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# Blockchain in the Energy Sector for SDG Achievement

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**Abstract:** Blockchain technology finds application in multiple sectors, including renewable energy. Numerous blockchain-based applications aim to provide support in the production, management, distribution, and consumption of green energy. The benefits offered are not only technological but also social, environmental, and economic. The purpose of this study is to examine how the application of blockchain in the energy industry may affect the achievement of the Sustainable Development Goals (SDGs). This study is composed of two parts. The first part concerns the identification and analysis of the most relevant categories of blockchain applications in the energy sector and their ability to contribute to the achievement of the SDGs. A knowledge base, comprising scientific articles, gray literature, and real-world applications, has been created and analyzed. With a keyword-based approach, each application was associated with one or more SDGs. In the second part, the Sustainability Awareness Framework (SuSAF) was used to examine the findings of the first part of the study and discuss them in terms of five dimensions of sustainability. Finally, potential risks associated with the use of blockchain in the energy sector are also covered. Results reveal that tracking energy production and consumption and renewable energy communities are the applications that have the most beneficial effects, and that the benefits linked to blockchain adoption go beyond the energy sector to include the environment, the economy, industry, infrastructure, smart cities, and society.

**Keywords:** blockchain; renewable energy; SDG; sustainability analysis

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## 1. Introduction

The global energy landscape is undergoing a transformative shift towards sustainability and decentralization, driven by the urgent need to address climate change and promote socio-economic development.

These changes are driven internationally through widely shared initiatives among countries, such as the Paris Agreement of the United Nations [1], whose goals set for 2030 the achievement of a complete supply of energy from renewable sources at a global level; and the European Green Deal [2], of the European Union, whose objectives aim for 2050 to reduce global warming. These agreements fall within the more general framework of sustainability, defined by the "2030 Agenda for Sustainable Development" [3], made up of 17 objectives, the so-called SDGs, that concern many thematic issues in addition to issues related to energy sustainability. Targets for the SDGs are specific, time-bound objectives that further refine each of the 17 goals, providing clear and measurable outcomes to be achieved by 2030 in order to promote sustainable development across various dimensions. Sustainable electricity production, consumption, and distribution are some of the key elements that allow for the achievement of the objectives. As a result, several governments throughout the world have made plans to implement renewable energy (RE) within the next few years. With the spread of distributed energy production systems from renewable sources, energy systems have become more complex, necessitating the use of information technologies for their management in order to maintain stability and operational safety [4]. In this context, the potential for blockchain technology to improve the energy sector in multiple dimensions is emerging, in particular regarding sustainable development. Blockchain technology, created to allow for the development of cryptocurrencies, is today an enabling technology for innovative services.

This paper aims to study the effects of blockchain technology applications in the energy sector on the fulfillment of the Sustainable Development Goals (SDGs). In particular, the following research questions were considered to guide our study:

**RQ1** How does the use of blockchain technology in the energy sector help to achieve the SDGs?

**RQ2** What effects can blockchain applications in the energy sector have on sustainability?

To answer the first research question, this study starts with the creation of a knowledge base. This consists of a selection of surveys and literature reviews collected from the Scopus database, as well as related gray literature. The analysis of the collected materials resulted in the identification of six categories of blockchain technology applications in the energy sector and related real-world projects. These categories include "Decentralized Energy Market", "Microgrid Development and Management", "Development of Renewable Energy Communities", "Data Management and Energy Flow Forecast", "Electric Vehicles and Green Mobility", "and Tracking Sustainable Production and Consumption". After identifying the applications, their impact on meeting the SDGs is assessed. This evaluation was based on the analysis of keywords, extracted both from research works describing blockchain applications and from UN documents [3] describing the SDGs, and finally, on their matching.

This provides a comprehensive understanding of how blockchain technology, in reshaping the energy sector, can lead to the fulfillment of specific Sustainable Development Goals: SDG 7 (*affordable and clean energy*), 8 (*decent work and economy growth*), 9 (*industry, innovation and infrastructure*), 11 (*sustainable cities and communities*), 12 (*responsible consumption and production*), and SDG 13 (*climate action*).

To answer the second research question, the results of the first part were studied and discussed using the Sustainability Awareness Framework (SusAF) [5] in a sustainability analysis. The Sustainability Awareness Framework provides five dimensions of sustainability—economic, social, individual, environmental, and technical—that allow us to discuss in detail and in a comprehensive and multidisciplinary way the connection between blockchain applications and the SDGs in the energy sector.

The contribution of this work differs from those already existing since the set objectives to be achieved. First of all, this work focuses on the search for the main fields of application of blockchain in the energy sector, highlighting the advantages and innovations provided by this technology, and the main projects and practical examples in the market. Secondly, it investigates how these applications help to directly or indirectly meet the Sustainable Development Goals (SDGs) related to the energy sector, environmental sustainability, social inclusion, and smart cities. Compared to works dealing with the potential impact of blockchain in SDGs [6–8], this work analyzes a larger number of goals and focuses on a specific sector.

The results obtained in this paper shed light on the potential implications of blockchain applications in the energy sector for accelerating progress towards achieving sustainability goals. The remainder of the paper is structured as follows. Section 2 presents a selection of existing literature reviews in this field that aided in establishing the foundation for this study. Section 3 describes applications of blockchain in the six different areas identified within the energy sector, and for each of them, discusses relevant ongoing real-world projects. Section 4 describes the method of the experiment and analyzes the resulting subset of SDGs related to the identified applications. Section 5 discusses, in terms of the SusAF, the effects on sustainability of blockchain applications in the energy sector, and Section 6 concludes the paper.

## 2. Background

In recent years, interest in blockchain applications in the energy sector has grown significantly, and numerous solutions that could improve the current system have been proposed in the literature.

This section discusses a selection of surveys and literature reviews on the use of blockchain technology in the renewable energy sector. These selected works served as foundation for constructing the knowledge base required to identify the fields of application of blockchain in the energy sector.

The selection process begins with querying the Scopus database for surveys and literature reviews generally regarding both blockchain technology and renewable energy. The used query consists of the string: “TITLE-ABS-KEY (“renewable energy” AND “blockchain” AND (“survey” OR “review” OR “state of the art”))”. We then limited the results to the *Document Types* “Article” and “Review” and to the *Subjects Areas* of “Computer Science” and “Engineering”. This query resulted in 42 documents.

Of these, based on the relevance of the content for the purposes of this work, 10 documents were selected for further investigation.

The main contribution of the selected papers and the differences from our work are discussed below.

In [9,10], opportunities, potential challenges, and limitations are discussed for several use cases, ranging from emerging peer-to-peer (P2P) energy trading and Internet of Things (IoT) applications to decentralized marketplaces, energy management, peer-to-peer trading, electric vehicle charging, and electric mobility. These two papers have provided part of the literary basis in the application fields mentioned above and, at the same time, contributed to identifying possible challenges for the continuation of this work. The current state of the power market transition is presented and discussed by the authors in [11], who then go on to examine the many applications of blockchain technology in the energy industry and talk about its challenges and promise. In [12], the most common energy blockchain application scenarios are covered in depth, along with an analysis of the general blockchain limits and how they affect energy systems, as well as potential routes that might solve these limitations for future blockchain-based energy systems. In-depth analyses of blockchain technology’s drawbacks and potential workarounds in the energy sector are provided in this article. Findings in these works provide material for the discussion of the difficulties and drawbacks reported in Section 5, and give an overview of the power market transition and uses of blockchain in the energy sector. In [13], a comprehensive survey of the application of blockchain in smart grids and significant security challenges of smart grid scenarios that can be addressed by blockchain are discussed. The article provides an introduction to the relevance of blockchain in the energy sector and presents various contributions centered around smart grids, including practical projects and blockchain-based solutions aimed at enhancing smart grid security. The content is divided into cryptocurrency initiatives and blockchain platforms; their main contribution, compared with other recent works, is motivating the adoption of blockchain across multiple aspects of smart grid technology. This survey was used in this paper to obtain a detailed background on blockchain technology, including some implementation projects reported in the next section.

