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Review

Blockchain Use Cases Against Climate Destruction

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Abstract: Based on the current measures, it is unlikely that the targets of the Paris Agreement on climate change will be achieved within the given time. Therefore, new solutions are needed to get climate change under control. Emerging technologies like blockchain allow for new ways to approach climate change. The blockchain serves not only as an enabling technology for cryptocurrencies but is also a stand-alone tool applicable for various purposes. This paper aims to shed light on the overlap between the areas of blockchain and climate change. Research in this area was examined for potential blockchain use cases to support climate action using a systematic literature review. The found applications can be grouped into the main categories of Emissions Trading and Green Certificates, Sustainable Energy, Sustainable Mobility, and Green Financing. Within these applications, blockchains are used as supporting technology. Especially transparency, traceability, and immutability are particularly beneficial in blockchain-based applications against climate change. As a downside of the technology, controversial aspects of the blockchain include the energy consumption of the technology.

***Keywords*:** blockchain application, climate change, use cases

1. Introduction

Lots of different examples over the globe show that there is climate change already ongoing and affecting millions of people. The criticality of the overall climate change situation gets to be understood in more and more detail, and responsible handling is on the agenda of all countries [1]. Recent studies show that the current ambitions are not sufficient to achieve the agreement's goals [2]. Therefore, even more substantial efforts and innovative approaches are needed. The authors of The United Nations Framework Convention on Climate Change [3] mentioned blockchain technology as one of them.

Blockchain technology is currently frequently promoted as the most disruptive technology since the internet was born, and the best-known applications are given by cryptocurrencies [4]. Based on the popularity, the research identified lots of different application fields for blockchain-based technology, according to its four main core principles: (1) decentralization, (2) transparency, (3) immutability, and (4) authentication [5]. With all these high expectations towards blockchain, whether the technology can meet them arises. Therefore, the given paper tries to find out if blockchain technology can assist the fight against climate change.

To tackle this promising field of research, the authors started with the following research questions to find out about the usability and the current usage of blockchain technology regarding climate change. The first research question (RQ1)

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deals with the support of the technology and asks: Can blockchain support actions against climate change? The second research question (RQ2) is intended to bring some light to blockchain use cases and therefore formulated as: What are currently deployed blockchain-based use cases against climate change?

After the short introduction in section 1, the theoretical background is given in section 2. The empirical study design is laid out in section 3, followed by the preliminary results in section 4, which are later discussed in section 5. Section 6 closes the research paper by showing the limitations and outlook of possible future work.

2. Theoretical background

Even though blockchain technology has already existed since 1991, its development curve has not flattened yet. The widespread application as the underlying technology for cryptocurrencies is only one way of using blockchain. The following sections will provide an overview of the concept of distributed networks and the components of blockchains. After that, various types and consensus algorithms will be elaborated.

2.1 *The blockchain*

In 2008, Satoshi Nakamoto [6], a pseudonym behind which the inventor or inventors of Bitcoin hide, published a paper describing a new electronic cash system called "Bitcoin". Briefly afterward, in 2009, the system was turned into reality for the first time to set up a worldwide peer-to-peer (P2P) network whose goal was to initiate a currency that does not need intermediaries as known in the traditional financial system [7]. Since decentralization makes intermediaries potentially dispensable, blockchain is expected to disrupt numerous industries by streamlining processes and enabling cost savings [8]. However, while blockchain technology comes with a variety of auspicious attributes and thus enables various new applications in diverse fields, e.g., [9-10], it has not yet reached mass adoption [11].

The term "Blockchain" technically describes a public distributed ledger, which is essentially a database mirrored across many nodes. The distributed network of identical databases allows seamlessly adding and removing nodes, maintaining the operability of the network even in case of a partial system failure. The information in a blockchain is accumulated and stored in blocks connected to an immutable chain. The network's task is to ensure the validity of these database entries using a consensus mechanism [12], leading to a high level of protection against manipulation [13].

According to Dorfleitner and Braun [14], five key features are associated with blockchain, making it a promising and versatile technology. One of them is transparency. All transactions and data stored on a blockchain are transparently stored for everyone with access to the chain. That makes the technology attractive for monitoring, reporting, and verification purposes. In addition to transparency, the information on the blockchain is immutable. That does not mean data cannot be changed after being stored in a blockchain, but changes require verification and always leave a trail that can be tracked.

Authentication and identity management are two more features that belong to blockchain's strengths. The users of a blockchain system are all provided with a unique identifier, making their interactions with the chain transparent and traceable. However, depending on how a blockchain is set up, this does not necessarily mean that identity is revealed. Usually, e.g., users are identified by their public keys only and can generate new private and public key pairs with the Bitcoin blockchain. Thus, except for cases where someone is willing to invest a lot of time and money, e.g., [15-16], cryptocurrencies show that blockchain is well suited to protect its users' privacy.

