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A Review on Blockchain Technology and Blockchain Projects Fostering Open Science

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Many sectors, like finance, medicine, manufacturing, and education, use blockchain applications to profit from the unique bundle of characteristics of this technology. Blockchain technology (BT) promises benefits in trustability, collaboration, organization, identification, credibility, and transparency. In this paper, we conduct an analysis in which we show how open science can benefit from this technology and its properties. For this, we determined the requirements of an open science ecosystem and compared them with the characteristics of BT to prove that the technology suits as an infrastructure. We also review literature and promising blockchain-based projects for open science to describe the current research situation. To this end, we examine the projects in particular for their relevance and contribution to open science and categorize them afterwards according to their primary purpose. Several of them already provide functionalities that can have a positive impact on current research workflows. So, BT offers promising possibilities for its use in science, but why is it then not used on a large-scale in that area? To answer this question, we point out various shortcomings, challenges, unanswered questions, and research potentials that we found in the literature and identified during our analysis. These topics shall serve as starting points for future research to foster the BT for open science and beyond, especially in the long-term.

Keywords: blockchain, open science, infrastructure, ecosystem, review, research potentials, requirements

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1. INTRODUCTION

The blockchain technology (BT) offers great potential to foster various sectors (Casino et al., 2018) with its unique combination of characteristics, for example, decentralization, immutability, and transparency. We see promising possibilities in the use of this technology for science and academia. In this paper, we want to show why the BT suits especially to open science. So far, the most prominent attention the technology received was through news from industry and media (Morini, 2016; Notheisen et al., 2017; Carson et al., 2018; Volpicelli, 2018) about the development of cryptocurrencies. Examples are Bitcoin, Litecoin, Dash, and Monero, which all are having remarkable market capitalizations[1]. BT, however, is not limited to cryptocurrencies. There are already existing blockchain-based applications in industry and the public sector like crowdfunding (Conley, 2017; Li and Mann, 2018; Arnold et al., 2019), tracking of goods in supply chains

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[1] https://coinmarketcap.com/

(Abeyratne and Monfared, 2016; Tian, 2016; Hepp et al., 2018), authentication (Cruz et al., 2018; Ihle and Sanchez, 2018), and voting services (Swan, 2015a; Osgood, 2016); many more are under development (Brandon, 2016; Davidson et al., 2016; Fanning and Centers, 2016; Nguyen, 2016; Scott, 2016). The Fraunhofer Institute for Scientific and Technical Trend Analysis (INT) in Germany published a study (Schütte et al., 2018) showing that currently BT can be most frequently found in applications used in the financial sector.

The typical use case in that area for BT is the exchange of value units without the need of intermediaries (Nakamoto, 2008; Ben-Sasson et al., 2014). Examples for that are the already mentioned cryptocurrencies and other applications that, for instance, allowing individuals to offer and sell their digital assets like art or data from sensors on a marketplace (Draskovic and Saleh, 2017), or enabling property owners to transfer their land without a notary (Kombe et al., 2017). The pioneering role of the financial sector seems obvious because cryptocurrencies were the first usable blockchain applications. Nevertheless, the potential of this technology has attracted the attention of other areas in recent years, leading to a vast number of new projects[2]. BT is still in an early development phase without widely adopted standardization and frameworks yet.

There are already some scientific sources (but far more gray literature) on how the BT can be used to mitigate existing problems in science like the reproducibility of results from published articles and experiments. Due to immutability, append-only function, and a viewable record of all transactions, BT can provide transparency for all users over every step done in a system. As a result of that, an environment gets created that does not need a trusted authority because malicious behavior is technically difficult. The decentralization enables researchers to build their own open ecosystem for research data, metadata, and communication that follows the philosophy of open science. For us, open science is characterized above all by the fact that everyone can openly participate, collaborate, and contribute to science. The results of these activities, such as research data, processes, studies, and methods, are freely available so that they can be reused and reproduced. In section 3, we go into open science and its definitions in more detail.

Besides reproducibility of experiments (Prinz et al., 2011; Collins and Tabak, 2014; Gilbert et al., 2016; Furlanello et al., 2017), BT can also get used to address several other scientific problems (Gipp et al., 2015, 2017; Anonymous, 2016; Dhillon, 2016; Golem, 2016; Wolf et al., 2016; Breitinger and Gipp, 2017; van Rossum, 2017; Androulaki et al., 2018; Bartling, 2018; Janowicz et al., 2018) like trust problems in the form of malicious behavior in peer-review processes (Stahel and Moore, 2014; Degen, 2016; Dansinger, 2017), lacking quality and redundancy of study designs (Macleod et al., 2014; Belluz and Hoffman, 2015), and the restriction of free access to scientific publications (Myllylahti, 2014; Teplitskiy et al., 2017; Schiltz, 2018). BT also has the ability to increase the trustability of studies and collaborations among researchers in complex science projects by the use of its characteristics.

BT stands out from other systems in its exceptional technical architecture, which allows the technology to get adapted for a variety of use cases. For example, developers have the possibility to design blockchains for open or private access combined with individual governance models depending on its purpose. In addition to the technical perspective, cryptocurrencies, for example, provide additional, unique opportunities to create business models and incentives for users or entire communities. However, besides BT, there are also other technologies that are applicable to open science. One example is the peer-to-peer data synchronization protocol Dat (Ogden et al., 2018) that also supports immutable and decentralized storage and can be used as an infrastructure for scholarly communication (Hartgerink, 2019). The protocol got inspired by several existing systems, one of them being BitTorrent (Pouwelse et al., 2005). Further non-blockchain-based approaches supporting open science include the research and collaboration platforms Open Science Framework (OSF) (OSF, 2019) and OPERAS (Mounier et al., 2018), the open access repository Zenodo (Zenodo, 2019), the research data infrastructure offered by the European Science Cloud (EOSC) (EOSC, 2019), and the publishing platform F1000Research (F1000, 2019).

We want to point out at an early stage of this paper that BT is just a technology and certainly not the silver bullet that will overcome all problems we are facing in science today. Some of the issues cannot get solved by technology alone, instead require the involved persons to rethink habits, behaviors, and processes. In some cases, it might even lead to researchers having to renounce privileges. There is also criticism of the use of BT for science. Hartgerink (2018) argues that blockchains can even amplify inequalities by increasing artificial scarcity and relying on free market principles. Another point of criticism affects the consensus principle as the fundamental definition of truth in a blockchain. Firstly, there is always a chance of hijacking a blockchain with a so-called 51%-attack. Secondly, and more relevant from a philosophical point of view, Hartgerink asks whether we need a consensus for scientific theories or ideas at all.

Overall, our work contributes to understanding the BT and the possibilities it offers to design, implement, and improve open science projects and applications across all different scientific fields. We think it is a suitable technology to support the transformation of open science. The motivation for this work lies in the circumstance that there is currently no systematic review of the general suitability of BT for open science, the state of the art or related vital challenges and research potentials. We are addressing these topics in this paper.

2. METHODS

The BT is, besides the financial area, also emerging in many other sectors and gets continuously more popular. It is difficult to overview the market of existing and planned projects since there is no holistic public database or repository for it. Further, the range of visions, concepts, and prototypes is constantly

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[2] For example, see https://github.com/ : The GitHub search engine with the search term "blockchain" delivers a general overview

increasing, which means that this review can only provide a snapshot and does not claim to be complete or exhaustive.

We conducted a systematic review of the research topic by first searching for relevant literature. It has turned out that this topic is quite novel, and there are just a few publications about how BT can be used to foster open science or science in general. In a literature review about the usage of BT in different domains (Casino et al., 2018), the application field of science did not even get mentioned as an application domain. Besides literature, we also focused our analysis on various blockchain projects that can foster open science in different ways. We want to provide a transparent and reproducible review, thus in the following, we describe our research questions and methodology.

1. What are the current requirements for a technical open science infrastructure, and how do they compare with BT features?
2. What is the current status and perspectives for the use of BT in science and academia?
3. What are the biggest challenges and obstacles that are preventing successful implementation and adoption of BT as supporting infrastructure for open science?

(1) We approached this question by comparing the characteristics of BT with the goals and needs of open science. We examined whether it is able to deliver a reasonable and adequate fundament for an open science ecosystem. At first, we studied existing literature to describe what open science is (section 3.1), what it aims to be, and what the requirements for such an infrastructure (section 3.2) are. Then, we examined the BT to understand how it works and what characteristics it has (section 4.1). Finally, we created a matrix that shows all related infrastructure requirements and compares them to the characteristics of the BT to determine how they match and whether they can be fulfilled (section 4.2).

(2) To answer the second research question, we discussed relevant literature, gray literature, and projects that we found, collected, and screened from different search engines and reference lists until April 2019. Primarily, we used Google Scholar[3], PLOS[4], CiteSeerX[5], Microsoft Academic Search[6], and GitHub as file hoster of software development projects. Secondarily, we examined research publications, whitepapers, and blogs. We found the most relevant literature and projects by using the search terms "blockchain" with "science," "publishing," "peer review," and "reproducibility." The relevance of literature was made sure by reading their abstracts and, partially, the whole work if the abstract was not clear enough to rate the specific content. If a paper had no meaningful content for our research, we excluded it from our review. From there on, we screened the reference lists of the remaining literature to find further suitable sources, known as snowballing. After that, we made a full-text review of the content of all papers to get an overview of the current research state that showed the potential and increasing interest in the BT for open science (section 5.2).