In [14], the authors compares the wholesale power markets in centralized and decentralized regions using pertinent literature. They emphasize how, under a centralized arrangement, the system operator determines how much to create for each production unit by receiving comprehensive cost data from generators the day before delivery. This is the primary distinction between the centralized design and the decentralized design, which depends on self-commitment instead and requires producers to provide less thorough cost information to the system operator. Markets in the United States have shifted in favor of a centralized structure, but in Europe, the tendency is the reverse. The study explores the benefits and drawbacks of the two strategies and makes recommendations for enhancing each design. This work therefore provided a formal definition of a decentralized energy market, which was adopted in the next section.

In [15], a systematic literature review (SLR) of the various existing studies related to the use of blockchain technology in the energy sector is provided. They analyze the types of blockchain applications and platforms in the energy sector, the types of energy sources for which blockchain platforms are implemented, emerging technologies that are being combined with blockchain solutions, and the types of consents used in energy blockchains. The analysis of this work made it possible to obtain an overview of what are the most widely used platforms in the market and most demanded by users, which is information used in the next section.

In [16], the use of other technologies associated with blockchain, such as the Internet of Things (IoT), in the energy sector is discussed. IoT can be used to improve energy efficiency, increase the share of renewable energy, and reduce the environmental impact of energy use. In this work, results are used to highlight how the use of IoT devices, such as smart meters, provide us with useful data for optimizing energy use and its system. Thus, energy efficiency comes from controlling overproduction peaks and the deficit of energy in the grid. This control can be performed through monitoring transactions by prosumers, and thus by adopting decentralized transactive energy systems (TES). In particular, ref. [17] discusses solutions in the literature and proposes a novel new consensus protocol for DLT-managed P2P energy exchanges, called proof of energy. The results from this study are useful for describing the data management and energy flow forecasting applications discussed below.

The systematic literature review in [16] uses a visual bibliometric analysis approach and the Scopus database from 2014 to 2020 to perform a thorough evaluation of blockchain theory and evaluate the state of energy blockchain research and applications. This SLR individuates and describes five use cases and two real-world projects for each of them. Specifically, these are divided into the following categories: distributed energy system, optimization of energy commodity trading processes, convenient electric vehicles, smart device connection and intelligent control, and finally, supporting climate action and improving carbon trading. The study of the results was useful for defining application areas and identifying real-world projects discussed in the next section.

Starting from the findings reported in the selected papers, relevant cited application-specific research papers, gray literature, and technical reports have been included in the theoretical background necessary for the subsequent phases of the study.

## 3. Blockchain Applications in the Energy Sector

Based on the literature selected and analyzed in Section 2, six macro areas of application were identified to be the most discussed and presented in the articles analyzed, and cover almost entirely all domains in the energy sector. For each area, a set consisting of scientific articles and technical reports was identified from the literature examined in the previous section. In the rest of this section, some concepts relating to blockchain technology will first be recalled. Subsequently, the six identified application areas of blockchain technology in the electricity sector will be discussed, together with existing real-world projects [13,16]. Finally, the keyword extraction process used will be described and discussed.

### *3.1. Blockchain Technology in the Energy Sector*

A blockchain is a distributed ledger that comprises a collection of successive blocks that record data in the form of transactions and whose growth and validity are governed by a consensus mechanism. It is one of the emerging technologies of the last decade that has found numerous applications in different areas of different domains [18]. The benefits offered by this technology have also been exploited for various functions within the energy sector.

As illustrated in Figure 1, blockchain technology is part of the information flow associated with energy flow, including consumption and production. For this reason, the benefits that this technology can bring to the energy field are spread across all of the application areas.

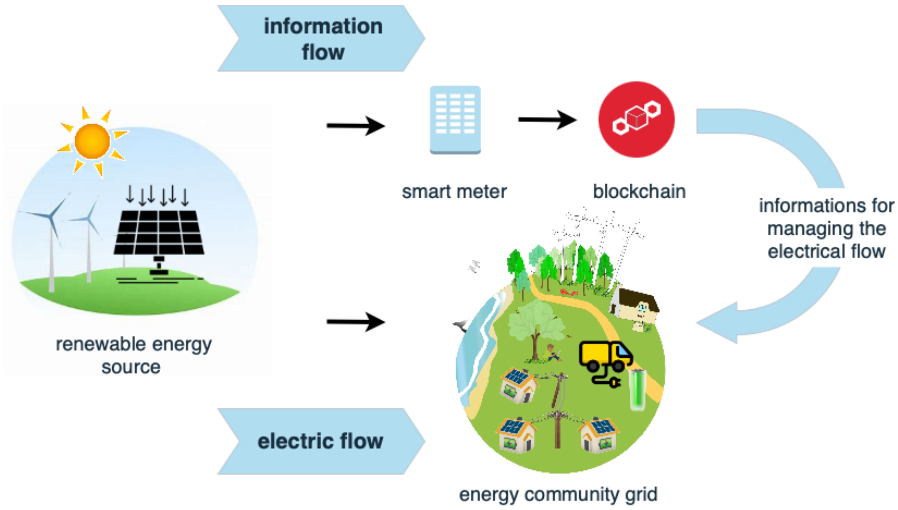


**Figure 1.** Representation of information flow and energy flow in a blockchain-based renewable energy management system. In order to have optimal energy flow management, the information contained in the blockchain is needed.

Blockchains can support the execution of programs called smart contracts. These allow for the implementation of automatism that is activated when certain conditions occur, and the creation of decentralized applications [19].

The various types of existing blockchain implementations enable the fulfillment of specific application requirements [20]. The characteristics of the application or service to be developed influence the design options.

As detailed in [13], blockchains can be:

- Public or private, depending on the selection of participants. In order to completely preserve privacy and confidentiality, application-specific blockchains can be configured as private.
- Permissioned or permissionless, depending on how the blockchain is restricted to participate in creating new blocks or creating new transactions. In order to implement an access policy, an application-specific blockchain can be configured to be permissioned.

Another differentiating element is the consensus mechanism, which is an essential part of blockchain technology for appending recently released blocks to the blockchain. Some examples, among the most widely used, are proof of work (PoW), proof of stake (PoS), and proof of authority (PoA). In [17], a specific protocol, called proof of energy, is presented.

There are further elements that make blockchains different. For example, the level of decentralization, scalability properties, trustlessness and security, immutability, transparency and auditability, and resiliency.