One of the most promising possibilities of blockchain technology is processing secure and trustworthy transactions. Through its design, transactions on a blockchain do not require the transacting parties to trust each other.

2.2 *Transactions in centralized, decentralized, and distributed systems*

To understand why blockchain is considered a disruptive technology, it is crucial to be aware of the difference between centralized, decentralized, and distributed transactional systems. Different kinds of transactions play a vital part in today's world within many institutions. Some of the transactions are so-called direct transactions where information is sent from A natural to B without intermediary institutions. However, most transactions are being processed supported by intermediaries [17]. A well-known example for an intermediary is a bank, whose task in transferring money is to ensure the money is taken from the correct account and securely transmitted to the target one. However, banks are not necessarily the only institution involved in the process. Other parties like credit card companies or payment providers can also be in charge of sub-tasks [18].

Particularly invaluable transactions, the trustworthiness of third parties, and the security of the process are crucial. In other situations, attributes like transaction velocity, low cost, or process transparency can be demanded by the sender or receiver [19]. The chain of parties that the transaction is routed through makes it difficult to fulfill these requirements. All processing parties have their closed systems to process and manage the transaction. They keep records in their data storage, making sufficient data protection a matter of trust [20]. Viewing transactional processes from an abstract perspective, they often represent centralized or decentralized systems, depending on whether the transaction is routed through one or more nodes [21]. Centralized systems, in particular, turn out to be highly vulnerable due to their star-network nature. Therefore, decentralized setups, consisting of a mesh of star networks, are often used in practice. Although these systems are more secure, as they do not rely on a single node, an attack on just a few central nodes can still massively impact the system's operativeness [21].

The drawbacks of decentralized and centralized systems show demand for an alternative. Thanks to technological advances over the past decade, distributed systems are becoming a viable alternative to fill that gap [8]. Contrary to public perception, blockchains are not limited to enabling cryptocurrencies but can be applied to set up smart contracts, data-sharing, peer-to-peer trading, and more use cases, which will be addressed in section 4 [5].

2.3 *Blockchain components*

To set up a blockchain, certain digital and physical elements are required. These elements can differ depending on the type of blockchain and its characteristics. The leading blockchain elements, namely digital signatures, blocks, hashing, nodes, and mining, and the consensus algorithms, are explained in the following paragraphs.

A *digital signature* is a tool to verify ownership, validity, or integrity. Digital signatures usually utilize techniques from asymmetric encryption. The key generation algorithm makes it practically impossible to recreate the private key from the public key in asymmetric encryption. With digital signature schemes, the data receiver can verify the signature calculated over the data with the public key belonging to the sender. That makes sure that the sender indeed signed the data package [22]. In the case of blockchain, digital signatures are used to verify transactions. Popular algorithms include the Digital Signature Algorithm (DSA), the Rivest-Shamir-Adleman (RSA) algorithm, and the Elliptic Curve Digital Signature Algorithm (ECDSA), which for example, is used in Bitcoin and Ethereum [23].

Hashing describes a process in which a mathematical function, called a hash function, turns an input of variable length into a fixed-length output, the so-called "hash value". It is worth noting that the output remains the same, as long as the input does not change, but minor changes to the input usually lead to vast changes in the output. Furthermore, as used in most blockchains, cryptographic hash functions ensure that given only the output of a hash function, calculating the corresponding input is only possible by investing massive computing power [24].

As the name indicates, the blockchain is a chain of blocks. In general, every *block* consists of a blockhead and a block body [25]. The blockhead contains general information about the block. It includes the block version, which determines how nodes can validate the block, the hash value calculated from the blockhead of the previous block, and, thus, chains the blocks together [26]. The block body contains all the transactions carried out once the block is added to the chain. Every transaction includes the public keys of both sender and receiver, the digital signature, and the transaction output and transferred data, which in the case of cryptocurrencies is the amount [27].

Nodes represent the actual network that makes up a blockchain. Various types of nodes take over distinct responsibilities and need to be differentiated. When talking about nodes, often "full nodes" are meant. Full nodes maintain the blockchain network by thoroughly verifying transactions and blocks, hindering transactions from being executed twice or stopping invalid ones. A proportion of full nodes acts as a miner. They differ in that they require special hardware and can add new blocks to the chain [25].