Besides the literature, we also collected exciting and promising blockchain-based projects consisting of concepts, prototypes, and already deployed applications. We found in numbers many more projects than relevant scientific publications. The majority of the projects got identified in the reviewed literature and the rest through search engines. These projects are either designed specifically for open science, or some of their functionalities are usable in that area. We also found some very early concepts and ideas that only exist in forums or social media networks. However, their potential is not ratable yet due to low progress and information scarcity, so we did not include them into detailed analysis. Altogether, we collected and analyzed 83 projects but removed 23 of them early due to cancelation, irrelevancy, or inactivity (no actions or news for more than 1 year), leaving 60 projects left. We summarized and mapped these into different categories according to their use and created an overview of our approach (section 5.1). The so built structure and the review of projects help to gain a better understanding of the current situation of research in this area (section 5.3). Finally, we made a summary and discussed our findings (section 5.4). For a complete overview, we created a database (see **Supplementary Material**) containing a short description, project state, and other characteristics for each project.

(3) As a basis to process the third research question, we used the knowledge gained from answering the first and second research question, and the analysis of literature and projects. First, we conducted a brainstorming, discussed all mentioned topics, and rated them each individually. Then we created a ranking of the topics by collecting and evaluating the ratings of all people who were involved in the brainstorming. Finally, we took the issues of rank one to five and described them in terms of current challenges, research potentials, and open questions that should be addressed to foster the BT for open science (sections 6.1–6.5).

3. OPEN SCIENCE

In this section, we briefly describe the philosophy behind open science and existing problems in science it can mitigate (section 3.1). Furthermore, we did an analysis to point out what requirements have to be met to establish a technical ecosystem that follows and lives the principles of open science (section 3.2). Finally, we created an overview of the requirements we determined in this section.

3.1. Overview

There are several definitions of what open science is, but there is not a universal definition that is generally valid. We think the definition of FOSTER[7] is a good representation of the term: "Open Science is the practice of science in such a way that others can collaborate and contribute, where research data, lab notes and other research processes are freely available, under terms that enable reuse, redistribution and reproduction of the

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[3] https://scholar.google.com/
[4] https://plos.org/
[5] https://citeseerx.ist.psu.edu/
[6] https://academic.microsoft.com/
[7] https://bit.ly/2lJEnTO

research and its underlying data and methods." There are other descriptions such as the "open" definition[8] and one from the OECD[9]. An illustrated story about the development of open science can be viewed here (Green, 2017). Overall, open science is an umbrella term for a multitude of assumptions about how the future of knowledge creation and dissemination (also education) will work (Fecher and Friesike, 2014). There are different types of implementations, such as sharing of computing and storage resources in an open science grid (OSG) (Pordes et al., 2007; Altunay et al., 2011) or open access repositories for research literature as SocArXiv[10], CiteSeerX, and arXiv[11]. We want to briefly discuss open science in its chances and challenges to provide a common point of definition from that we will link the possibilities of BT to the fundamental concept of open science. Fecher and Friesike (2014) structured open science in five schools of thought and Tennant et al. (2019) expanded them by a sixth (see **Table 1**). It summarizes the identified schools with their central assumptions, their goals, and keywords.

As we have learned only late about the sixth school (community school), which is also quite new, we refer in the further work to the original five schools, which are the basis of our requirements analysis. For the sake of completeness, we included the sixth school in **Table 1**. After analyzing the community school, we can say that the result of this review would not have changed if it had been included, on the contrary, the principles of this school harmonize well with the characteristics of the BT. However, it should get considered in future research work.

Today's communication technologies have opened up the way to practice open science; in detail, the methods for producing, storing, sharing, and accessing information have been progressing, and new research opportunities have developed (Nentwich, 2003). Opening research processes provides, among other things, the chance to get valuable feedback from other researchers for work in progress, for example, through a platform like the Open Science Framework (OSF)[12] (Bartling and Friesike, 2014). It can be called scientific-self correction if the scientific community and also non-experts are able to access research data while it is still in process and to provide feedback in the form of possible mistakes and potential improvements of the underlying work. Such an approach can also help to find solutions to specific problems more efficiently (Bartling and Friesike, 2014).

Adjustments in science are needed because many studies in different scientific fields, for example, medicine, psychology, and computer science are irreproducible (Schooler, 2014; ASCB, 2015; Baker and Penny, 2016; Smith, 2017); sometimes even the original researchers are not able to reproduce the results of their earlier experiments (Pashler and Wagenmakers, 2012). That situation is known as reproducibility crisis, and the open principles are a promising approach to mitigate such a problem, as it can make research more transparent and understandable. We would also like to mention that there are critical voices that do not see a reproducibility crisis in science and calling it a narrative. For example, Fanelli (2018) concludes a literature review on that topic with the statement that it is empirically unsupported to say science would be undergoing a reproducibility crisis. Rather, it would be counterproductive fostering cynicism and indifference among young researchers instead of inspiring them to do more and better research.

Researchers usually aggregate and compress their collected research data for their final publication to meet the requirements of journals and especially conferences that request to stay within a specific limit of pages. In computer science, the cap for full papers on conferences is mostly ten pages (Gray, 2009). So other researchers often have no access to the unedited raw data that can be very useful for the understanding and reproduction of the results of a paper. The aggregated data often lacks the needed degree of detail to reproduce the process of creation (Murray-Rust, 2008). The transparency of open science shall serve as an example of how it can foster and improve general scientific procedures. However, researchers need a secure and trustable environment for that purpose.

In addition to the raw data, researchers create further content such as ideas and study designs in early research phases that usually do not get published. If the experiments and analysis give negative results, the same picture appears since the focus is on publishability (Nosek et al., 2012) and publication bias for positive results exist (Matosin et al., 2014; Van Assen et al., 2014; Mlinarić et al., 2017). So, the current system in science leads to the waste of much potentially valuable data (Van Assen et al., 2014; Mlinarić et al., 2017). An open research culture during all phases along the research cycle with published supporting data can enhance the quality of work. Supplementary, from an economic perspective, researchers may check ongoing projects to prevent the waste of time and resources for topics that are already getting processed by others.

Open science still has to overcome significant obstacles in different dimensions to get widely applied. Most of the points mentioned here require such drastic changes in research processes and habits and behaviors of researchers that their realization in the foreseeable future is doubtful. For example, the traditional workflows of researchers need to be changed; they usually do not contain steps to publish research data or publicly discuss different topics about it before the final publication. Research is most of the time taking place in a closed institutional framework without the integration of individuals from the outside, so these barriers need to put down to build an open research environment. Around the whole open science discussion, a legislative framework has to be developed, but not only on the national level; it has to be international to set the global rules for the disclosure of incoming and outgoing data and also to protect the rights of all people involved. It is also a discussion of how the crediting of contributions is working fairly when researchers are creating micro-contributions (data sets, hypothesis, ideas, and reviews) (Tennant, 2018) in addition to traditional publications.

Altogether, in this section, we described on the one side different challenges and problems of science and the other side how open science can mitigate them and what benefits

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[8] https://opendefinition.org/

[9] https://www.oecd.org/science/inno/open-science.htm

[10] https://osf.io/preprints/socarxiv

[11] https://arxiv.org/

[12] https://osf.io/

TABLE 1 | Six open science schools of thought. The sources (Fecher and Friesike, 2014; Tennant et al., 2019) got combined.

		Description		
		Assumption	**Goal**	**Keywords**
Open Science School of Thought	Democratic School	The access to knowledge is unequally distributed	Making knowledge freely available for everyone	Open Access, intellectual property rights, Open Data, Open Code
	Pragmatic School	Knowledge-creation could be more efficient if scientists worked together	Making the process of knowledge creation more efficient and goal oriented	Wisdom of the crowds, network effects, Open Data, Open Code
	Public School	Science needs to be made accessible to the public	Making science accessible for citizens	Citizen Science, Science PR, Science Blogging
	Infrastructure School	Efficient research depends on the available tools and applications	Creating openly available platforms, tools, and services for scientists	Collaboration platforms and tools
	Measurement School	Scientific contributions today need alternative impact measurements	Developing an alternative metric system for scientific impact	Altmetrics, peer review, citation, impact factors
	Community School	Science requires all voices to be heard and a committed community	Ensuring diversity and inclusion in scholarly conversations	Diversity, inclusivity, standards, public goods, public funding

it can deliver if a suitable technical infrastructure is found. For that purpose, we are analyzing in the next section what specific requirements such an open science infrastructure has to fulfill.