As discussed in [13], in the case of the energy sector, the blockchain will need to have high throughput, especially if it is a large-scale platform; a consensus mechanism that consumes little energy to confirm a transaction; a high level of security against possible attacks; transparency; security; and privacy of user data. Research is currently focusing on interoperability between multiple blockchain platforms in order to communicate with other production systems or other energy communities.

### *3.2. Decentralized Energy Market*

The energy market system is currently plagued by a number of issues, including cost and security issues brought on by centralized administration [21].

Therefore, we are transitioning from a highly centralized to a more decentralized energy system that depends on more dispersed generation, energy storage, and a more engaged customer base through demand response [22]. In this direction, blockchain and DLT solutions can be valuable allies.

The decentralized and distributed nature of blockchain technology, which has transformed the financial sector, can also lead to major changes in the energy market [23].

According to the definition in [14], an energy market is considered decentralized if there are no structured physical exchanges before the real-time market or if there is a self-committed day-ahead market. In this scenario, producers can sell their energy directly to the highest bidder without the need for a centralized entity to manage the buying and selling. Decentralized marketplaces often rely on market design that rewards efficient behavior and encourages competition. The presence of a central system operator in decentralized markets is not entirely ruled out, but with the sole authority to control the electricity system in real time and schedule the transmission grid. Through these models, an attempt is made to reduce the monopolistic effect of the operator on electricity markets.

Decentralized solutions such as blockchain and DLTs can help address reducing the operational costs of energy markets, protecting privacy, and strengthening cybersecurity in decentralized markets [24].

As highlighted in [9], the development of blockchain technology offers solutions to these challenges. The underlying properties of blockchain, such as anonymity, decentralization, and transparency, also contribute to its appeal.

There are already several initiatives to build blockchain-based peer-to-peer energy trading, but they are not yet completely operational. Applications of blockchain in the energy market are related to management, P2P trading, EVs, and carbon emissions trading. Among the main blockchain platform implementations for the energy market, that facilitate energy trading and P2P exchanges, we can cite EXERGY [25], Energy Web Chain [26], Powerledger [27], WePower [28], and SunContract [29]. The last platform quoted is implemented in Slovenia and is the smallest energy marketplace among those cited. An interesting result reported in a work by Khezami et al. [15] concerns the blockchain platform used in the energy sector. Nearly 90% of the projects analyzed in the work just quoted use Ethereum, and 7% use Powerledger.

Several blockchain-based initiatives have been introduced to address challenges in the smart grid energy trading system and promote green energy adoption. PriWatt [30] offers a token-based decentralized system with blockchain-assisted smart contracts, multisignatures, and anonymous encrypted messaging streams to ensure secure and private transactions in energy trading. Electronic Energy Coin (E2C) [31] utilizes Ethereum's ERC-20 token standard, providing a more secure and efficient marketplace for purchasing and selling green energy while enabling users to forecast energy supply and demand. LAMP-Project [32] implements a private blockchain protocol in Landau, Germany, creating a decentralized energy system through local energy markets (LEM) for residential households. Meanwhile, in [33], a blockchain-based crowdsourced energy system (CES) framework facilitates peer-to-peer energy sharing at the distribution level using smart meters and distributed blockchain implementations, addressing real-time demand shortages and motivating participation in microgrid ecosystems. The specific characteristics of each project, such as major contribution, technical approach and focus, are summarized in Table 1.

As reported in Table 1, these blockchain-based energy projects share several common features and similarities. They all aim to enhance energy trading through secure and transparent transactions while promoting peer-to-peer energy sharing and forecasting capabilities. By using blockchain technology, they contribute to energy savings, low energy pricing, and increased access to energy for all, ensuring a more inclusive economy. Moreover, these initiatives align with the goals of creating smart and sustainable cities, fostering sustainable industries, mitigating the impact of climate change, and promoting environmentally responsible practices. By revolutionizing energy systems, they offer promising solutions for addressing global energy challenges and advancing sustainable development objectives.

**Table 1.** Summary of blockchain-based solutions for decentralized energy markets.

| Work | Major Contribution | Technical Approach | Focus |
| --- | --- | --- | --- |
| [30] | An energy pricing negotiation proof-of-concept using blockchain to provide safe energy transactions and privacy-preserving methods | Multi-signature, anonymous messaging streams, PoW, ECDSA | Decentralized energy trading and pricing |
| [31] | An Ethereum implementation project, smart contract-based marketplace for purchasing and selling green energy | Smart contract, ERC-20 | Purchasing and selling green energy market |
| [32] | Decentralized energy systems through local energy markets | Private blockchain | Market prices and self-consumption |
| [33] | An energy trading and crowdsourcing energy system operating concept supported by blockchain | Smart contract, RBFT, permission blockchain | CES, P2P energy trading and energy market |

### *3.3. Microgrid Development and Management*

Smart grids are interconnected power networks with cutting-edge control and communication technologies that support renewable energy sources. The concept of "smart grids" encourages two-way energy and information transfer in order to manage and integrate sustainable and renewable energy sources and distribute energy efficiently. In a nutshell, smart grids offer an improved mechanism for managing energy [34]. A microgrid is a localized energy network made up of connected prosumer and consumer energy units. Local energy production, storage, and distribution improve community sustainability, resiliency, and effectiveness, promoting the decentralization of the energy system. Such electrical networks can function either in an island (independent) mode or as an extension of the primary power network [35]. Growing energy needs and the acceleration of global warming necessitate better grid management and the integration of renewable energy sources. Growing worries about cyberattacks on the grid force us to take security precautions into account in the design of the microgrid system. Blockchains have proven to be a successful method for facilitating safe transactions. In work [36], the authors go through use cases for blockchain in the energy industry and suggest using two blockchain frameworks: the Energy Web Chain for operational techniques and CordaR3-based Distributed Ledger Technology for grid-wide energy trading and other financial operations. The US and other nations with widespread use of distributed generation (DG), microgrids, and neighbor-to-neighbor energy trading likely have the best infrastructure and regulatory environment for this kind of technology. In fact, one of the most recent initiatives, the microgrid on President Street (New York City), manages energy transactions using blockchain technology [37]. Another interesting project for using blockchain in microgrids is NGRcoins [38], where a virtual energy market in smart grids with its own coin has been established.

### *3.4. Development of Renewable Energy Communities*

Renewable energy (RE) is derived from constantly replenishing but flow-limited sources like sunlight, geothermal heat, wind, water, and biomass. It must come from renewable natural resources and produce minimal greenhouse gas emissions [39]. Energy communities involve local power exchange among consumers, managing power nodes through peer-to-peer exchange, communal storage, and peer-to-grid concepts [40]. Renewable energy communities (REC) engage citizens and stakeholders in purchasing, generating, selling, and distributing renewable energy through photovoltaic systems connected to microgrids. These models promote a decentralized electrical network where customers are also energy producers (prosumers), assuming responsibility for grid management.

Blockchain technology could be used to optimize and trade extra energy generated by microgrids [35]. In [41], the authors propose to create an energy open data ledger using blockchain that stores and tracks information about the energy use of public structures and public energy communities. Using blockchain-enabled smart meters, the built platform enables the recording of energy output and consumption in public buildings. Once verified on the blockchain, these data may be made publicly available for technical and economic evaluations for research projects and internal or external audits. The revealed data stored in the platform can also be useful for the calculation, validation, and exchange of sustainability indicators for public buildings and facilities, enabling the tracking of their advancements in sustainability objectives.