The *mining* itself is done by the miners, who compete to solve the cryptographic problem to decide who is allowed to add the upcoming block to the blockchain [25-26]. Once a miner successfully added a new block to the chain, there are two options for reward payout. First, the miner will receive a fee paid by the parties that initiated the transaction. Secondly, the system will create new coins and award the miners with them.

One of the distinguishing elements of blockchain technology is the consensus algorithm. It is required to ensure that the whole network agrees upon a single version of the truth of the transacted data. Thanks to consensus algorithms, no central authority is needed in this process. Thus, blockchains are seen as systems of distributed control and power [28]. Every system with weakly authenticated identities, i.e., no central identity validation, is prone to adversaries creating many participants, a so-called Sybil attack [29].

Reaching consensus in such a system with relatively few nodes is considered achievable and straightforward using a proof of authority (PoA) algorithm. However, it is much more challenging in a distributed system, as a public blockchain. Therefore, according to Bashir [26], consensus algorithms in blockchains need to meet these five requirements: (1) Agreement: All honest nodes decide on the same value, (2) Termination: All honest nodes terminate execution of the consensus process and eventually reach a decision, (3) Validity: The value agreed upon by all honest nodes must be the same as the initial value proposed by at least one honest node, (4) Fault-tolerant: The consensus algorithm should be able to run in the presence of faulty or malicious nodes and (5) Integrity: This is a requirement that no node can make the decision more than once in a single consensus cycle. The best-known algorithms achieving consensus in distributed systems with weak identities are the Proof of Work (PoW) and Proof of Stake (PoS) algorithms [26], which are widely spread used for different use cases.

Summarizing the above, a typical blockchain consists of blocks containing digitally signed transactions and hash values distributed to all nodes within a network. New blocks can be added to the blockchain by miners, and all nodes adhere to a consensus algorithm for maintaining a common state of the blockchain.

2.4 *Climate change*

Climate change needs to be differentiated between weather and climate when it comes to climate change. The former means the weather conditions in a short-term period, usually days, hours, or minutes, and climate usually means the average weather condition or temperature over several years [30].

The term “climate” comes from the Greek word “Klima”, which means “inclination” in English. It refers to the different angels in which solar radiation strikes the earth’s surface. The irradiation angle is steep near the equator, resulting in high absorption of solar energy, while at the poles, it is the opposite. Changes in the amount of solar radiation reaching the earth’s surface significantly impact the functioning of the ecosystem and the interactions of its subsystems, including humans and animals [31].

There is no explicit agreement among experts in the field on how to describe the phenomena of climate change. Two of the best-known definitions come from the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC), both organizations supported by nearly every country in the world. For this paper, the definition of the UNFCCC will be used.

According to Hoegh-Guldberg et al. [32], the climate between 2006 and 2015 was about 0.87 °C higher than between 1850 and 1900. Newer studies confirm this trend. From 2011 to 2020 was the warmest decade ever recorded, with the 2019 global average temperature of 1.1 °C above preindustrial levels. According to IPCC estimates, this will result in human-induced global warming, increasing the global average temperature by 0.2 °C every ten years [33]. By the end of the 21st century, the IPCC projects a likely temperature increase of between 2.6 °C and 4.8 °C if no action is taken to reduce greenhouse gases and the world continues to rely heavily on the use of fossil fuels.

The damage to property, infrastructure, and health caused by global warming causes immense costs for society and the economy. Climate change is expected to impact global economic growth [34-35] negatively. Particularly developing countries suffer from the consequences, as they are most affected and have the few resources necessary to cope [36]. The Paris Agreement once more reinforces what was already stated in the Kyoto Protocol: carbon markets or emissions trading systems are an essential tool to fight climate change [37].

The given short introduction to the current challenge of global climate change, together with the basic knowledge given in this section about blockchain technology, lays out the needed understanding of the topics and their combination. The methodology used to answer the research questions mentioned in section 1 will be explained next.

3. Methodology

To answer the paper’s research questions (RQ1 and RQ2), a systematic literature review (SLR) was conducted.

Literature reviews have been proven helpful for academics and practitioners, as they help find, summarize and evaluate multiple papers about one domain [38]. According to Pare et al. [39], literature reviews are essential to gain an overview of a particular topic, find trends and clusters in a specific field, summarize empirical evidence concerning a particular research question, develop frameworks and theories, and find areas of future research. Reduced bias and the structured approach yielding reliable and relevant results were the main reasons the authors chose the method of a systematic literature review. In conducting the review, the steps by Fettke [40] were followed.

3.1 *Data sources*

The literature search has been limited to specific digital meta catalogs or scientific search engines and was carried out between December 2020 and March 2021.