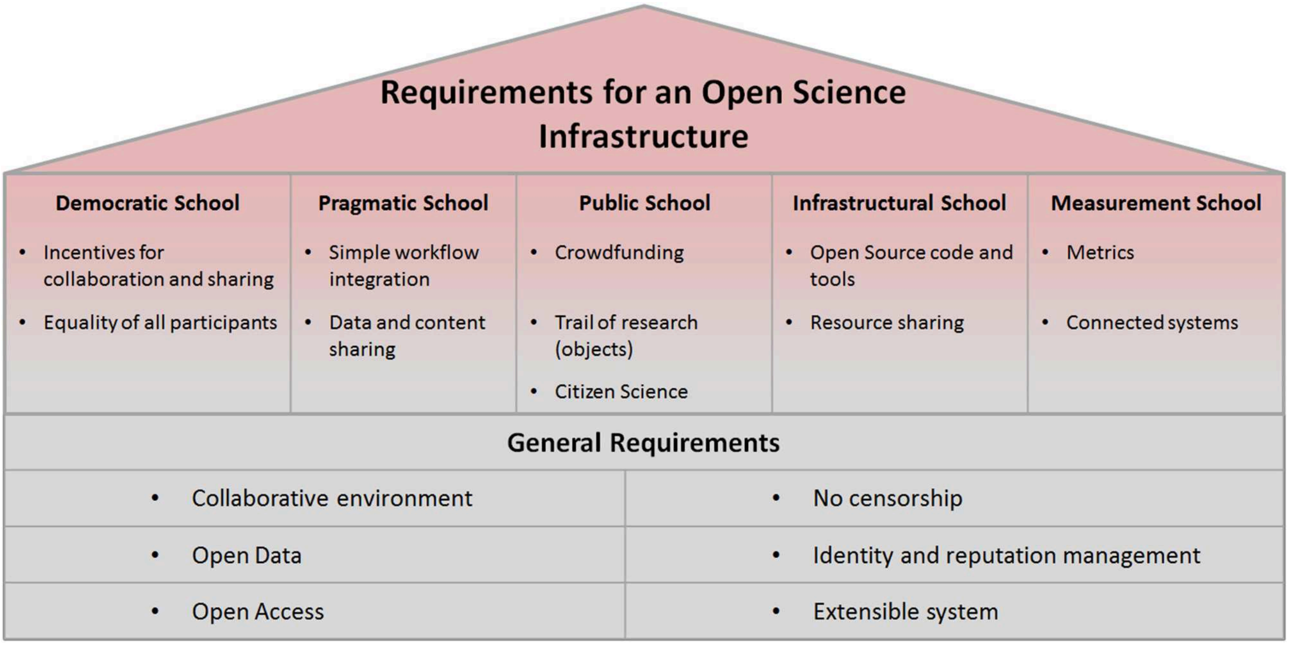
3.2. Requirement Analysis for an Infrastructure

With the underlying five schools of thought by Fecher and Friesike (2014), we systematically analyzed what requirements for an open science infrastructure following the open principles are. Therefore, we first made a detailed requirement list of every school and compressed them to a superordinate and more abstract level. Then we identified cross-school elements of such an ecosystem by checking if certain schools sharing the same needs. Finally, we have assigned all other requirements to the specific schools. Out of this analysis, we created a overview of requirements (see **Figure 1**). In the following paragraphs, we briefly describe all single points.

One essential requirement of an open science infrastructure is to provide a *collaborative environment*, which means that researchers and also non-experts are able to work together, author collaboratively, and share information, materials, reagents on different projects (Hunter and Leahey, 2008; Tacke, 2010). The performance in a (research) team compared to single researchers is far more effective and efficient on different levels, for example, better quality, higher productivity, and fewer errors by additional review bodies. The requirements *Open Data* and *Open Access* are supporting the collaborative environment while they address different scientific problems. Open Access portrays free access to knowledge, for example, scientific publications (Cribb and Sari, 2010; Rufai et al., 2011; Sitek and Bertelmann, 2014). Quite often, research publications are behind a paywall with continuously increasing costs (Carroll, 2011) that can hinder researchers and the general public from reading and citing them; ironically, research is often funded by tax money. Among other researchers, Cribb and Sari describe the access to knowledge as a necessity for human development (Cribb and Sari, 2010; Phelps et al., 2012). One aspect of Open Data addresses the reuse of published scientific data (Pampel and Dallmeier-Tiessen, 2014). Often, an academic third party like a publisher holds the rights, so the scientific community is not allowed to reuse this data without permission (Murray-Rust, 2008; Molloy, 2011). Considering the philosophy behind open science, research results should be reusable preventing the waste of resources for collecting already existing data again and allowing for synergies between researchers and their works (Murray-Rust, 2008).

Everyone should be able to express their opinion freely without being *censored* in any way as long as the law is respected. The same applies to science (Salyers, 2002) and related networks; censorship should not be possible in any way by any participant. We think that there should not be an entity that controls a scientific infrastructure and data on it; rather, collaborative management is preferable in an open science environment. However, each platform needs a governance model that provides the framework for the user community. In this regard, still many questions have to be answered in future work, for example, who initiates, develops, and maintains the platform, who creates the rules and decides about contributions and which parties are trustworthy?

Another essential requirement is to provide an *identification and reputation system* that can identify researchers and other participants of the ecosystem and link them to their contributions. So, it should be possible to credit the valuable work and invested effort of all contributors appropriately and to calculate scientific metrics, for example, impact factor or h-index to build a reputation (Woolston, 2015). The last general requirement we identified is that every element in a technical infrastructure should be *extensible* to make sure the whole ecosystem is sustainable (De Roure et al., 2008). Extensibility is vital, especially in today's digital age in which computer technology develops so fast and delivers more efficient new tools regularly. Overall, it allows the community of the ecosystem to upgrade and improve the single components steadily, so no costly and time-consuming substitutes are necessary for the long-term.



Requirements for an Open Science Infrastructure

Democratic School	Pragmatic School	Public School	Infrastructural School	Measurement School
- Incentives for collaboration and sharing - Equality of all participants	- Simple workflow integration - Data and content sharing	- Crowdfunding - Trail of research (objects) - Citizen Science	- Open Source code and tools - Resource sharing	- Metrics - Connected systems

General Requirements

- Collaborative environment	- No censorship
- Open Data	- Identity and reputation management
- Open Access	- Extensible system

FIGURE 1 | Overview of general and specific requirements for an open science infrastructure/ecosystem.

The five schools of thought have their own more specific requirements for an open science ecosystem. The *democratic school* demands *incentives for collaboration and sharing of data* that are crucial for such an environment (Arazy et al., 2006; De Roure et al., 2008; Haeussler, 2011). Participants should get an extrinsic motivation, for example, a form of counter-value (Haeussler, 2011) for sharing their data and contributions in an open infrastructure (De Roure et al., 2008). Incentives can also work in harmony with a reputation system. The democratic school also highlights that all users in an open science environment should be *treated equally*, for example, in the perspective of access to knowledge (Rufai et al., 2011; Fecher and Friesike, 2014). So, no participant has more rights than another except in terms of administration and governance of such an infrastructure, which represents a special matter. Decisions about the future development of an ecosystem and how valuable contributions are should be made democratically by independent experts, so in our case, people who have experience in research and the scientific system.

In the view of the *pragmatic school*, the *integration* of an open research process into existing established procedures needs to be as *simple as possible* to convince researchers to change or adjust their *workflows*. If it is complex, costly, or challenging, it will be a deterrent, so most researchers will not adapt their processes and hence not participate in the network. The complexity also affects the willingness of the researchers to provide and *share data and content* in general (Vision, 2010). If integration takes too much time, or there are no visible incentives or counter-values, information very likely will not be shared (Campbell et al., 2002; Vision, 2010; Boulton et al., 2011). The effort needed is a crucial element for a working open infrastructure; simplicity lays the foundation for participation and complements the used incentive systems.

Crowdfunding opportunities in an open science ecosystem are one of the requirements of the *public school*. It allows that every participant can decide privately to fund individual research projects that are following promising goals; thus, crowdfunding expands funding methods of research. In exchange, these backers can get monetary or non-monetary (for example, usage rights) benefits (Fecher and Friesike, 2014). Furthermore, the public school aims to record the *trail of research for every research object* like papers, data sets, ideas, used tools, results, and hypothesis so that the involved people get credit for these objects according to their contribution. It is also an important factor to retrace the creation process of, for example, a study or an experiment to replicate its results. A chronological chain of milestones about data creation, and also the availability of raw data can be part of the solution for the current reproducibility crisis. There are two crucial points to fulfill the requirement of a trail of research. First, the researchers need to make proper documentation about their works what they always should do (Vasilevsky et al., 2013). Second, the underlying technical system should record all transactions immutable, so censoring is not possible in any way afterwards.

Another part of the public school is *citizen science* (Hand, 2010; Gura, 2013) that allows regular citizens to participate in certain research projects, even if they have no specific experience in science. A fictional example would be the setting up of temperature sensors in the homes of various participating citizens throughout the world; thus, the global average temperature can be determined. There are several examples of citizen science projects (Irwin, 2006; Hand, 2010;

Catlin-Groves, 2012) - see Rosetta@Home[13], EchidnaCSI[14], or eOceans[15]. Opening up research processes to citizens can be beneficial, but it strongly depends on the nature and goals of the particular project (Irwin, 2006; Powell and Colin, 2009; Gura, 2013). Therefore, an open science infrastructure should provide possibilities to integrate the wide publicity into research.

The *infrastructural school* contains the requirement of using *open source code and tools* in projects that include the development of new software (Nentwich, 2003). That procedure enables other researchers to use the same algorithms and processes, which eases the reproduction of results and a general understanding of unknown programs. Schubotz et al. (2018) published a practical guide about using open source tools over the complete research cycle that supports researching by the open principles. One more requirement of the infrastructural school is the ability to *share resources* like digital storage space or computing power; one example is the OSG (Pordes et al., 2007; Altunay et al., 2011) we mentioned. We also see the potential to share workforce for different research projects if they require it.

