact and CO2 production by the power system.

On the island of Lampedusa, the electricity system is managed by a single company, SE.LI.S S.p.a., which handles all aspects of electricity, from production to distribution and sales. Production is managed through a single power plant consisting of 8 diesel generators, with a total of about 22 MW.

Diesel generation is very expensive and inefficient, as well as having a large environmental impact in terms of pollution.

In addition, between June and September, the overall load on the island is much higher than in winter, and during peak hours, some lines can be overloaded and cause blackouts in some areas.

From this context, DR in Lampedusa has as its first objective the reduction of the load during peak hours, thus allowing a flattening of consumption and therefore better management of lines and generating units.

In fact, in addition to the overloading of power lines, there is greater fuel consumption, as it is often necessary to run low-efficiency generating units to meet demand.

Using the Blorin platform for DR service delivery to reduce fuel consumption and increase the efficiency of diesel generators is estimated to reduce CO2 emissions by 250 tons/year.

4.3.1. Application of blockchain technology in the energy sector: Energy Communities

While using blockchain for aggregation involving all market actors requires a disruptive change in the business model and in the electricity market, a closer application is devoted to peer-to-peer transactions among private citizens belonging to an EC.

The European Renewable Energy Directive II (REDII), or Directive 2018/2001/EU, promotes the transition to a more sustainable energy system based on renewable energy, setting binding targets for the share of energy from renewable sources to be achieved in the European Union by 2030 (32 %), underlining the importance of renewable energy certificates to facilitate the monitoring and tracking of energy produced from renewable sources, and strengthening the concept of self-consumption of energy. A tentative agreement was reached on March 30, 2023, for a binding 2030 target of at least 42.5 percent, but with a goal of 45 percent. Once this process is completed, the new legislation will be formally adopted and go into effect.

The REDII directive thus provides a regulatory framework that fosters the development of Energy Communities (ECs). It establishes clear rules and provides guidance on the self-consumption of energy, decentralized production of renewable energy, and citizen participation in energy management.

Circular economy in energy ECs involves the application of circularity principles in the energy sector, where local communities join to generate, consume, and manage energy in a sustainable way [30].

This involves adopting approaches that promote energy efficiency, decentralized renewable energy production, and the sharing of energy resources.

Circular energy ECs aim to optimize energy use through the adoption of energy efficiency measures. This can include the thermal insulation of buildings, the use of energy-efficient appliances, and the implementation of smart energy management systems. By reducing energy consumption, waste and associated emissions are also reduced. Circular energy ECs also promote renewable energy production at the local level. This can be done through the installation of solar photovoltaic systems, wind turbines, or other renewable energy sources. Locally produced energy can be used within the community itself, reducing dependence on traditional energy sources and reducing greenhouse gas emissions. The goal is to optimize the use of local energy resources, maximizing the overall efficiency of the energy system.

Applying circular economy principles in ECs can lead to several benefits, including reduced greenhouse gas emissions, increased resilience of the local energy system, and increased citizen participation in energy production and management. It also promotes the transition to a low-emission economy with a positive impact on climate change.

Blockchain technology, thanks to its characteristics of transparency, distribution, immutability of data, and especially the possibility of using Smart Contracts, can help promote the development of ECs and the application of the circular economy on them.

Certification of energy produced and self-consumed within an EC can take place through specific Smart Contracts executed and shared on Blockchain nodes. Smart Contracts are stored on the Blockchain, thus distributed, and no user who is part of the system has complete power over them.

When a new transaction proposal is requested, it is processed by the Smart Contract of the node to which it was sent; if the response to the proposal is consistent with the logic implemented by the Smart Contract, the new transaction is sent to the other nodes, which repeat the process. At this point, only if all the responses processed by the Smart Contracts running on the other nodes match, the new transaction is recorded in the ledger. This process allows for a unique and reliable certification of transactions. Thus, Smart Contracts running on the Blockchain nodes, in addition to implementing the transaction logic, would enable certification of the energy community's self-consumption for the purpose of incentive calculation.

The following Figure 6 shows a possible Blockchain architecture to support ECs.