In Table 1, all of these sources are listed. Initially, digital libraries from the fields of digital technologies or information technology (IT), geography, and general libraries were to be searched for relevant articles.

Table 1. Data sources of the literature search

Data Sources	URL
ScienceDirect	https://www.sciencedirect.com/
SpringerLink	https://link.springer.com/
MDPI	https://www.mdpi.com/
IEEE Xplore Digital Library	https://ieeexplore.ieee.org/Xplore/home.jsp
Google Scholar	https://scholar.google.com/

After an initial test, it became apparent that there were hardly any articles on blockchain in geography-specific publications.

3.2 *Search strategy*

Table 2. Keywords of the literature search

Blockchain-Related	Climate Change-Related	General
Blockchain	Climate change	Use case
Distributed ledger	Global warming	Case study
Ethereum	Sustainability	Approach
Bitcoin	Carbon	Framework
Hyperledger	Emission	Architecture
P2P	CO_2	Model
Peer to peer	Renewable	Fintech
Distributed network	Energy	Practices
Smart contract	Footprint	Project Application Initiative

For the literature search, the "Advanced Search" functions of the online libraries have been used to narrow down the search results and make them more precise. The search terms used are listed in Table 2. Once relevant papers had been found, the literature cited in these articles (go backward) was also reviewed. Similarly, information about where an article has been cited (go forward) will be considered [41].

3.3 *Literature selection and analysis*

Searching the digital libraries produced several hundreds of results per database. An iterative selection process was applied to determine which literature should be analyzed in detail. Through the method of going back and forward, as suggested by Webster and Watson [41], a few more relevant pieces of literature were added. First, abstracts have been screened if they are relevant to tackle the research questions. All relevant papers are then read thoroughly, and a decision of relevant or not was made. That led to a total number of 61 papers that were selected for the in-depth review.

For data analysis, the methodology has been followed according to the steps and information provided by Fettke [40]. When it comes to data extraction, the approach was not flexible enough for the explorative nature of this review. The qualitative content analysis proposed by Mayring [42] was considered for use. However, it is also less suitable for explorative research and was rejected. The one used was inspired by a sample form for small-scale systematic literature reviews by Levett [43]. The data was extracted from the literature using a data extraction form.

4. Results

When looking at the identified use cases from all different literature sources, it became clear that although they differ significantly in their specifics, they can be grouped into four supercategories, as shown in Table 3. The first and largest category is Emissions Trading and Green Certificates, wherein this paper will dig into more details and use case examples. It includes all applications related to Emissions Trading Systems (ETS), private carbon offset programs, and tokenization of CO_2 or energy. The main topics in the Sustainable Energy category are P2P energy trading and grid management. New mobility concepts and ideas for expanding charging infrastructure for electric cars through blockchain are grouped in the Sustainable Mobility category. Finally, the Green Finance section describes use cases and frameworks that enable sustainable investments.

Table 3. Overview over selected literature by category

Category	Literature	Count
Emissions Trading and Green Certificates	Dorfleitner and Braun [14]; Kouhizadeh and Sarkis [44]; Burke [45]; Zhao and Chan [46]; Verschuuren [47]; Hartmann and Thomas [48]; IBM [49]; Morris [50]; Lopez and Farooq [51]; Eckert et al. [52]; Li et al. [53]; Sadawi et al. [54]; Climate Change Authority [55]; Karakashev et al. [56]; Fleuret and Lyons [57]; Poseidon [58]; Szewczyk [59]; Clean Energy Regulator [60]; Pichler et al. [61]; Pan et al. [62]; Howson et al. [63]; Dong et al. [64]; Fu et al. [65]; Chacra et al. [66]	23
Sustainable Energy	Islam et al. [67]; Trbovich et al. [68]; Gomes et al. [69]; Mengelkamp et al. [70]; Brooklyn Microgrid [71]; Nehai and Guerard [72]; Orsini et al. [73]; Kounelis et al. [74]; Kounelis et al. [75]; Burger et al. [76]; Mihaylov et al. [77]; Mihaylov et al. [78]; Mylrea and Gourisetti [79]; Pilkington [80]; Telma and Ribeiro [81]; Johanning and Bruckner [82]; Pipattanasomporn et al. [83]; Li et al. [84]; Pop et al. [85]; Liu et al. [86]; Lilliu et al. [87]; Mouhaffel and Ṕerez [88]	22
Sustainable Mobility	Nguyen et al. [89]; Fridgen et al. [90]; Sümmermann et al. [91]; Khanji and Assaf [92]; Zhao et al. [93]; Vanrykel et al. [94]; Chanthong et al. [95]	7
Green Financing	Yoshino et al. [96]; Chen and Volz [97]; Malamas et al. [98]; Al-Abbasi and El-Medany [99]; Rylander and Maltais [100]; Green Assets Wallet [101]; Dorfleitner and Braun [14]; Livingston et al. [102]; Schletz et al. [103]	9