Measurement school focuses on standards of *measuring metrics* of old (like print journals and conferences) and new, mainly internet-based (for example, open access journals, blogs, and social media platforms) publishing formats (Weller and Puschmann, 2011; Priem et al., 2012; Yeong and Abdullah, 2012). So, for an open science infrastructure, the school demands the capability to calculate old and potentially new metrics to create a measurable environment for the participants. Performance values are substantial for a reputation system and are an excellent possibility to provide incentives in the form of key figures that researchers can improve by their work. The measurement school contains a second requirement that is essential for an open infrastructure; there must be interfaces to *connect internal and external systems*. In that way, participants have the opportunity to share all kind of data from their own software with the ecosystem and to add new external tools and functions.

4. BLOCKCHAIN TECHNOLOGY

In this section, we briefly describe the blockchain technology (BT), its characteristics, and functionalities to provide fundamental knowledge about it (section 4.1). After that, we compare the requirements of an open science infrastructure (section 3.2) with the characteristics of the BT (section 4.2). Finally, we present an overview matrix and several examples showing that the technology as a technical basis fulfills the requirements and hence suits as a solution.

4.1. Overview

When talking about BT, the distributed ledger technology needs to get mentioned since it is an umbrella term that includes blockchains as one type (Benčić and Podnar Žarko, 2018). A distributed ledger uses independent systems (nodes) to record, share, and synchronize transactions in a decentralized network (Kakavand et al., 2017). A blockchain works similar but organizes its data into blocks which are cryptographically and chronologically linked together and also may use other kinds of consensus mechanisms and smart contracts (Anwar, 2019). Haber and Stornetta did already basic work for the BT in 1991 by describing a cryptographically secured chain (Haber and Stornetta, 1991), and in 1993 they and colleagues improved that idea with certain functionalities like timestamping (Bayer et al., 1993). Their design still had some flaws, for example, the double-spending problem (Chohan, 2018) and the need for a trusted party for validating all transactions.

In 2008 a pseudonym "Satoshi Nakamoto" released a whitepaper about a novel peer-to-peer-based digital currency called "Bitcoin" (Nakamoto, 2008) that overcame these flaws. Finally, the Bitcoin network went live in 2009 and had a wild journey in the context of its market value (short time over 20,000$[16]) and media relevance. It gained most popularity through the high number of news about its value development. We refer to a Wikipedia article[17] that contains numerous sources to reconstruct the detailed history of Bitcoin. Since 2009 many more cryptocurrencies have been developed (so far over 2,000 different currencies) and BT got noticed as a technology that not only can provide an infrastructural environment to manage currencies but also it is enabling the realization of much more use cases (Casino et al., 2018). Due to the possibilities, a research offensive started a few years ago by researchers from all over the world to analyze the use of BT in many different areas (Casino et al., 2018).

The BT does nothing new in a perspective of its single elements, but as a bulk, these elements (for example, decentralization, immutability, transparency, and cryptographic hashing) are unique and avoiding the double-spending problem (Nakamoto, 2008; Beck et al., 2016). A blockchain network works without a centralized server. Transactions made in such a network are verified by the decentralized nodes (user systems) (Abraham and Mahlkhi, 2017; Zheng et al., 2017) and stored in so-called blocks with a timestamp (Gipp et al., 2015; Lin and Liao, 2017). The size limit of blocks can differ between varying blockchains. The blocks are getting linked in chronological order because every one of them (except the first "genesis" block) contains the cryptographic hash of the previous one, so they form a chain (Beck et al., 2016; Crosby et al., 2016). The block hash considers not only structural data of a specific block but also its content like, for example, transactions.

It depends on the blockchain whether users can store complete files on-chain or they need to use off-chain solutions like a cloud or an InterPlanetary File System (IPFS) (Benet, 2014) due to file sizes. An IPFS is a peer-to-peer distributed file system for storing and sharing data. It connects computing devices with the same network of data, and each device holds and distributes a portion of the overall data. In relation with a blockchain, the chain only stores an associated hash that references to the actual file on an IPFS. Note, that off-chain solutions (sometimes referred to as "second-layer" blockchain solutions) introduce new challenges

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[13] http://boinc.bakerlab.org/rosetta/

[14] https://grutznerlab.weebly.com/echidna-csi.html

[15] https://www.eoceans.co/

[16] https://coinmarketcap.com/currencies/bitcoin/#charts

[17] https://en.wikipedia.org/wiki/History_of_bitcoin

and are an interesting research topic on their own, but one that goes beyond the scope of this paper.

In general, a blockchain is a type of database that only supports reading and appending (Swan, 2015a; Yli-Huumo et al., 2016). Due to its decentralized architecture, it operates as a peer-to-peer network, so users (peers) are interacting directly with each other without the need of trusted intermediaries or authorities (Hoffmann, 2015; Catalini and Gans, 2016; Christidis and Devetsikiotis, 2016) calls it "trustless trust." Participants that trade with each other make an agreement for transferring, for example, physical or digital assets (Casino et al., 2018). The nodes of the other users in the network are then verifying the transaction by the programmed rules of the system to make sure everything is valid before it gets executed (Nakamoto, 2008). The verification is essential because all records and transactions in a blockchain are immutable (tamperproof) (Gipp et al., 2015; Zyskind et al., 2015). The consensus mechanism of the network is responsible for how verifications for the users are working. As an example, we mention the consensus mechanism Proof-of-Work (PoW) (Nakamoto, 2008; Tschorsch and Scheuermann, 2016) which is, among other blockchains, used in the Bitcoin network and is the best-known method, but heavily criticized for its high energy consumption (O'Dwyer and Malone, 2014). Another one is Proof-of-Stake (PoS) (King and Nadal, 2012; BitFury Group, 2015; Tschorsch and Scheuermann, 2016; Zheng et al., 2017) that offers a more efficient way for verification and consensus finding, in terms of energy consumption and performance.

Literature categorizes blockchain networks in terms of their access and governance system into the following different types: public, private, and consortium, which is also called federated (Buterin, 2015; Swanson, 2015; Kravchenko, 2016; Zheng et al., 2017). Additionally, they become separated in perspective of their consensus process into permissionless and permissioned infrastructures; these are getting combined with the various blockchain types. In public (permissionless) blockchains like Bitcoin, everyone can join and participate in the system. In private and consortium (permissioned) blockchains, only users have access who are on a whitelist; typically, parties that know each other. Other combinations of the types and consensus process permissions are also possible. For more information and a comparison between the different kind of blockchains, we refer to Zheng et al. (2017) and Casino et al. (2018).

Application programming interfaces (APIs) are essential for a blockchain to connect off-chain (external) hardware and software with the network. It enables communication as well as the transmission and exchange of data between the systems (Linn and Koo, 2016; Liang et al., 2017). In such a way, external applications (including web-services, Beck et al., 2016) can integrate the characteristics and functionalities of an existing blockchain for specific use cases (Linn and Koo, 2016; Xu et al., 2016). For example, it is possible to hash and store research data directly from external sensors, algorithms, and other data creating processes. So, an API is an important feature of a blockchain in terms of interoperability that developers always should provide and document to maximize the blockchain's potential and ease its use.

BT has developed continuously; Swan (2015a) describes three evolutions (Blockchain 1.0, 2.0, and 3.0) that led to new possibilities of using the technology to realize steadily more complex applications and projects. Ethereum (Buterin, 2014) is a blockchain application that provides an infrastructure, comparable to an operating system, which everyone can build their applications on top without the need of the cost-intensive development of an own blockchain. Ethereum introduced smart contracts (SCs) that are programmable in specific languages, for example, Java, GO, and Solidity (Dannen, 2017), and allowing for the automatic enforcement of a digital contract with typically if-then clauses (Bhargavan et al., 2016; Christidis and Devetsikiotis, 2016; Kosba et al., 2016). There are even projects to create complete decentralized autonomous organizations (DAOs) to automate organizational governance and decision-making with SCs (Swan, 2015b; Jentzsch, 2016).

We noticed that there are slightly different characterizations of BT in the literature (Aste et al., 2017; Puthal et al., 2018; Treiblmaier, 2019; Viriyasitavat and Hoonsopon, 2019). Therefore, we summarized the properties of the technology and made the following compressed list of relevant characteristics concerning the open science use case.

- *Decentralization*: A blockchain is a distributed redundant peer-to-peer system of nodes each storing the whole blockchain or a part of it (Abraham and Mahlkhi, 2017; Zheng et al., 2017). The architecture even allows for distributing software and other content through the network automatically (Kiyomoto et al., 2017). Further, decentralization also eliminates a potential single point of failure and removes the dependency of a central authority that has to be trusted (Kshetri, 2018).
- *Cryptographic Hashing*: Due to the hashed connection embedded in every block of a blockchain to the previous block, a chronological chain gets created (Nakamoto, 2008; Gervais et al., 2016). Besides the consensus mechanism, hashing ensures that the complete chain, inclusive the content, cannot be altered because a change would affect one specific hash value, and from there one, all subsequent hash values, and hence the chain would get invalid (Zheng et al., 2017). It also allows generating a unique hash of files of any size to create an identifier. For more information about the hashing process, see the following references (Zain and Clarke, 2007; Nakamoto, 2008; Lemieux, 2016).
- *Timestamping*: Every record (block creation, transaction, data storage) in a blockchain gets chronologically timestamped. It provides traceability, transparency, and full transaction history for the users (Nakamoto, 2008; Gipp et al., 2015; Mattila, 2016; Zheng et al., 2018). Timestamps in combination with a cryptographic hash can also be used, for example, as a Proof-of-Existence for certain information at a particular time (Gipp et al., 2015).
- *Immutability (Append-Only)*: Data, once stored on the blockchain, cannot be altered or deleted anymore; the cryptographic hashing and decentralized validation (consensus) process ensure that (Swan, 2015a; Yli-Huumo et al., 2016). Exceptions are specific attacks like the 51%-attack, see Dowd and Hutchinson (2015) for more information.