Further implementations, such as an energy virtual coin called Helios Coins (HEC), are reported in the JRC Technical Report entitled "Blockchain in Energy Communities" [42], where the authors present different models of energy blockchain depending on the structure of the energy community and subsequent tests conducted by the European Commission's own laboratories.

### *3.5. Data Management and Energy Flow Forecast*

Associating IoT devices with blockchain allows for the improvement of energy efficiency based on the data they provide [16]. One of the most important components of a smart grid are smart meters, electronic devices that record real-time consumption and production of electricity, whether in a household or in an industry, and send the data to the electricity retailer for monitoring and billing [43]. Smart meters thus play a key role in the smart grid, as they can provide useful information on consumption and consumer profiles, which can lead to load forecasting and peak load reduction. In addition, the energy supplier can use this information for possible consumption control through load shifting. On the other hand, smart meters can be a useful tool for interaction between the energy supplier and the end user, through which consumers can be actively involved in reducing their consumption [44].

The unpredictable and irregularity that renewable energy sources (RESs) contribute to power networks may cause unexpected peaks in energy output that may not match energy demand [17]. Flexibility in grid management, and how it is required by all actors in an energy community in order to optimally manage energy in the grid, are other important topics touched upon in this article. Data from smart meters can also be of great use for this purpose; in fact, if data from smart meters are available on the blockchain, aggregators and TSOs can also access them in order to make the energy grid as flexible as possible based on production and demand data [40].

Two interesting examples of a government's implementation of a blockchain platform for managing sensitive citizen data are given in [45]. The former is in the United Arab Emirates, where they created a regulatory sandbox for technology companies to test blockchain solutions for FinTech and for streamlining data interoperability across government services [46]. The latter is in the United States. It is the Boldline Accelerator program, which is similar in its support of public–private collaboration and faces the issue of how to use blockchain for identity management, tracking human trafficking, visas, and shipping fraud [47].

### *3.6. EV and Green Mobility*

The European Green Deal's aims to achieve climate neutrality also have an impact on the mobility sector; by 2050, transportation emissions must be reduced by 90%. Providing people with more cheap, accessible, healthier, and cleaner mobility options is essential to achieving sustainable transportation [2].

Hybrid electric vehicles (HEVs) and electrical vehicles (EVs) reduce transportation's dependency on fossil fuels and lower greenhouse gas emissions. The advantages from an economic and environmental standpoint are significantly changing the current transportation industry. As explained in [48], the smart grid (SG) faces a number of obstacles as a result of transportation electrification (TE), including issues with power quality, dependability, and control.

In the context of electric vehicles and green mobility, blockchain technology is being leveraged to enhance transaction security and develop innovative charging coordination systems. For instance, in [49], a peer-to-peer (P2P) energy trading model among plug-in hybrid EVs demonstrates the potential of blockchain to improve transaction security. In [50], a permissioned blockchain with smart contracts is proposed to create a safe framework for EV charging, connected to renewable energy sources and smart grids in smart communities. Similarly, in [51], blockchain assists in a charging coordination system for transparent and decentralized charging requests from utility providers to energy storage units. Moreover, in [52], a security architecture for managing EV charging employs blockchain and the Lightning Network to increase security and decentralization. The transparent and privacy-preserving strategy presented in [53] allows EVs to locate affordable charging stations based on energy costs and travel times, leveraging blockchain for transparent bid requests. Additionally, Charg Coin [54] utilizes blockchain to expedite the delivery of distributed renewable energy and enable instant energy exchange among individuals while facilitating crowdsourced EV charging stations for enhanced accessibility and efficiency.

### *3.7. Tracking Sustainable Production and Consumption*

Energy production and consumption have an influence on the environment, so it is important to find innovative technologies that rely more on renewable energy sources and less on fossil fuels. Rethinking the architecture of energy management is necessitated by the dispersed nature of those physical assets. Energy sources and energy storage systems (ESS) are categorized as "Assets" in these new designs, which can be either consumer or prosumer goods. Green certifications may be issued using the blockchain and DLTs' helpful qualities of security, transparency, and traceability of transactions [55].

Energy attribution certificates (EACs) demonstrate that a given unit of energy is generated from clean energy sources, and serve as a market tool to incentivize the introduction of clean energy. The owner of an EAC can demonstrate achievement of a regulatory mandate (e.g., an electricity supplier with a target share of renewable energy) or a voluntary commitment (e.g., RE100 companies with a renewable energy target).

As pointed out in the thematic report prepared by the European Union Blockchain Observatory & Forum [56], blockchain offers significant advantages for the challenges faced by industry in order to use EACs, which is why several initiatives have been launched at different stages of development to implement blockchain to improve EAC markets. The benefits of using blockchain to improve EAC marketplaces are:

- Accurate and verifiable traceability of each energy unit throughout its life cycle due to the decentralized nature and capabilities of cryptography;
- Real-time issuance and transfer of EAC as generators produce electricity, instead of the current monthly issuance;
- Automation of EAC trading due to smart contracts and less reliance on a centralized entity to verify transactions;
- Efficient cost management of the growing number of small generators and consumers as blockchain makes any transaction financially viable;
- The creation of new market opportunities based on digital data capture and reduced EAC issuance costs.

Table 2 presents the most interesting examples of blockchain applications for EAC.

These blockchain applications, EcoGox, Gaia-X, TEO, and RESpring, share common features in their utilization of blockchain technology to enhance the Energy Attribute Certificate (EAC) scheme. They enable secure registration, issuance, transfer, and redemption of EACs, ensuring transparency and efficiency in energy transactions. By using blockchain, they contribute to energy savings, low energy pricing, and increased access to energy for all, supporting inclusive economic growth. Additionally, these initiatives promote smart and sustainable cities by fostering an end-to-end energy system encompassing all products, advancing sustainable industries and promoting environmentally responsible practices. Furthermore, the use of blockchain helps mitigate climate change by verifying carbon dioxide-free power production and ensuring continuous monitoring of renewable energy generation. Through these shared features, these blockchain applications have far-reaching implications for advancing sustainable development goals, including energy accessibility, affordability, and environmental sustainability.

**Table 2.** Summary of blockchain-based solutions for tracking sustainable production and consumption.

| Work | Major Contribution | Technical Approach |
|---|---|---|
| EcoGox by XM [57] | It enables device registration, monthly issuance, transfer and redemption of EACs in line with XM's certification standard | Multichain-based private or permissioned network |
| Gaia-X [58] | A Europe-wide initiative supported by several organizations that aims to develop a holistic blockchain-based EAC scheme to enable an end-to-end energy system that encompasses all products | EVM–compatible blockchain, PoA, ERC721 smart contract, pointers to a webspace, decentralised off-chain storage, ERC20 |
| TEO by ENGIE [59] | It transforms energy data into digital EAC assets by leveraging blockchain. In addition to electricity, TEO is involved in tracking and certifying other products, such as green gases | Energy Web Chain, Ledger Origin |
| RESpring by Flexidao [60] | It enables users to verify the production of power without the emission of carbon dioxide (CO2) using non-fungible tokens (NFTs). The hourly Energy Attribute Certificates (EACs) are represented as an immutable attribute by the energy NFTs that were issued. To make sure that power is generated from renewable resources, these characteristics may be monitored around-the-clock | Energy Web Chain, Token ERC-1888, NFT |

### *3.8. Summary and Keywords Analysis*

To summarize and clarify all the analysis just described in the following, we list all the previously mentioned literature contributions for each of the six application areas analyzed:

1. Decentralized energy market [14,23];
2. Microgrid development and management [61,62];
3. Development of Renewable Energy Communities [35,41];
4. Data management and energy flow forecast [43,44];
5. Electric vehicles and green mobility [48];
6. Tracking sustainable production and consumption [55,56].