4.1 *Emissions trading and green certificates*

As shown in Table 3, the most often counted (based on available papers number) categories about use cases where blockchain can support the fight against climate change are carbon emissions trading and green certificates. Therefore the authors will focus on that category in this paper. While carbon certificates describe CO_2 emissions that are already emitted, Emissions Trading Systems, green certificates, or carbon offsets are the counterparts representing emissions saved through green technologies or CO_2 that have been removed from the atmosphere. Blockchain is highly suitable for applications in Emissions Trading Systems (ETSs), as both blockchains and ETSs are similar. According to Pan et al. [62], "Blockchain is a form of existence of data, while emissions trading is the use of data".

While emission allowance and offset trading schemes are functioning and acknowledged concepts, exchanging or extending them with blockchain-based systems could deliver significant improvements. A common problem is shallow, illiquid, and inefficient business-to-business (B2B) certificate trading markets. The accessibility of blockchain systems can help to increase liquidity by allowing more stakeholders to participate [46, 53-54]. Blockchain accessibility also enables interactions between stand-alone markets from various ETSs [37, 45, 55]. Further, the information asymmetry between buyer and seller about the carbon certificates quality is addressed in literature [55]. That can be circumvented by storing information about the origin of allowances transparently and traceably on a blockchain.

Consequently, this leads to a higher reputation of the emissions trading systems and their underlying market mechanisms [48, 64]. The transparency of carbon offsets is limited due to sensitive information. Sadawi et al. [54] show how this can be circumvented by combining an auditable private blockchain with a public one. Increased transparency and predictability of carbon offset purchase commitments through smart contracts provide more precise investment signals for emission reduction projects [58, 61, 63]. Regarding emissions trading, several projects tout lower transaction costs through blockchain. These will lead to higher efficiency compared to markets based on centralized systems [46, 52-53, 64]. Considerable inefficiencies in monitoring, reporting, and verification (MRV) can be addressed with blockchain. Data collection and reporting can be automated by applying smart contracts acting upon emission sensors and smart meters [52-53, 65]. The current audit process is subject to faults and personal bias.

Further, costly intermediaries responsible for audits and carbon certificate verification will be obsolete, as Verschuuren [47] shows. It is estimated that applying blockchain can improve the duration of the audit procedure, which ranges from 6 weeks to several months depending on the ETS, to real-time and reduce costs by approximately 30% [48-49, 60]. On the side of carbon offset projects, MRV through blockchain is promising, too. Oppositely, real-time and data-based verification of green certificates through blockchain increases the quality and reputation of carbon offset projects. Some of the current use cases are mentioned as examples of blockchain applications in ETSs and green certificates in the following paragraphs.

In a case study, Fleuret and Lyons [57] describe a project between the French energy provider Engie and The Energy Origin (TEO). They have created a platform in a dApp (a decentralized App) running on the Energy Web Foundation Blockchain. The dApp allows people who want to live sustainably to monitor the energy's origin and sustainability [57]. They aim to prevent fraud and increase trust in green renewable energy [50]. The TEO platform can record energy produced and consumed in real-time using sensors in homes and energy generators. TEO can calculate how much energy flows from sustainable energy producers to the consumer based on this. In addition, it calculates the positive impact due to saved energy emissions.

"Saved CO_2" is tokenized and stored tamper-proof and transparently. Currently, the blockchain serves in this use case only as an information store. However, the authors mention the possibility of expanding the use case to include, for example, a reward system for energy or CO_2 savings by making the tokens tradeable [56-57, 59].

Poseidon is another practical example of a blockchain application for CO_2 emissions. The foundation has developed a dApp that serves as a platform for carbon offset programs. Through the Poseidon Reduce Platform, the greenhouse gas footprint of purchases can be assessed and then offset through micro-donations. These donations are used to protect forests, national parks, and local communities, positively impacting the environment.

Their target group is retailers. Their technology is based on the Stellar blockchain and uses a highly energy-efficient PoS consensus algorithm. By integrating their blockchain with retailers' point-of-sale systems, they can automatically score a product or service for its emissions and offset them via the dApp. The steps of this process are transparently stored on a public blockchain and are thus traceable for everyone. The Stellar Blockchain ensures the project's scalability while making the platform highly accessible and transparent. The so-called OCEAN token serves as a cryptocurrency that can be converted or exchanged for CARBON CREDIT tokens, enabling immediate carbon offset [58, 66]. The first notable partnerships were set up with Liverpool and the ice cream manufacturer Ben and Jerry's [104].