- *Consensus Mechanism*: They define how users validate transactions in a blockchain among each other (Abraham and Mahlkhi, 2017; Zheng et al., 2017). Since the Bitcoin blockchain and PoW, many new unique methods and combinations of existing consensus procedures got developed and implemented in new blockchains. For more information about consensus mechanisms, see Zheng et al. (2017), Abraham and Mahlkhi (2017), and Nguyen and Kim (2018).
- *Access and Governance System*: Every blockchain gets also characterized through its access (public/consortium/private) (Peters and Panayi, 2016; Lin and Liao, 2017) and governance system (permissionless/permissioned) (Gervais et al., 2016; Peters and Panayi, 2016). These properties are crucial to the potential use cases (Lin and Liao, 2017).

Note, that the characteristics mentioned above are not exclusive to BT. As mentioned in the introduction, there exist other approaches that also have one or more of these properties.

4.2. Blockchain Technology as an Open Science Infrastructure

In this section, we compare the characteristics of BT with the needs of an open science infrastructure. With this, we study whether the technology suits as a foundation. Therefore, we made a matrix that shows which characteristics are important for the specific requirements and can meet them (see **Figure 2**). It is crucial to understand the matrix as a whole because several demands and characteristics complement each other. For example, it is useful or needed for many functions like for providing a *trail of research* that there is *no censorship* possible in a blockchain network to provide a trustworthy environment (Swan, 2015a). Altogether, in this section, we describe, along with different examples, how the specific blockchain characteristics meet the requirements of an open science infrastructure. We do not claim to make a detailed model or concept of an ecosystem.

In terms of *accessibility and governance*, we concluded in an early analysis phase that a consortium/private blockchain makes no sense for its application as an open science infrastructure. One fundamental essence of open science is to share knowledge globally and the science process itself plus the results out of it accessible for a broad audience or even everyone (Bartling and Friesike, 2014), without differentiation according to characteristics of any kind. A public blockchain is suitable and can meet that purpose while a consortium/private blockchain would restrict the access. The comparison of a permissioned and permissionless blockchain goes far more in-depth and is connected to different factors like governance models and consensus mechanisms, so it is a research review on its own. In order to gain insight, we will describe two possibilities superficially.

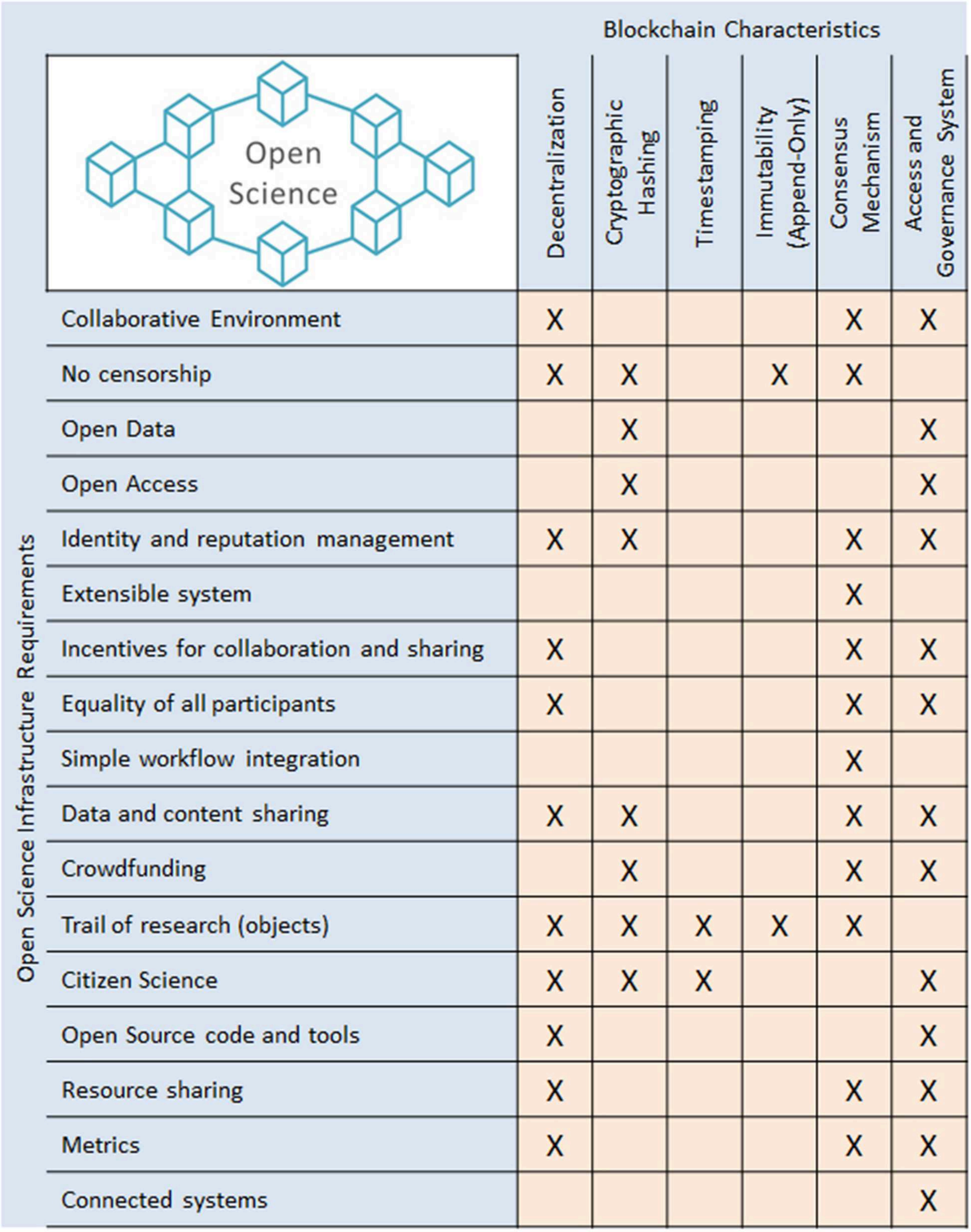
In a permissioned network, the governance is not taken over by all equally, but an organization (we call it committee) must be formed. One possibility could be to democratically elect the members of the committee through a network of universities and research institutions. This committee then decides how the open science infrastructure will develop or what value specific contributions in the network have. The division of roles justifies itself on the fact that non-experts / non-scientists lack the necessary experience to make well-founded decisions in such a system, which is why a permissioned blockchain is elementary with this governance model. So, users get divided into two roles ("user" and "committee user"), which differ in the ability to participate in certain decisions but have the same permissions for all other aspects.

In a permissionless network, everyone is equal in all aspects, but it also opens ways to system abuse. Therefore, a suitable consensus mechanism is mandatory to make collaborative decisions about how the underlying blockchain system is developing and also to prevent malicious behavior in the network. PoW is not the right choice for open science, not least because of its high energy consumption. Instead, more appropriate are mechanisms like PoS, which could be adopted to open science purposes. The distribution of tokens, which are representing voting rights in this system, could be based on scientific experience and merit. How these values are determined and composed would have to be studied in detail beforehand. However, this approach would make the use of a permissionless blockchain possible, since people without a scientific background do not have to be excluded, their impact gets minimized by the size of their stake.

Both approaches have advantages and disadvantages, and it depends on many factors which method is better. There are even more ways to build such a system. A detailed examination of these approaches would be the next step toward a blockchain-based open science infrastructure but goes far beyond the goal and scope of this manuscript. In the following, we concentrate on the comparison of the identified requirements for an open science infrastructure with blockchain features.

An essential topic of an open science system is the possibility to provide a *collaborative environment*. BT and its *decentralization* can support that goal by enabling, among other things, all users to share the same data version. In detail, data consists of, for example, experiment results, communication content, drafts, open peer-reviews, and raw data. Also, as mentioned, specific groups or the whole network can make decisions collaboratively through ordinary votes that can follow, for example, a democratic approach (Osgood, 2016). Subjects of these polls could be topics like the future development of the network, to add/remove specific features, or to accept/rate proposed projects and contributions. On a technical perspective, the validation and management of a blockchain infrastructure work as well collaboratively through the *consensus mechanism* in which all users take part. It also ensures data integrity and consistency in a blockchain.