To analyze the effects of blockchain technology on each of the six application areas, a keyword-based approach was adopted. For each application, all article keywords present in the papers reviewed above were extracted. To reduce the number of keywords, these were handily grouped by the authors under one main keyword. Following that, a subset of key words was associated with each of the six identified application areas, succinctly highlighting the impact of blockchain technology in each of them.

The eleven identified main keywords are listed below. Each main keyword group contains a list of keywords extracted directly from the analyzed papers.

- P2P Energy Trading: Wholesale electricity markets, energy buying and selling, energy trading, and decentralized market;
- Economic and Financial growth: Economic and financial network, double auction, economic growth and productivity, economy and GDP;
- Access to energy and energy availability: Access to electricity by all citizens, energy sharing, and energy availability in all areas and at all times;

- Social and local growth: Growth of society, local economy, local energy market, savings, entrepreneurship, employment, and industry;
- Individual Inclusion and engagement: Inclusive economy, inclusion of each individual citizen, direct and democratic participation, privacy protection, public transportation, and unit-commitment;
- Sustainable management: Sustainable practices, sustainable and efficient management, sustainable development, energy efficiency, grid management, Peer-to-Peer energy management, and efficient use of energy;
- Energy flow: Distributed energy resources, energy services, demand response, local materials, energy analytics, energy production and consumption;
- Environmental safeguard: Climate change, environmental impact, pollution reduction, waste management, sustainable mobility, green and zero-emission vehicles, sustainable transportation, renewable production, CO2 emissions, and sustainable management;
- Control and optimization: Information sharing, smart meters, energy sector optimization, supply chain management, energy data, energy certifications, control and taxation;
- Smart cities and urban planning: Green and sustainable buildings, urban planning, city management, system integration, smart and green cities, distribution network, and green certificates;
- Energy Infrastructures and distribution: Energy infrastructure, energy storage, critical infrastructure security, and distribution systems.

Table 3 shows the list of the main keywords associated with each identified application area, hence associated with each of the six different categories in which blockchain applications have been divided.

**Table 3.** Keywords associated with each blockchain applications category in the energy sector.

| Application Category | Keywords |
|---|---|
| 1. Decentralized energy market | P2P Energy Trading, Economic and Financial growth, Access to energy and energy availability, Individual Inclusion and engagement, Sustainable management |
| 2. Microgrid development and management | Energy flow, Energy Infrastructures and distribution, Access to energy and energy availability, Social and local growth, Sustainable management, Control and optimization |
| 3. Development of Renewable Energy Communities | Social and local growth, Energy flow, Sustainable management, Environmental safeguard, Smart cities and urban planning, Individual Inclusion and engagement |
| 4. Data management and energy flow forecast | Control and optimization, Sustainable management, Energy Infrastructures and distribution, Social and local growth, Smart cities and urban planning |
| 5. EV and green mobility | Environmental safeguard, Energy Infrastructures and distribution, Smart cities and urban planning, Sustainable management, Individual Inclusion and engagement, Social and local growth |
| 6. Tracking sustainable production and consumption | Control and optimization, Environmental safeguard, Social and local growth, Economic and Financial growth, Smart cities and urban planning |

## 4. Achieving the SDGs through the Application of Blockchain in the Energy Sector

The Sustainable Development Goals (SDGs), established by the United Nations in 2015 [3], form a critical framework guiding global efforts toward sustainable energy production and consumption.

This section examines the 17 SDGs in order to identify those that could benefit from the use of blockchain in the energy sector.

Following the methodology adopted in Section 3, and starting from an analysis of the documentation provided by the United Nations [3], for each SDG, a set of keywords was extracted. In particular, the analysis included a target and indicator that characterize each SDG and that serve as measurable benchmarks to track progress toward achieving the broader goal. With the keyword-based approach, a subset of targets, specifically those most strongly related to the keywords of blockchain applications in the energy sector, was selected. For each target, the subset of indicators (specific and measurable benchmarks used to assess progress toward achieving the broader goals of each SDG) affected by the blockchain applications was selected.

### 4.1. Selected SDG

Based on the analysis of the documentation [3], 6 of the 17 SDGs were identified as being affected by the energy sector. In particular, goals 7, 8, 9, 11, 12, and 13 concern aspects closely linked to the energy sector, and their achievement could be facilitated by the adoption of the blockchain. In particular:

- SDG 7 strives for universal access to affordable, reliable, sustainable, and modern energy;
- SDG 8 promotes inclusive economic growth and decent work;
- SDG 9 focuses on resilient infrastructure and sustainable industrialization;
- SDG 11 aims to create inclusive, safe, resilient, and sustainable cities and human settlements;
- SDG 12 centers on ensuring sustainable consumption and production patterns;
- SDG 13 is dedicated to combating climate change and its impacts.

Based on the results reported in Section 3, it is possible to identify how blockchain applications in the energy sector contribute to the fulfillment of the selected SDGs. Decentralized energy markets, facilitated by blockchain technology, empower individuals and businesses in peer-to-peer energy trading, fostering cleaner energy choices and local economic growth (SDGs 7 and 8). The inclusion of all citizens in these markets enhances sustainable economic growth and promotes inclusivity in cities and human settlements (SDG 11). Additionally, blockchain-based traceability ensures certificates for sustainable production and consumption (SDG 12). Microgrid development and management through blockchain advances energy access in remote regions and establishes resilient infrastructure (SDGs 7 and 9). The verification and certification of renewable energy sources using blockchain align with SDGs 7 and 12, encouraging sustainable energy practices. Moreover, blockchain-based transparent data management aids sustainable industrialization and innovation (SDG 9), while its integration into electric vehicles and green mobility addresses SDG 11 by encouraging responsible energy practices and sustainable urban transportation. In this comprehensive context, blockchain applications significantly contribute to SDG 13's urgent call to combat climate change and its impacts.

Table 4 provides a summary of the analysis just illustrated. Note that each application category is identified with a number, following the classification made in Table 3.

In the following, more details about how blockchain applications in the energy sector can help achieve each single SDG and its targets and indicators are presented.