Similar concepts to Poseidon are pursued by other companies, too. Inuk, for example, is a French start-up that enables people to measure the carbon footprint of their everyday activities, like shopping or traveling. After that, it provides the possibility to offset one's footprint via investments in solar energy production, thus fostering the production of green energy. Running the platform on the public Ethereum Blockchain makes the carbon offsets transparent [61].

4.2 *Sustainable energy use case*

Another blockchain-based use case in the energy field worth mentioning is the NRGcoin, developed by the artificial intelligence (AI) Lab of the Vrije Universiteit Brussel. This coin aims to create more non-government incentives to reward the production and consumption of renewable energy. It uses blockchain to ensure scalability and for the tokenization of energy. Instead of operating a new microgrid, the NRGcoin integrates with local grid operators (distribution system operator) and utilities just as prosumers and consumers [78].

The basic principle is similar to the Brooklyn Microgrid. Prosumers inject their green energy into the local low-voltage grid. Every 15 minutes, the energy consumption is measured by collecting data from the prosumers' and consumers' smart meters via the NRGcoin smart contracts. In addition, by integrating local grid operators and other data sources, such as weather data, it is possible to determine whether a prosumer's meter has been tampered with [77]. The energy is not sold on a local marketplace opposite to the previous use cases. Instead, every prosumer receives one NRGcoin per injected one kWh plus a little more through the generation of new coins by the NRGcoin minting algorithm. Thanks to the integration with the local grid, if energy demand exceeds the supply of locally produced renewable energy, the blockchain automatically connects consumers to the general grid of the utilities, which also handles the payment [87].

The main advantage of NRGcoin is that prosumers can participate in the energy market instead of selling their energy to a utility at a discounted price. Further, as the NRGcoins are traded publicly, they will always be valued similarly to the local energy price per kWh. As the issuance of NRGcoins is governed by smart contracts that cannot be modified or canceled, the system will provide stable returns. Thus, using NRGcoin ensures the profitability of small energy producers. It makes green investments more predictable and independent from government subsidies [78, 87-88]. For consumers, NRGcoin offers more ways to counter rising energy prices. First, they can decide at any time whether to buy electricity through the regular utility or NRGcoin, depending on where the price is lowest. Second, NRGcoin can be purchased at any time and used to buy 1 kWh of energy when needed. Thus, a buffer amount can be purchased when the price is low and used when it has risen again. In addition, since the coin represents only green energy, consumers can express how much they value locally generated green energy by buying it at a higher price than the general price of gray energy [78, 88].

4.3 *Sustainable mobility use case*

Share & Charge is a German company developing a blockchain-based solution for shared charging piles. According to Wang et al. [105], the limited number of charging options and opaque and inconsistent payment methods are limiting factors for the emergence of electric vehicles.

To fix these issues, the Share & Charge Foundation created, together with industry partners, the Open Charging Network. With the help of the Ethereum blockchain, they want to make charging of Electric Vehicles (EV) easier and independent from charging piles operators. Thus, they connect EV owners with charging network operators on their platform. On top of that, they allow private charging pile owners to add their charging stations, too. The blockchain allows the EV owners and private charging pile owners to make payments in exchange for energy in a P2P manner [93-94]. EV owners can always retrieve live prices from the blockchain via a smartphone app. Through the Ethereum blockchain, the process of charging and the related optimization of the electricity price is fully traceable and queryable. That significantly reduces the need for trust [95]. At the same time, the payment details of all participating parties are stored on-chain and, thus, protected by Ethereum's cryptographic standards [93].

4.4 *Green financing use cases*

Green Assets Wallet is a blockchain platform that launched in 2019. It is not handling green investments directly but instead acts as a supporting technology. The issue is that although investors worldwide seek to invest in sustainability projects, there are not enough well-certified ones available. Moreover, many projects cannot be funded due to the lack of certification. Green Assets Wallet tries to fill that gap. The company platform allows project sponsors to publicly and credibly certify the eco-friendliness of their undertakings. At the same time, investors can access the platform to discover new opportunities and monitor the environmental impact of existing investments. The transparent and trustworthy presentation of data through the blockchain differentiates it from other certification labels. These usually only disclose the certification to the public but do not specify on what information basis it was issued [96, 99-101].

WePower is another company that is active in the area of green financing. It combines traditional investing forms like debt and equity financing with crowdfunding through cryptocurrencies. The wind parks and solar plants that it builds are mainly financed through conventional investment forms. However, a small portion of each project is funded from selling crypto tokens representing a fraction of the project. Everyone who buys these tokens can trade them for energy once the plant operates. Thus, in this case, blockchain simplifies the development of renewable energy projects by lowering the entry barriers for green investments and adding another financing option [14, 102].