The *immutable* (tamper-proof) nature of the BT is an ideal feature to fulfill the requirement to prevent *censorship* of any kind. As we described in section 4.1, *cryptographic hashing*, a *consensus mechanism*, and *decentralization* in combination guarantee the *immutability* of a blockchain. Participants of a network can only append data but not modify stored data. This property suits to science that should not underlie any *censorship*. Everyone should be able to freely express his or her opinion without getting restricted in any way. In the use case of research, it also includes the publishing of scientific work that has critical



Blockchain Characteristics

Open Science Infrastructure Requirements	Decentralization	Cryptographic Hashing	Timestamping	Immutability (Append-Only)	Consensus Mechanism	Access and Governance System
Collaborative Environment	X				X	X
No censorship	X	X		X	X	
Open Data		X				X
Open Access		X				X
Identity and reputation management	X	X			X	X
Extensible system					X	
Incentives for collaboration and sharing	X				X	X
Equality of all participants	X				X	X
Simple workflow integration					X	
Data and content sharing	X	X			X	X
Crowdfunding		X			X	X
Trail of research (objects)	X	X	X	X	X	
Citizen Science	X	X	X			X
Open Source code and tools	X					X
Resource sharing	X				X	X
Metrics	X				X	X
Connected systems						X

FIGURE 2 | Matrix about open science infrastructure requirements and blockchain technology characteristics that are fulfilling them.

statements or topics. Overall, an open science infrastructure based on BT can provide such a censorship-free environment.

Considering data created in scientific work, we follow an approach that the data should be open for reuse with appropriate credit to the originator(s), but in reality, often a third party holds the rights for its usage (Dulong de Rosnay, 2006). A blockchain-based open science network with interfaces for data import/export can serve as a solution while the contributors themselves can decide every time to publish their files for sharing and reusing (*Open Data*). In such a case *cryptographic hashing* plays an important role, so the originator(s) can integrate a hash value that is formed from the content itself and also the names of the authors and other meta information before the data gets published; in that way, they create a digital footprint. It prevents that someone falsely claims and obtains credit for work that other people did (Dansinger, 2017). For additional security, it is always possible to check over a blockchain network the source and time of the creation of certain content (*trail of research*).

In addition to *Open Data*, an open science network shall represent an *Open Access* repository of knowledge which means in respect to the open principles that there should not be paywalls that hinder the people from acquiring knowledge for themselves and the scientific progress. A large spread of research works can also contribute to more citations and a better reputation for the authors. Paywalls are technically possible and implementable with BT, but considering the open principles and requirements we determined in section 3.2, we suggest not to integrate any to preserve a real public character. As with *Open Data*, of course, every participant and group must have the possibility to decide for themselves about the *accessibility* of their work; *hashing* can also be used here to create digital footprints.

To accurately reflect the reputation of researchers, an *identity and reputation system* is indispensable. It creates an incentive for network participants in the form of acknowledgment for their work. As a kind of database, a blockchain fits to function as an identity register to securely store pertinent user data. Each participant can upload content and contribute to the network. Therefore, a rating mechanism is mandatory to measure the quality and impact of stored data. Finally, the reputation of the participants is determinable. In detail, it shall enable all or only specific users to review and rate contributions, for example, papers and certain data like experiment results and micro-contributions to ascertain their value; Casati et al. already proposed an approach how crediting of micro-contributions may work (Casati et al., 2011). *Decentralization* and the *consensus mechanism* of a blockchain network ensure that no central authority controls the data and so reputations will be created naturally and independent through the network participants and their feedback.

Similar to ResearchGate[18] and other platforms, the identities and lists of contributions must be *accessible by everyone* to achieve an optimal recognition of the researchers and their work. These platforms can use such a blockchain-based open science infrastructure as a shared database to access and display identities and metrics. A search engine and filters can help to guide through the users and data to find possible collaboration partners and citable work in different research phases. Linking every account to a real person allows creating a research curriculum vitae that shows the chronological research history of an individual along with all positive (prizes, awards) but also negative (proved plagiarism) milestones. An interesting optional function would be anonymous publishing that allows researchers to work on controversial or critical data and topics without the fear of negative consequences like discrediting. The user name expanded by some random characters can get *hashed* to prevent any traceability and create a pseudonym for publishing.

Technical infrastructures need to be sustainable. A key factor here is to provide *extensible systems*. The possibility to expand a blockchain is equivalent to other systems; for example, APIs are enabling to link software with an ecosystem. So, it is possible to communicate with external software and platforms to exchange all kind of content but also to use web-services and functionalities from them. Thus, the range of application scenarios can be steadily expanded. An additional reason is the speed of how technologies are developing today, which makes it crucial to provide opportunities to easily extend existing systems to avoid the need for the time and cost-intensive creation of new software. The *consensus mechanism* of a blockchain also plays a role since the majority of authorized users must accept a system change so that it gets implemented.

Incentives for using a network are fundamental to motivate people to join and participate. BT can provide different factors to create incentives for an open science infrastructure. One of them is security created by blockchain-based proofs (for example, Proof-of-Existence) and the trail of research that are allowing to support intellectual property protection and to determine who contributed certain content (papers, results, and supporting data) to a network. Note, that timestamping services like, for example, OriginStamp (Gipp et al., 2015) do not protect intellectual property, rather only prove that some person possessed some information at a certain point in time. The protection only gets supported if research objects are timestamped immediately after creation and continuously as they change so that no one else can obtain the information beforehand. Additionally, the creation process can get traced by several timestamps.

Another *incentive* is decentralization that makes sure everyone has the current version of all data hence assists the dissemination of published work. People are expecting a kind of counter-value when they contribute knowledge what shall be satisfied through the access to published content of others. Another positive aspect is constructive feedback of the community for the provided material (scientific self-correction or open peer-reviews). The technology can further provide monetary incentive systems that use coins/tokens as a reward for contributions; a *consensus mechanism* can serve as technical implementation (more on this in sections 5.2, 5.3). So, on a technical level, BT offers the possibility to create new forms of reputation and incentives. However, they are worthless if not getting accepted by the respective target groups. The analysis presented in McKiernan et al. (2019) shows that a big part of universities and research institution rely on and trust in well-known metrics like the Journal Impact Factor (JIF) and use them in reviews, promotions,

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[18] https://www.researchgate.net/

and tenure documents. It is improbable that they will supplant well-established metrics by novel BT-based approaches in the near future.

A network can offer *equality of participation and governance model* decoupled from a central authority, which is aligned with the open principles. That, in turn, may result in a rise of an incentive to use an open science ecosystem. Basically, in such an infrastructure, all people shall have access to science and experience the same chances to gain knowledge and improve themselves. *Decentralization* and an appropriate *consensus mechanism* can technically make sure that the users do not get differentiated by country, race, wealth, level of education, or any other characteristics. If needed, the BT is also able to manage different user roles, for example, to form a committee that collaboratively decides how a blockchain develops as we mentioned in this section.

Besides the incentives that should motivate people to use a network, it also must be *simple to integrate* its capabilities and services *into existing workflows* and external software without serious effort or costs. If that is not the case, potential users will likely refuse the system upfront. We think it should be mainly a one-time effort. Proper documentation, a sophisticated network design, and an individual easy-to-use API are essential to ease the integration of subsystems. Also, the *consensus model* is a relevant factor since it partially defines how much resources of storage space and computing power are needed to participate in the network. In the end, the users shall still use their familiar software to manage their projects and data but with the possibility to benefit from the provided features of a blockchain-based open science infrastructure.

In terms of *sharing data and content*, a blockchain guarantees that there is no single point of failure due to its *decentralized* characteristic. So, there is no potential data loss, and the network ensures availability as long as the connection to it exists. For storing new data in a blockchain, a *consensus mechanism* should validate all incoming files to avoid, for example, dangerous software like viruses or redundant data; a blockchain itself gets already redundantly stored across all users. In the perspective of content management, all originators should have the opportunity to restrict access to their content for whatever reason. Then data gets stored encrypted in a blockchain, so it is not accessible until its owner makes it open to other users; off-chain storages like a traditional database or an IPFS are connectable and usable via APIs as well. In that case, a blockchain only stores the associated hashes of the contents. We also see potential in sharing specific software licenses via an open science network, for example, to optimally use multi-user licenses.

A growing economy is *crowdfunding* that gained much popularity through platforms like Kickstarter[19] and GoFundMe[20]. Such a crowd-driven method also contains the potential for science to raise money or resources to realize promising research projects (Swan, 2015a; De Filippi, 2016). BT can offer a *consensus* controlled monetary coin/token system to allow users supporting projects of their choice. Another option is the connection of external payment systems like PayPal to enable people to invest through traditional digital ways. Concerning identities, *hashed* pseudonyms offer the possibility for anonymous participations. As an extension, SCs can serve to manage crowdfunding projects, for example, to distribute funds in complex subprojects, to perform votes, or to execute automatic orders and other digital actions.

Another promising element that BT can provide in an open science infrastructure is the ability to create a *trail of research* that chronologically shows how research objects develop. *Timestamping* all contributions from scratch (idea, study design) up to the finished paper allows to transparently store all transactions with related *hashes* in a blockchain and hence to reconstruct the research process in order to improve the reproducibility (Benchoufi and Ravaud, 2017) in science and the acknowledgment of researchers. Contributors can get steadily and *immutably* linked to their data no matter if it is an idea, a new draft, or a finished paper. The tamper-proof property of the BT ensures that the trail cannot be changed subsequently. If uploaded data has to be changed, for example, because of mistakes or updated content, it is possible to add new versions while the old files can get marked or archived; realizable over the front-end (software or website surface) or potentially the *consensus model*.