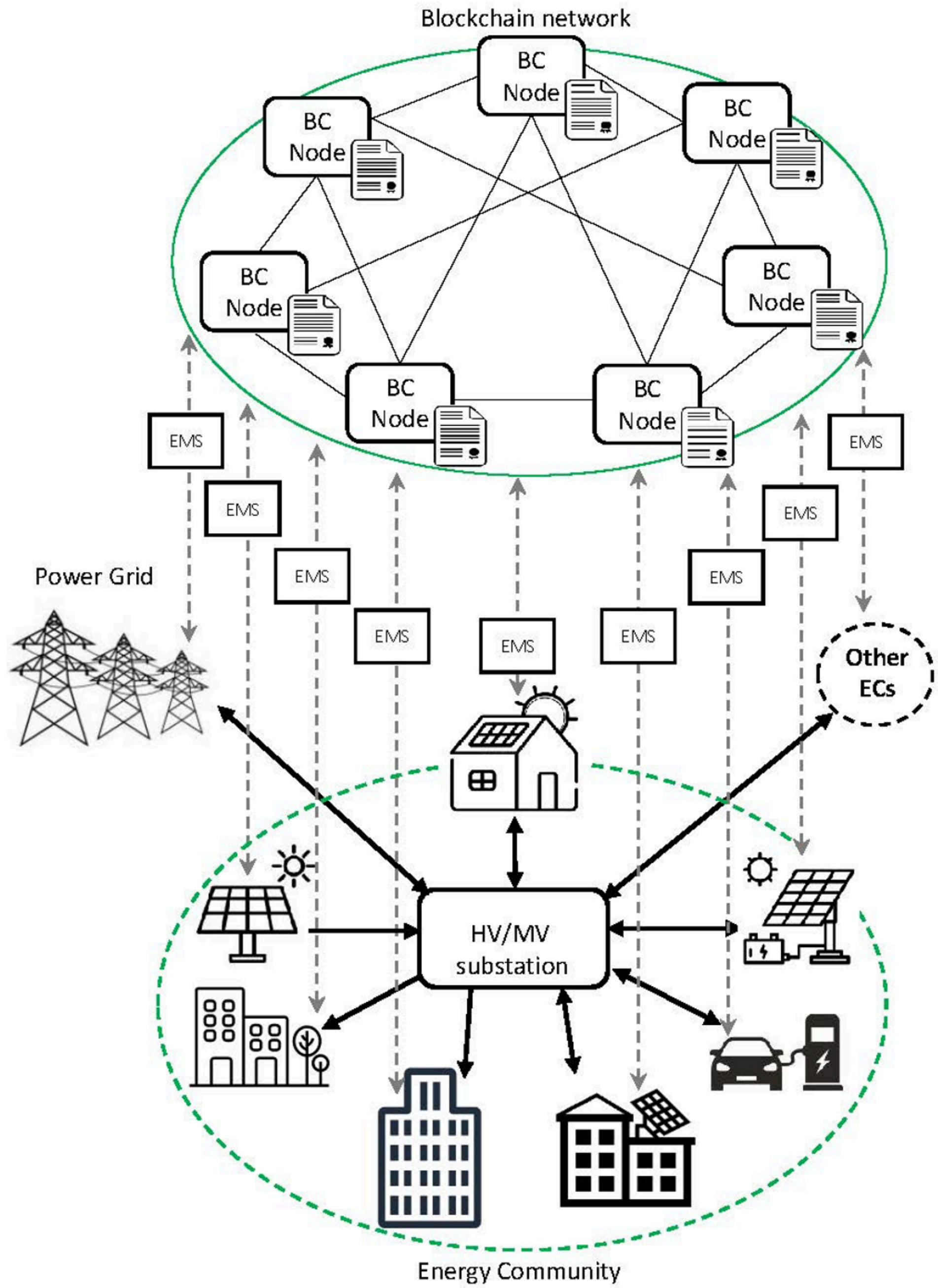

Figure 6. *Blockchain architecture for an Energy Community.*

For users to interact with the blockchain network, a device is needed that, in addition to recording the energy consumed/produced by users, can send/receive data from the blockchain.

Such a device, in addition to an energy meter, must therefore integrate a Blockchain Client, i.e., an application that acts as a bridge between the physical and virtual worlds. This task can be performed by an Energy Management System (EMS).

The EMS is the system that enables monitoring and control of passive household user loads and consists of a data processing controller and an energy meter.

The controller works as a personal computer, within which a blockchain client is implemented, enabling communication with the blockchain platform. To optimize the shared energy, though, for example, a home assistant installed inside the EMS, it is possible to control some of the user's loads.