5. Discussion and conclusion

This paper provides a comprehensive overview of the current research on climate change and blockchain intersection through a systematic literature review. Case studies and use cases mentioned in science were elaborated. In all of the implementations, the technology only serves as supporting technology and is not reducing emissions itself. Concerning research question RQ1, this allows the conclusion that blockchain can support climate-protective measures based on the 19 use cases identified during literature research. To answer research question RQ2, the findings will be outlined in the following paragraphs.

The landscape of blockchain applications against climate change is diverse and therefore is categorized into four categories, as mentioned in section 2. The most promising approach for blockchain support is Greenhouse Gas Emissions. These categories show that the blockchain-based applications against climate change correlate with the domains responsible for most emissions. While through the connection between blockchain and ETSs, heavy-polluting industries, in general, are targeted, in the cases of mobility and energy, the blockchain-enabled applications directly address sectors with a significant impact on climate. For the category of Green Financing, a link to the Paris Agreement can be identified, which stresses the need for sustainable investments in third world countries. Both of these links suggest a high relevance of the identified applications and their domains.

Most applications were assigned to the category Emissions Trading and Green Certificates. Within this category, five applications can be attributed to the area of public emissions trading systems. In two other cases, blockchain enables emissions trading in the private sector.

Table 4. Overview of the purposes for which blockchain is used in climate-related applications

Purpose	Explanation	Frameworks and Use Cases
Digital exchange platform	Blockchain is being used to connect multiple parties for the P2P exchange of data, tokens, and funds.	HBUETS, BC-ETS-RT, cBSMD, BCELF, Inuk, Poseidon, Brooklyn Microgrid, Helios, NRGcoin, AdBEV, Share & Charge, MaaS framework by Nguyen et al. [89]
Certification platform	Blockchain is being used to prove status and handle certificates.	Green Assets Wallet, TEO, Poseidon, Inuk
Liquidity handling and payment	Blockchain is being used to improve liquidity and handle payment processes.	GreenRide, NRGcoin, WePower, green financing framework by Yoshino et al. [96]

On a more abstract level, all applications can be classified into three purposes pursued with the blockchain. An overview of the purposes and associated applications can be found in Table 4. In some cases, multiple purposes could be identified.

Using blockchain to replace or complement emissions trading systems is the most researched topic in the domain. Blockchain seems to make a significant, positive contribution in this area, knowing the importance of emissions trading schemes. The second outstanding application type is P2P trading in the energy sector, and this application is also being intensively studied and tested in the scientific community. Case studies, such as Brooklyn Microgrid, show that blockchain can make a valuable contribution here.

Applications in Emissions Trading and Green Certificates indirectly help reduce emissions by improving and fostering private (Inuk, Poseidon) and public ETSs (HBUETS, BC-ETS-RT, cBSMD, BCELF). In Sustainable Energy, applications encourage the production of green energy (Brooklyn Microgrid, Helios, NRGcoin) or help mitigate the consequences and side-effects of green energy production (AdBEV). In the context of Sustainable Mobility, the impact originates from promoting eco-friendly transportation (Share & Charge) or more efficient mobility services (MaaS framework by Nguyen et al. [89] and GreenRide). All the applications related to the Green Financing category aim to lower the access barriers for investments in sustainable projects.

Next to the advantages that blockchain brings, some controversies need to be mentioned. Neves and Prata [106] identify several vital problems that impose limitations on blockchain technology. One problem is the legal framework. Disruptive technologies such as the blockchain change the status quo and introduce new use cases, business models, and possibilities on the one hand but also create uncertainties and threats on the other hand. That poses fundamental challenges for lawmakers as they need to regulate the new technology adequately. Such regulations can have positive or negative effects on the new technology. Enabling regulations are supposed to facilitate the usage of the technology and enable new use cases. Prohibitive regulations are supposed to prohibit or constrain certain usage scenarios to limit the impact of negative effects and establish trust in the new technology. However, both over-regulation and lack of regulation pose a serious threat to new technologies as it could also harm positive development on the one hand and cause distrust in the technology on the other hand. Blockchain technology is still immature, and future regulations' impact is yet to be seen. Only HBUETS, Green Assets Wallet, and GreenRide address this problem out of the investigated applications.