Non-experts can also participate and provide valuable data in research (called *citizen science*), especially in larger data collections that are consisting of simple information. In a blockchain-based open science infrastructure, participants can use digital sensors for measuring all kinds of properties and benefit from the unique characteristics of the environment. The measurements are automatically getting stored in a blockchain, so *tampering* or *censoring* is not possible (Wortner et al., 2019). Sensors can produce storage-intensive data, in that case, a blockchain allows storing hashed data sets as identifiers that save a lot of space, and the associated measurements can get stored in a traditional database or an IPFS instead. Further, *timestamps* can complement and additionally validate time-related values like temperatures. Finally, the *decentralization* ensures that there is no central authority or system that users need to trust; data is always available (no single point of failure). The reuse of acquired results enables other researchers to make additional insights and to give feedback. So, they do not need to make another time-consuming/costly experiment to gather already existing information.

As an important requirement for an open science infrastructure, the *source code and tools should be open* and hence transparent for all users, so they can precisely understand what the algorithms and tools are doing. Openness provides trust, but also the advantage that all participants of a network can collaborate in its development and make or suggest ideas, plugins, and updates to steadily enhance the underlying ecosystem. That also involves prototypical software from researchers for their projects, so experienced programmers can help with feedback to achieve the best possible solutions. If users do not want to make their code or tools accessible, they must additionally have the possibility to encrypt them. The combination with a blockchain allows using its *decentralization*

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[19] https://www.kickstarter.com/

[20] https://de.gofundme.com/

and the *trail of research* to support the management and traceability of open source projects.

Besides citizen science and individual contributions in a blockchain-based open science network, people can also participate in research by *sharing* their *unused resources* like storage space or computing time of their systems (for example, computers/servers) for scientific purposes. The *decentralized* peer-to-peer architecture of a blockchain provides an optimal ground to efficiently allocate resources to share them (Vishnumurthy et al., 2003); a *consensus mechanism* can support the fair distribution. Developers may disseminate their algorithms in a corresponding network, so a multitude of systems (nodes) with different configurations tests them. Such a procedure suits to verify the stability of certain software and to prove that an algorithm delivers precise results. So, researchers are potentially able to run experiments that they could not do on their own, for example, because of a local lack of resources.

Metrics are an inherent part of science and can express, for example, the impact factor of researchers or publications and also show the rankings of conferences and journals (Van Noorden, 2010). They can further serve as a factor for funding bodies to decide to whom they give their resources like in application procedures for specific research topics. We see a blockchain as a great possibility to calculate accurate and reliable metrics for all scientific stakeholders by providing and sharing of a trustable open infrastructure. BT can achieve that through *decentralization* and the *consensus mechanism*, so every node in a network participates in the calculation and verification of the key figures. Essential for the qualitative determination of metrics is the complete data foundation. As an example, a personalized impact factor shall cover the full range of a scientist's contributions. However, BT can only help to calculate and validate metrics but does not answer the question of which figures are relevant and meaningful for an open science environment. The current research metrics are a very topical and much-discussed topic (Brembs, 2018; DORA, 2019).

The last requirement is about using *connected systems* that are not only beneficial for metrics. They are also useful to ease the exchange of all kind of data like experiment results, study designs, and papers. With particular APIs, it is even possible to automate the file distribution across system boundaries. For instance, if researchers store a file in their local storage, its dissemination could automatically take place in a connected infrastructure if desired. It behaves similarly with communication; users can send messages from one to another network. Such functionalities are supporting the integration of a blockchain-based infrastructure into external workflows and reducing the effort to work in two or more systems.

At the end of this section, we would also like to point out that the realization of a scientific platform is often made difficult or impossible by the lack of consistent funding. These are long-term projects that require detailed and well-considered preliminary planning and cause costs not only for development but also continuously for maintenance and expansion. Blockchain-based infrastructures also face this difficulty, but with the possibility of providing incentives such as cryptocurrencies that can create speculative value for investors. Thus, people outside the scientific environment get also addressed, but with this type of funding, called initial coin offering (ICO) (Conley, 2017; Li and Mann, 2018), science and business inevitably merge. Two examples with scientific background are EUREKA[21] and Scienceroot[22]. The further investigation of ICOs for this purpose should be considered in the future, when the hype about BT has flattened, in order to get a realistic picture.

Altogether, in this section, we answered our first research question and described how the characteristics of the BT can fulfill the requirements of an open science infrastructure and provide many advantages regarding replication of results, transparency of research processes, and also the traceability of research objects. The current technological state is already capable of the realization of such a platform. Nevertheless, a variety of general and technical questions in terms of a suitable consensus and governance system, incentive factors, law, and data storage still have to be answered in future research work; we explain some of these issues in more detail in section 6. Current literature and projects are focusing on different goals, a few of them describing specific use cases like resource sharing, publishing, and especially reproducibility. More are following visions of holistic science platforms that are offering different functionalities to support research. Therefore, we will analyze the state-of-the-art in the next section to answer our second research question and overview what literature and projects are already available or in development and what is the current state of the BT for open science.

5. STATE-OF-THE-ART

This section starts with a description of how we analyzed the current state of research and how we categorized relevant blockchain projects to clarify our approach (section 5.1). After that, we give an overview of available literature (section 5.2) and projects (section 5.3). Finally, we summarize and discuss the state-of-the-art (section 5.4).

5.1. Research Overview

To create an outline of the current research, we have read and analyzed research papers, concepts, and applications up to April 2019 that are connecting BT and open science or are relevant in other forms to this topic. Currently, there is not much pertinent literature, but the amount is growing, suggesting that this research subject is in an early phase. Since there is little literature, it would not make sense to structure it. It is different with practical blockchain projects, of which we finally examined 60 in detail: 18% in a concept, 52% in a prototype, and 30% in a deployed status. We assigned each project to one of the six categories shown in **Figure 3** to provide a structured overview of the current research situation. Some of the projects can also offer functionalities that are useful in other categories than their assigned one.

The category *Reproducibility* contains projects that aim to improve the replication rate in science and so the quality of research. *Resource sharing* focuses on functions to share unused resources, for example, storage space and computing

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[21] https://icoholder.com/en/eureka-26261

[22] https://icoholder.com/en/scienceroot-23156

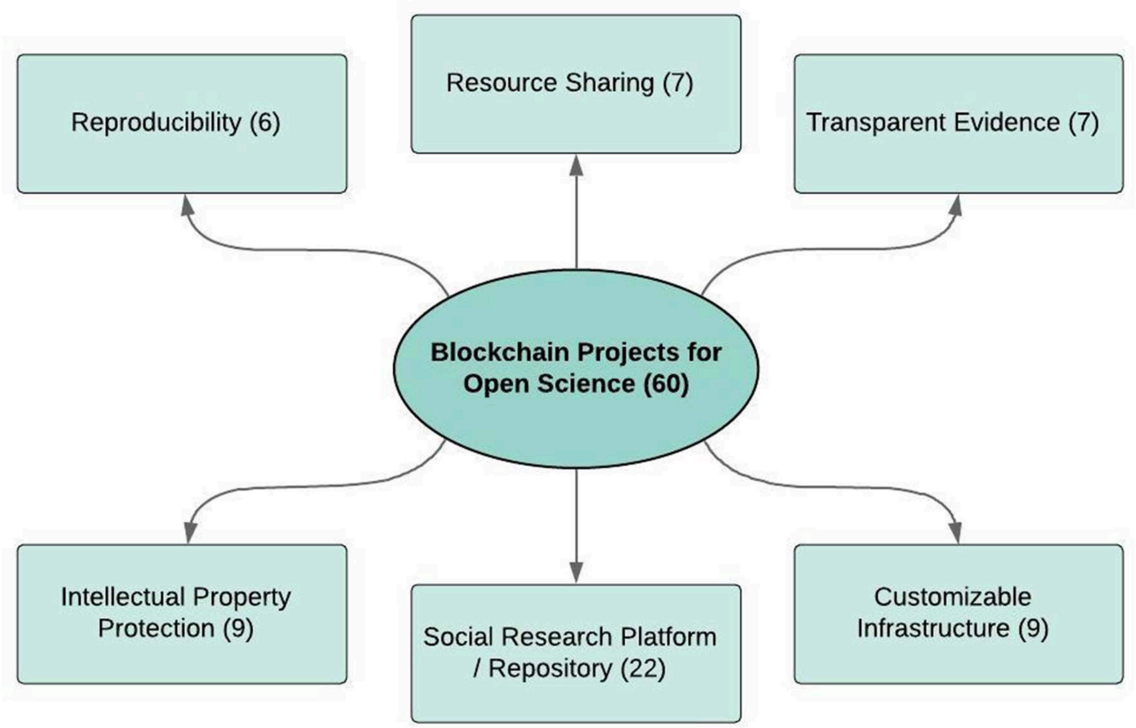

FIGURE 3 | Overview of categories of open science-related blockchain projects. The figures in brackets show the number of projects in the respective category.

power. The category *transparent evidence* mainly revolves around proof keeping like Proof-of-Existence to prove that information existed at a certain time and was in possession of a specific person or Proof-of-Submission of manuscripts to journals or conferences. Projects with the classification of *intellectual property protection* focus on the protection of ideas, contributions, data, and everything an individual submits to make sure to give appropriate credit to the originators. *Social Research Platforms/Repositories* feature a multitude of science-related functions like communication, data storage/processing, reputation, and identity mechanisms; most projects fell into this category. *Customizable infrastructures* allow building individual solutions on top of existing blockchains to prevent the effort and costs to develop a custom blockchain.