**Table 4.** Summary of the SDGs analyzed, their respective targets and indicators, and the applications that support their fulfillment.

| SDG | Targets | Indicators | Applications |
|---|---|---|---|
| 7 | 7.1 | 7.1.1 | 1, 2, 3 |
| | | 7.1.2 | 4, 6 |
| | 7.2 | 7.2.1 | 3, 6 |
| | 7.a | 7.a.1 | 1, 4, 6 |
| | 7.b | 7.b.1 | 2, 3, 5 |
| 8 | 8.1 | 8.1.1 | 1, 2, 6 |
| | 8.2 | 8.2.1 | 1, 6 |
| | 8.3 | 8.3.1 | 3, 6 |
| | 8.4 | 8.4.1 | 3, 5, 6 |
| | | 8.4.2 | 2, 3 |
| 9 | 9.1 | 9.1.1 | 5 |
| | 9.2 | 9.2.1 | 3 |
| | | 9.2.2 | 3 |
| | 9.4 | 9.4.1 | 3, 4, 5, 6 |
| 11 | 11.2 | 11.2.1 | 4, 5 |
| | 11.3 | 11.3.2 | 3, 4 |
| | 11.6 | 11.6.2 | 3, 5, 6 |
| | 11.c | | 3, 6 |
| 12 | 12.2 | 12.2.1 | 2, 3, 4, 5, 6 |
| | | 12.2.2 | 2, 3, 4, 5, 6 |
| | 12.6 | 12.6.1 | 1, 6 |
| | 12.8 | 12.8.1 | 2, 3 |
| | 12.a | 12.a.1 | 3, 6 |
| 13 | 13.b | 13.b.1 | 3 |

### *4.2. SDG 7: Ensure Access to Affordable, Reliable, Sustainable and Modern Energy for All*

Target 7.1 aims to ensure universal access to affordable, reliable, and modern energy services by 2030. Blockchain, in this sense, would help build a network accessible to all. Specifically, the applications that would meet indicator 7.1.1 (proportion of population with access to electricity) are 1, 2, 3, as they would provide access to RES and the development of RECs in isolated regions, fostering local management. In order to meet this, however, certain prerequisites are needed, such as access to the Internet, level of user expertise, and DSO organization. For indicator 7.1.2 (proportion of population with primary reliance on clean fuels and technology), the applications that would provide more certification and simplify the process are 4 and 6. Thus, the applications analyzed in a complementary way help meet target 7.1.

Target 7.2 is focused on substantially increasing the share of renewable energy in the global energy mix. Through applications 3 and 6, blockchain can support indicator 7.2.1 (the proportion of renewable energy in total final energy consumption), since it would make access to RES possible, create RECs, and certify production and consumption. This is because the use of renewable energy sources generates a direct consequence for the increase in renewable energy in the global energy mix. Similarly, it is true for energy communities, which, by encouraging collective self-consumption, encourage citizens to produce and use renewable energy within the community. Finally, tracking production and consumption allows us to certify the increase in renewable energy. Target 7.a aims to strengthen, by 2030, international cooperation to facilitate access to clean energy research and technologies, including renewable energy, energy efficiency, and advanced cleaner fossil fuel technologies, and promote investment in energy infrastructure and clean energy technologies. The main blockchain applications that would help this goal are 1, 4, and 6, as well as the others in a lesser form, as a decentralized energy market would help provide energy market access to all citizens, energy management and flow forecasting, and finally, energy tracking and certification. A decentralized energy market promotes international cooperation and investment in green energy, as with this form, all citizens can actively participate in the energy market. Data management and energy flow forecasting combined with energy tracking improve energy efficiency and promote investment in energy infrastructure and clean energy technologies, as production and consumption data obtained through smart meters will make it possible to optimize the grid, production, and consumption. Finally, for target 7.b, applications 2, 3, and 5 would help expand infrastructure and improve technology for the provision of modern and sustainable energy services for all in developing countries. The development and management of microgrids expands infrastructure and improves technology for energy service delivery. Check meaning retained. In fact, developing countries often have large urban centers and many smaller agglomerations far apart; the development of local microgrids would enable even small towns to have state-of-the-art infrastructure. Energy communities are among the services that would enable improved local energy service delivery. Finally, the use of electric vehicles would allow for connecting large centers with small villages in an easier and more accessible way by breaking down, in a sustainable and environmentally friendly way, travel barriers for those citizens who do not own a vehicle.

### *4.3. SDG 8: Promote Sustained, Inclusive and Sustainable Economic Growth, Full and Productive Employment and Decent Work for All*

Relative to this SDG, blockchain can make a contribution to targets 8.1, 8.2, 8.3, and 8.4 to promote sustained, inclusive, and sustainable economic growth. Target 8.1 and related indicator 8.1.1 have the goal of achieving GDP per capita growth. This can be fostered by applications 1, 2, and 6, as a decentralized market, the development of efficient microgrids, and production tracking can provide a source of income. Conversely, the development of ERCs could lower GDP, since they are not intended to make income but to lower citizens' expenses, thus indirectly providing welfare to society. Target 8.2, on the other hand, aims to achieve higher levels of economic productivity through diversification, technological upgrading, and innovation. Blockchain is a technological and innovative tool that, especially through the applications of decentralized markets and certified sales 1 and 6, could allow for an increase in the annual rate of real GDP per employed person and achieve indicator 8.2.1. Target 8.3 aims to create policies to support job creation. One policy that we believe is effective is to use technologies, and in particular blockchain, in order to build job opportunities. This can be performed through certified commerce, and thus, applications 6, but also through the development of energy communities with citizens at the center 3. As explained for target 8.1, ERCs do not directly increase GDP, but they foster local entrepreneurship because they lower costs by fostering economic growth. Finally, Target 8.4 aims to progressively improve global resource efficiency in consumption and production, and strives to decouple economic growth from environmental degradation. In this sense, the use of RES and the development of CERs 3 and the tracking of production and consumption 6, but also the use of green vehicles, help to reduce the material footprint, and thus fulfill indicator 8.4.1. Regarding 8.4.2, on the other hand, in order to reduce domestic material consumption, applications 2 and 3 can help. From the analysis performed, we can therefore conclude that all applications contribute in different ways to inclusive and sustainable economic growth.

### *4.4. SDG 9: Build Resilient Infrastructure, Promote Inclusive and Sustainable Industrialization and Foster Innovation*

The use of blockchain in the energy sector also provides benefits to infrastructure and industry, which are the focus of SDG 9. In particular, the targets that could be most affected by the blockchain applications are 9.1, 9.2, and 9.4.

Target 9.1 aims to develop quality, reliable, sustainable, and resilient infrastructure. The use of electric vehicles, and thus, the development of green mobility 5, would help lower the percentage of rural population distant from a road (indicator 9.1.1) and increase the volume of passengers and freight by mode of transport (indicator 9.1.2). Rural areas, most of the time, have resources such as sun, water, and wind that therefore enable easy access to renewable energy sources; therefore, a green mobility system can be easily implemented to enable suburban citizens to easily reach large urban centers. Internet access and adequate electrical infrastructure, even in isolated areas, are needed for its development.

Target 9.2 aims to promote inclusive and sustainable industrialization; this could be achieved indirectly through the creation of energy communities 3 and through certification of production. More and more industries are trying to implement green policies in order to increase their reputation and access funds, and blockchain can be used to certify their production, consumption, and emissions 6.

Applications 3 and 6 also help in the fulfillment of target 9.4, which aims to upgrade infrastructure and retrofit industries to make them sustainable with greater resource use efficiency and the increased adoption of clean and environmentally friendly industrial technologies and processes. Other applications that can help achieve this target are data management and energy flow forecasting 4 and the use of EVs, and the development of green mobility 5. Target 9.b supports domestic technology development, research, and innovation in developing countries. All the applications of blockchain presented in Section 3 help to achieve this target. For example, the creation of energy communities promotes the development of sustainable buildings. Similarly, the development of microgrids, data tracking, and data management enable improvements to existing buildings and support the development of domestic technologies and innovations in developing countries. While target 9.c, rather than being an achievable goal through blockchain, is more of a prerequisite for its application in the energy sector, Indeed, increasing access to information and communication technologies and striving to provide universal and affordable access to the Internet in less developed countries, as extensively emphasized above, is a necessity in order to utilize all the blockchain applications seen in Section 3.