Another problem is privacy [107], which is one part of the General Data Protection Rules (GDPR). GDPR Guidelines are implemented worldwide in different agreements and national laws [108]. For verification purposes, the blockchain needs to be accessible, including all information stored. For some uses of blockchain technology, there is also the need to store highly sensitive information where privacy is an issue. Transaction information is usually stored as hashes and cannot be directly linked to real-world entities. However, through analysis, transactions may be indirectly linked to real-world entities, thus breaking privacy. Also, although sensitive information can be encrypted, some information needs to be stored unencrypted for smart contracts to work correctly. There is also a serious problem concerning the "right to be forgotten" concept. Due to blockchain technology's inherent technical nature, any information stored on the blockchain is immutable and cannot be erased without invalidating the blockchain: only BUETS and Green Assets Wallet store sensitive data on private blockchains out of the investigated applications. GreenRide does not store any personal data on blockchain for privacy reasons but instead handles it in the cloud. For dealing with the risks of implementing blockchain technology and not being compliant with the GDPR requirements, the paper from Campanile et al. [109] could help by describing risk according to the "Risk management-Principles and guidelines (ISO 31000: 2009)" as: is the effect of uncertainty on objectives, and can be calculated by the two factors of likelihood and severity of the event. The authors of the paper [110] describe a useful combination of quantitative and qualitative risk measurements for information technology implementations which can also be used for the GDPR risk validation.

Another factor that needs consideration in choosing a blockchain is energy consumption and the associated environmental impact [111]. TEO, Inuk, NRGcoin, GreenRide, Share & Charge, and WePower are Ethereum based solutions. However, while the Ethereum blockchain is transitioning to PoS, the energy-intensive PoW consensus algorithm is still operating. Furthermore, PoW is used in Bitcoin. PoW algorithms have a substantial environmental impact based on the enormous energy consumption of dirty coal power plants in many cases. That leads to assumptions that the worldwide power consumption for bitcoin mining is equivalent to the power consumption of Austria per year

[112].

Regarding the issue with power consumption-although it secures the cryptographical challenge well-Etherium announced to switch from PoW to PoS. More details about the bad influence on sustainability and the world distribution of the mining industry are given by Schinckus [112]. Nevertheless, one prerequisite for eco-friendly blockchain applications should be to use the blockchain in the most energy-efficient way possible. Otherwise, a project's potential success and positive impact are reduced by its operation.

While blockchain is often used for disintermediation in climate change, external data input is needed in most discovered use cases. That can be from sensors, objects, cars, energy meters, or auditors. According to Dorfleitner and Braun [14] and Yoshino et al. [96], if data input in blockchains is not designed tamper-proof, systems are not trust-free anymore and, therefore, become dysfunctional. The paper's authors gave an excellent example of how relevant data could be collected. Ahl et al. [112] describe a technical implementation of how sensors are included in a power grid and the corresponding blockchain and discuss the challenges and opportunities. In the context of Green Financing, corruption in third world countries was a key reason for blockchain to be implemented. While the transparency and traceability possibilities through blockchain might make it easier to detect malicious transactions or information, the need for trust in auditors is a weak spot in the system.

Relating to RQ2, the results show that several features and capabilities of blockchain can be used to advantage when applied to climate action. The technology helps manifest and transparently track the invisible impacts by emissions or offsets. Applying blockchain makes the fight against climate change more inclusive and enables all relevant stakeholders' involvement in climate action, rather than large corporations only.

In summary, blockchain can significantly support various innovative and promising measures to combat climate change. Considering how important it is for humanity to get global warming under control, these approaches should be pursued and developed further. However, the above criticism gives rise to further research in the domain.

6. Limitations and future research

This paper provides an overview of connections between the fields of blockchain and climate change. The underlying literature review of this paper firmly focused on scientific literature. Therefore, it needs to be stated that this paper does not include use cases and frameworks not mentioned in a scientific context. Besides, although conducted according to predetermined variables, the data extraction might be somehow subject to bias. In addition, there are several shortcomings related to blockchain and climate change. First, these two fields of research span a broad range of subareas where active research is being conducted, constantly leading to new information.

Future research could focus on determining the success factors of applying blockchain in the context of climate change, using information from practitioners. It is recommended to narrow the focus and analyze single applications in-depth regarding their impact on the environment and potential drawbacks. On top of this, conducting further case studies is necessary to gain insights into the feasibility and attractiveness of frameworks from a business perspective. This literature review also further stresses the need for blockchain research in the context of GDPR. The topic is already a known area of concern in blockchain and requires more attention, especially concerning the mentioned applications. Another weak spot of the identified applications was the connection to external data. Research should be directed towards finding a solution for making sensor input tamper-proof and fraud detection.

Conflicts of interest

The authors declare no competing financial interest.

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