The blockchain platform allows the flow of data from both users and production systems to be securely managed and processed. It also allows easy integration with existing systems; the only component to be installed at the user's premises is the EMS, while the blockchain platform can be developed on a cloud system.

At this point, the question is whether the costs of developing and maintaining the platform are acceptable.

In this regard, we consider an EC consisting of 25 passive users and a 100 kWp PV system.

The average annual producibility of the PV system is about 160 MWh, while for the users, an average annual consumption of 5 MWh is considered, for a total of 125 MWh/year.

In Italy, for ECs, an incentive of 110 €/MWh for 20 years is recognized for energy shared among community users [31].

This shared energy is defined as the hour-by-hour minimum between the sum of the energy produced by renewable source plants and the sum of the energy consumed by all users who are part of the community.

If all energy consumed by users contributes to the shared energy, the annual incentive due to the community will be about 14,000 €.

In this calculation, we assume that income from the sale of energy goes only to the owners of the PV systems and is therefore not considered in the evaluation.

The initial investment for creating the infrastructure is:

- 250 €/user for the measurement, data acquisition, monitoring, and load control system (EMS).
- 20,000 € for the design and development of the blockchain-based distributed platform for EC management, generation attestation, and data validation, including a web app for energy information tracking and documentation for up to 25 users, which can be either residential or business.
- 15,000 € for the design and development of mobile apps for interaction with the blockchain platform.

For a total of about 50,000 €, to which 10,000 €/year should be added as a fee for the management and maintenance of the platform, including cloud services.

The payback time of the investment is about 12 years, after which only the management costs of about 10,000 €/year should be considered. This value decreases significantly as the number of EC users increases.

Considering, for example, an EC consisting of 70 passive users and PV systems with a total of 200 kWp, applying the same reasoning, the payback time is reduced to 4/5 years.

The following Table shows the comparison of the operating costs of a CE in 3 different cases for an energy community consisting of 25 users and a 100 kWp PV system:

1. EC managed through a blockchain platform.
2. EC managed through centralized platforms.
3. EC managed by people.

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	EC supported by BC platform		EC supported by centralized platform (i.e.: regalgrid[32])		EC managed by humans	
Measurement, data acquisition, monitoring, and load control system	250 €/user	Optimized operation and increased self-consumption	250 €/user	No optimization, just monitoring	150 €/user/year	Accounting operations performed by the EC administrator
Platform development	20,000 €		10,000 €		-	
Cloud service	10,000 €/year		-		-	
End user App	15,000 €		10,000 €		-	
Expenses for EC establishment (contract)	Included in the platform development (Smart Contract)		10,000 €		10,000 €	
Payback time (25 users' community)	12/13 years		10/11 years		5/6 years	

Table 1. Comparison of operating costs of a CE for 3 different cases.

It can be seen from Table 1 that in the analyzed case, the use of blockchain would be the most expensive.

But this cost drops significantly as the number of users who are part of the community increases.

Finally, the aspect of CO2 emissions must be considered.

With the use of blockchain and thus an EMS that can optimize shared energy by shifting users' energy consumption during the same production hours as the renewable energy systems that are part of the community, a significant reduction in emissions would be achieved.

With the use of the other two systems analyzed, the lack of an EMS does not guarantee the optimization of shared energy, which results in higher emissions.

Thus, it is concluded that the use of blockchain for CE management, even if it achieves greater emission reduction, is only acceptable if the number of users is very large.

5. Conclusion

This study describes the European perspective on circularity in the energy sector. Policy documents about circularity at the European level call for innovative digital technologies to support our society in reducing inputs and waste and closing cycles. The paper shows how blockchain technology, with its intrinsic features, is feasible for managing the issues related to tracing CO2 emissions certificates or rather raw materials, the ageing of devices and components, and extending their lifetime. Tracing materials and products also allows for more effective recycling and more environmentally safe disposal. Finally, personal data concerning the use of energy or habits of consumption can also be traced back on the blockchain, but only end users can give permission to access those only to certain actors. This feature of data circularity reinforces the ownership of data and the right to disclose them from the end users, while keeping control of them.

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Declarations

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can have a significant and tangible impact on the industrial scenario of the island and the whole society. The set of activities is developed around the common thread of micro and nano technologies, microelectronics, materials, microsystems, and devices, accumulating methodologies and applications and directing them toward six main areas: energy, health, smart mobility, environment, cultural heritage, and smart agriculture.

Potential competing interests: No potential competing interests to declare.