### *4.5. SDG 11: Make Cities and Human Settlements Inclusive, Safe, Resilient and Sustainable*

In order to make cities and human settlements inclusive, safe, resilient, and sustainable (SDG 11), blockchain can provide a boost to achieve targets 11.2, 11.3, 11.6, and 11.c. Target 11.2 aims to provide access to safe, affordable, accessible, and sustainable transportation systems for all. In this case, the deployment of electric vehicles 5 combined with the development of microgrids 4 would enable this to be achieved. Target 11.3, and especially its indicator 11.3.2, aim to encourage the direct participation of civil society in urban planning and management in a regular and democratic manner. Blockchain applications for energy communities 3 and for data management and energy flow forecasting 4 promote the active inclusion of citizens in community planning and governance. Target 11.6 aims to reduce the environmental impact of cities, and in particular, indicator 11.6.2 focuses on reducing annual average levels of fine particulate matter in cities. Achieving these results is aided by the use of RES and the development of renewable energy communities 3, the use of EVs and green mobility 5, and the tracking of production and consumption 6. Finally, to support LDCs, including through technical and financial assistance, in the construction of sustainable and resilient buildings using local materials (target 11.c), the creation of RECs 3 can be used, whose objectives include making community buildings as sustainable as possible and, through the certification of material production 6, encouraging the use of local materials.

### *4.6. SDG 12: Ensure Sustainable Consumption and Production Patterns*

The applications of blockchain to the energy sector also help to ensure sustainable consumption and production patterns; specifically, targets 12.1, 12.2, 12.6, 12.8, and 12.a in particular receive the greatest effects.

Target 12.1 and its indicators are targets that aim to increase the number of countries that develop, adopt, or implement policy instruments to support the shift to sustainable consumption and production. Blockchain is not a governmental and political tool, such as a regulation or a law, but countries can encourage the use of this technology through specific policies, which, as pointed out many times, provide tools that certify sustainable production and consumption.

Target 12.2 aims to achieve the sustainable management and efficient use of natural resources. In order to reduce the material footprint (12.2.1) and domestic material consumption (12.2.2), the benefits provided by the application of blockchain can be used for microgrid development and management 2, for the development of renewable energy communities 3, for data management and energy flow forecast 4, for the use of EVs and green mobility 5, and finally, for the tracking of sustainable production and consumption 6.

Target 12.6 aims to encourage companies, especially large and transnational ones, to adopt sustainable practices and integrate sustainability information into their reporting cycles. This can be fostered by decentralized energy markets 1 and production and consumption tracking 6, which, as mentioned, allow companies to demonstrate the fulfillment of certain sustainability goals and improve their reputation.

The development and management of microgrids 2 and the creation of energy communities 3 help ensure that people everywhere have the information and awareness needed for sustainable development and lifestyles in harmony with nature (target 12.8).

Finally, again, the creation of energy communities 3 and the tracking and certification of production and consumption 6 help in meeting target 12.a. In particular, they support developing countries in strengthening their scientific and technological capacity to move toward more sustainable consumption and production patterns.

### *4.7. SDG 13: Take Urgent Action to Combat Climate Change and Its Impacts*

Regarding combating climate change, Target 13.b points to promoting mechanisms to increase capacity for effective climate change planning and management in LDCs. For this, blockchain provides a useful tool, and in particular, through the creation of energy communities 3, strategies to combat climate change could be managed locally. In fact, as pointed out earlier, developing countries possess many renewable sources, and through local decentralized management, these countries could exploit these sources more effectively than through centralized management.

## 5. Discussion

From a quick overview of Table 4, it is observed that all the applications of blockchain in the energy sector presented in Section 3 contribute to the achievement of one or more SDGs.

The results of this comparison are given in the following subsection, in which, based on the Sustainability Awareness Framework (SuSAF) [5], the consequences of the Karlskrona Manifesto for Sustainability Design [63], and the analysis of the SDGs in the SuSAF [64], the cross-cutting sustainability consequences of blockchain applications in the energy sector on the SDGs are identified in five dimensions: economic, social, individual, environmental, and technical, in order to capture the positive values or impacts of using blockchain technology for proper energy management.

### *5.1. General Analysis*

Analyzing the results presented in Table 4, we observe that the most influential applications are energy communities 3 and energy tracking 6, which are present for 17 and 14 indicators out of 24 analyzed, respectively. This is due to the fact that among the applications are, on the one hand, those closest to inclusion in daily life and, on the other hand, those that are less specific and offer broader benefits. Electric vehicles and green mobility 5 have an average impact, with eight indicators influenced. This is because it is a very interesting topic that has begun to be implemented in recent years and still has ample room for further study. Two of the less influential applications are those related to microgrids 2, data management, and energy flow forecasting 4, which are present for only seven indicators. However, this result is ephemeral because the development and management of microgrids go hand in hand with the development of energy communities, while data management always follows energy tracking. Therefore, although less present in the analysis, they have a strong link to those more present. The least influential application is the decentralized energy market 1. This is because buying and selling energy is only a small part of the whole process of energy production and management. Therefore, it influences only five specific indicators of the SDGs.

### *5.2. Sustainability Dimensions*

#### 5.2.1. Economic Dimension

Economic growth is positively affected by the implementation of new technologies. The development of blockchain platforms for the energy market helps users participate in an active way; in fact, each citizen can produce his or her own renewable energy, feed it into the grid, and sell it to the highest bidder. In this way, on the one hand, the production and use of energy produced from renewable sources are encouraged, and on the other hand, an inclusive and sustainable energy market is built [65]. This is an aid to innovation and the energy supply chain, and consequently, a boost for SDGs 8, 9, 11, and 12. Microgrid optimization, coupled with energy flow forecasting, allows data to be leveraged to manage times of energy surplus or need, thus helping citizens save energy and generating indirect economic growth [66]. An indirect effect also occurs through the creation of energy communities; in fact, at the economic level, RECs cannot generate profits but allow users to save money. This savings generates wealth and capital that can be invested in other sectors, thus promoting indirect GDP growth [67]. Reliable blockchain data on the availability, quantity, and quality of production, consumption, and emissions can motivate citizens and businesses to produce and use more energy from renewable sources. At the same time, it provides support to governors for taxation [45], helping governance and supporting SDGs 8, 9, 11, and 13. The use of smart contracts can help the producer model and monitor particular information such as energy ownership, accountability, and quality assurance in a certified and automated form without the need for a central operator [68]. The use of a blockchain system can also create new job opportunities related to the production, certification, sorting, and sale of energy.

#### 5.2.2. Social Dimension

A blockchain-based energy management system would enable producers and consumers to engage and motivate each other to adopt practices to use renewable energy while contributing to the preservation of natural resources. Most of the impacts highlighted by the application of blockchain are based on the direct participation of citizens and companies. Decentralized markets and energy communities provide energy to all citizens at the local level and encourage active participation in the energy process [69]. Through the use of certified data on the blockchain, a reward mechanism can be implemented to encourage the use of renewable energy. Users could be rewarded with tokens that can be used within the community based on the quality of renewable energy produced and consumed or whether they use electric vehicles [70]. Still, the collected data can also be used to monitor citizens' habits and could help municipalities decide on appropriate strategies. Companies that implement transparent green policies can also improve their social image and reputation, which would benefit their sales—the so-called "emotional sustainability" [71]. Last but not least, the use of electric vehicles and fostering green mobility with electric car sharing systems: in addition to providing great support for sustainability and the environment by reducing fossil fuel pollution, it also allows citizens without a means of transportation to be able to get around, thus reducing the problems of isolation in some areas of developing countries [72]. This inclusive organization that fosters participation and equity among citizens is a strong supporter of SDGs 8, 9, and 11.

#### 5.2.3. Individual Dimension

Decentralized energy management offers numerous advantages to the individual citizen: users can produce and consume their own energy, saving transportation costs;

they can sell any surplus energy, generating a profit; and most importantly, they can track, monitor, and certify their data on the blockchain, thus obtaining valuable support for not only paying taxes but also for improving their consumption and lifestyle [73]. This solution puts the citizen in the game, who feels personally involved and will be more stimulated to implement sustainable behaviors aimed at saving their money [74]. Sharing one's data in the blockchain with the DSO generates an indirect effect for citizens; in fact, the operator will be able to use it for efficient management of the infrastructure and smart grid, thus offering a better service to the community [75]. Blockchain also provides privacy and security to citizens for both data management and energy buying and selling. These advantages promote lifelong learning (SDGs 8, 12, and 13) and health (SDGs 9 and 12).

#### 5.2.4. Environmental Dimension

The motivation of citizens toward the use of renewable energy and the consequent reduction of fossil fuels are beneficial to the environment. Energy communities, from this perspective, are a valuable tool that includes citizens actively in the energy transition process [76]. Access to shared information on blockchain about energy and emissions can lead to reducing pollution, minimizing environmental impact, and, as a result, helping in the fulfillment of SDGs 8, 11, and 12. Blockchain enables the government or local authorities to monitor the sector by including actions to support citizens and companies that have green behaviors [45]. Energy tracking data can be automatically analyzed by smart contracts to counter the problem of grid overload and energy waste [77]. Developing and encouraging the use of electric vehicles have a positive reflection on the environment and climate change by promoting the use of renewable energy, local materials and resources (SDGs 8, 11, and 13), sustainable energy use (SDGs 7, 11, and 12), and finally, logistical and organizational support (SDG 11).

#### 5.2.5. Technical Dimension

The use of blockchain solutions in the energy sector increases security in process management and provides platforms that are extensible and adaptable to the needs of each community. At the technical level, different technologies are used, starting with the choice of blockchain, where more scalable platforms with high throughput are being developed [25–28]. Despite this, however, Ethereum still maintains a monopoly on energy-related projects [15]. Often, then, data management is realized through smart contracts that receive information from smart meters and then share it in the blockchain [68], while certification of production, possession, consumption, and emissions is realized through the issuance of tokens [58,60]. Energy market management can be realized with both public and private blockchains, and energy exchange is performed by exchanging tokens through smart contracts [31–33]. All technical solutions place user usability at the center by facilitating the fulfillment of SDGs 8 and 11.

### *5.3. Threats to Applicability*

Blockchains are a potential technology for a wide range of services and use cases in the energy industry, according to the blockchain applications and research activities covered in this paper. The substantial participation in DLT initiatives by well-known utilities and energy businesses, as well as the interest of investors, clearly demonstrates the potential worth of this new technology for the energy sector.

The main difficulties involve technical issues related to blockchain technology that still need to be perfected, such as security, scalability, transparency, complexity, uncertainty, and a lack of standards [11].

Barriers to technology adoption encompass both regulatory and legal aspects, with the potential for blockchain to align with existing goals. However, overcoming challenges requires regulatory amendments to accommodate consumer-to-consumer energy trading and flexible tariff structures, ensuring integration with current practices [10].

Finally, as far as developing countries are concerned, there are some other obstacles compared to developed countries that will have to be overcome in order to implement these solutions. First of all, in order to use blockchain applications, one of the prerequisites is a stable and efficient Internet connection. The infrastructure must be modern and reachable by all citizens [61], and the DSO must have an efficient organization that allows blockchain solutions to be included in its system [75].

With these gaps filled, developing countries will also be able to have these technologies and thus contribute to the fulfillment of the SDGs.

### *5.4. Challenges and Future Research Directions*

Blockchain technology is evolving and being implemented in the renewable energy sector; however, as previously stated, this sector of application faces several technical challenges, such as the need for decreasing transaction load and high speed of validation, to meet the requirements related to the structure and organization of the power grid and its management. Future research should focus on analytically quantifying obstacles and threats that hinder the diffusion of the set of applications areas discussed in this paper, as well as overcoming strategies.

A possible further analysis object consists of the international agreements post-SDG, such as the European Green Deal [78] of the European Union. That analysis could provide an additional and more detailed remark on the positive effects of blockchain implementation in the energy sector.

## 6. Conclusions

This paper investigates the main applications of blockchain technology in the renewable energy sector and their effects on achieving the Sustainable Development Goals (SDGs). To accomplish this and answer the two research questions, this study is divided into two phases, the first of which focuses on choosing blockchain applications in the energy sector and determining how they match with the Sustainable Development Goals, and the second of which examines the sustainability aspects and difficulties in applying blockchain technology. Results of the first phase highlight that the most popular applications are those related to production and consumption tracking and energy communities, which are undergoing strong development in the world, especially in developed countries. In particular, in response to RQ1, blockchain helps in the fulfillment of the SDGs 7, 8, 9, 11, 12, and 13 by securely certifying the production and consumption of renewable energy, developing inclusive and sustainable forms of community that indirectly improve the quality of life of citizens, infrastructure, buildings, and services.

The results of the second phase emphasize that blockchain applications do not only provide help for energy-related goals but also have positive implications in other fields such as the economy and markets, climate change, smart cities, mobility and infrastructure, and the social and economic integration of all citizens, which directly and/or indirectly lend support to meeting the SDGs. Hence, and in response to RQ2, blockchain applications in the energy sector foster sustainability in the five dimensions described in the SusAF. In particular, in the economic dimension, it helps to develop a free and inclusive energy market; in the social dimension, it helps to provide energy services to all citizens by putting them at the center of the system, and thus also fostering their individual growth. In the environmental dimension, it enables the tracking of renewable production and the development of energy communities that will lead to the diminishing use of fossil fuels and the emission of pollutants. Finally, in the technical dimension, it provides a valuable technological tool that helps in the efficient management of the energy production, buying and selling, and consumption systems.

Concerning the threats related to the applicability of blockchain to the energy sector, results show that the basic prerequisites are an efficient Internet connection, a modern energy infrastructure that reaches all citizens, and an organized DSO. Other challenges that will need to be improved to include blockchain more and more in the energy sector are related to scalability, interoperability, regulatory frameworks, transparency, and privacy.

In order to fully realize blockchain's potential for developing a sustainable energy landscape, this paper emphasizes the importance of fostering collaboration among policymakers, researchers, and stakeholders. It also implies that government policies can encourage communities to adopt blockchain technology for these advantages.

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