In total, we investigated 83 projects (see **Supplementary Material**) and excluded 23 of them because they provided insufficient information, were not mature enough to improve a scientific aspect, or were inactive/canceled. Most of the remaining projects have in common that they use BT to enhance different factors and elements of research, for example, trustability, workflows, transparency, reproducibility, and collaborations. The others offer specific mechanisms that are promising for improving processes in science. In order to show the current capabilities of the BT for open science, we will describe relevant literature (section 5.2) and different concepts, prototypes, and applications (section 5.3) in the next parts of this paper.

5.2. Literature

Since it is an early research phase, there is little literature about open science in combination with BT, but still, there are exciting and promising concepts, ideas, discussions, and approaches that we want to describe and highlight.

Dhillon wrote an article (Dhillon, 2016) and with others a book section (Dhillon et al., 2017) about BT and open science. They start the relevant chapter in their book with the current reproducibility crisis (Prinz et al., 2011; Collins and Tabak, 2014; Baker and Penny, 2016; Gilbert et al., 2016) and the rare publications of negative results (Matosin et al., 2014; Van Assen et al., 2014; Mlinarić et al., 2017). Dhillon et al. state that the BT has the potential to mitigate the crisis. They use a clinical trial as a practical example and define a workflow making the complete research process transparent while protecting critical data of patients (Dhillon et al., 2017). Also, other publications are proposing the use of BT in the medical or biological area to provide, among other aspects, transparency and trust (Nugent et al., 2016; Benchoufi and Ravaud, 2017; Ozercan et al., 2018). Further to the research process, Dhillon also proposes to apply their approach to implement a kind of reputation system (with an API) as a reward for researchers and an indicator for the quality of contributions (Dhillon et al., 2017).

Another use case highlighted by Dhillon et al. is blockchain-based prediction markets, where mainly experts try to predict a specific outcome like the potential of reproducibility of an experiment (Almenberg et al., 2009; Dreber et al., 2015; Dhillon et al., 2017). To create an incentive to participate, users get rewarded for the right prediction, for instance, by monetary coins/tokens of the related blockchain. An article by Extance (2017) contains similar statements saying that the BT can enhance the current replication situation in science, but he additionally mentions the potential of the technology for the peer-review process to build up trust due to immutability and transparency. But also, the article reiterates the statement made by Pagliari (Extance, 2017) who expresses concerns about storing possibly incorrect data in a blockchain that are then immutable. A patent about the usage of BT in open scientific research (Ahn et al., 2018) complies with the open principles and focuses on the integration of the technology into research workflows to allow such a tamper-proof sharing of information to improve the trustworthiness in science.

Bartling manages an open living document about the usage of the BT for open science that contains many promising ideas, projects, and hypothesis (Bartling, 2018). It is special because everyone contributes to the paper by feedback, visions, or suggestions, so a collaborative and constructive discussion can take place about its contents. The statements in the living document are consistent with those by Dhillon suggesting to use the BT for science to enhance reproducibility, collaborations, and trust, but they advance even a step further. Besides many blockchain projects, they also introduce novel ideas for funding research, incentive systems for all kind of scientific activities, and an open repository for data sharing (Bartling, 2018). For example, ICOs can be used to fund research projects (Conley, 2017; Li and Mann, 2018). Interested parties (also citizens) can take part in funding and get a consideration for it what could be a later service (like usage rights/licenses) or monetary coins/tokens of a newly generated blockchain.

Statements in the living document criticize the publication bias for positive results because negative outcomes may also be valuable and prevent the waste of time and money that researchers are using for experiments that already failed for others. In that sense, Chen et al. (2018) propose an architecture for blockchain-based provenance sharing of scientific workflows to provide a secure and easy way for scientists to share their research data, for instance, to prevent the waste of resources. Bartling also founded a company "BFS Blockchain for Science"[23] that aims to foster the usage of BT in science, among other things, by organizing conferences/workshops[24], supporting blockchain projects/startups and upcoming developers with relevant knowledge, and providing new ideas. Dhillon's and Bartling's suggestions match Rachovitsa's statements (Rachovitsa, 2018). She mentions the potential of the BT to implement novel incentive models and to improve the transparency of open data and open access systems while enabling researchers to manage their intellectual property through SCs.

van Rossum (2017, 2018) also identifies blockchain as a technology that can foster especially open science in many aspects hence corresponding to most of the statements by Dhillon, Bartling, and Rachovitsa. In addition, he highlights that BT can change the role of academic publishers in the future. He notes an increasing commercial interest in science, dominated by a few large publishers who established paywalls around research works to make a profit out of them (van Rossum, 2017). On top, focusing on current metrics can lead researchers to pursue the goal of high ranking rather than primarily doing good research. BT can help to mitigate such problems, but a significant factor that Van Rossum mentions is the adoption rate of the technology by the scientific community and its stakeholders. Acceptance will have a decisive role in the futures development of the technology for open science and other application areas. Another success factor he brings up is the existence of a common communication interface, so a trustworthy collaborative environment gets created.

The report (van Rossum, 2017) of Van Rossum contains two interviews as well; one with Efke Smit[25] and another one with Philipp Sandner[26]. Smit says that we already have a working academic world and puts into question why the scientific community should take the effort and costs of changing to a new system with BT. She summarizes that the technology, whether it is widely established or not, will be probably unnoticed anyway by non-geeks; the future will show if blockchains prove themselves as a game-changer or as a hype. Sandner sees the potential for using BT and SCs in science; as application examples, he mentions funding, publishing, scholarly communication, and incentive systems. Further literature and a web article by Bell et al. (2017), Brock (2018), and Opoku-Agyemang (2017) likewise describe the many possibilities of BT to improve science and all kind of research activities as statistical analyses, data evaluations, and medical trials.

Intellectual property is a regular output in science which can be very valuable and should be protected so others are not able to steal it and the originator can appropriately be credited. de La Rosa et al. (2017) analyzed how blockchain-based protection of intellectual property in open innovation processes can work; such an approach is also critical for scientific environments. The safeguarding has to start right at the first appearance of an idea (Schönhals et al., 2018) to provide a trustworthy system and to motivate researchers and other individuals for open collaborations. As a simple example, an idea that appears the first time can be timestamped and immutably stored in a blockchain to prove its existence at a certain time point; also, originators can add metadata like their names to these transactions.

Since most projects we found are social research platforms and repositories that allow their users to discuss ideas and hypothesis openly before they are processed, we see the protection of intellectual property as fundamental. de La Rosa et al. (2017) conclude that the BT can provide great benefits for open innovation processes and the protection of its outcomes; other researchers confirm this in their research papers (Gürkaynak et al., 2018; Rivière, 2018). But there is still much to do: it lacks approaches to prevent unauthorized reuse of intellectual property, and most existing blockchain applications are not

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[23] https://www.blockchainforscience.com/

[24] http://www.blockchainforsciencecon.com/

[25] https://www.rd-alliance.org/about/organization/key-profiles/eefke-smit.html

[26] https://www.frankfurt-school.de/en/home/research/staff/Philipp-Sandner

mature yet (Schönhals et al., 2019). A few more ideas about this topic can be found here[27,28].

Another core part of the scientific process is the peer-review of submitted research work. It is one of the most important activities because not only the acceptance of papers for conferences or journals and hence the progression of PhD students and researchers are depending on it, but also research grants and hiring are related to it. Therefore, reviews need to be neutral, trustworthy, and transparent without any bias to provide a fair chance for all participants in science. But there are some concerns about the fairness and quality of today's review system and the opportunities to abuse it (Smith, 2006; Tennant et al., 2017). Most of the time, peer-review is a black-box process, so reviewers are anonymous (authors mostly not), and malicious behavior is difficult to detect. Such lack of transparency can lead to a loss of trust. In that regard, several researchers see potential in the BT to improve and open up the peer-review process (Spearpoint, 2017; Tennant et al., 2017; Avital, 2018; Jan et al., 2018).

In a multi-disciplinary study of Tennant et al. (2017) about innovations in peer-review, they identified the BT as a potential future model with promising possibilities. Examples are incentive systems with coins or tokens that reward the reviewers for their efforts, and authentication/certification methods for fraud control and author protection. They conclude that the technology can enhance the quality and responsiveness of the review process. Both Avital (2018) and Spearpoint (2017), are independently underpinning these statements by proposing two different blockchain-based systems that use monetary incentives along with new metrics to address inefficiencies of the review process. Jan et al. (2018) are also sharing the opinion and utilized BT and SCs to develop a peer-review prototype.

Tenorio-Fornés et al. (2019) criticize the oligopolistic position of the publishers in academia regarding policies, embargo periods, and restrictions about the dissemination of data and propose a blockchain-based publication system for open science to address that. They say that the BT has the potential to realize the promise of open access with new models of data distribution. Another interesting idea comes from Hoffmann et al. (2018) who are naming their approach Smart Papers, which are SCs that are managing attributions and annotations of scholar publications. They aim to use the trustworthy environment of the BT to provide a framework for collaborative authoring and to implement a web client in future work.

Janowicz et al. (2018) wrote a paper about blockchain-based open science and publishing. They propose an informal model of how to use the BT to enhance and partly automate the general scientific workflow, particularly academic publishing, with the support of SCs. Besides their primary focus, they identified promising use cases of the technology in open science that we partially already mentioned in this section, for example, creating transparency of the peer-review process, storing and tracing all kind of scientific data to foster reproducibility, and connecting researchers to potential investors and vice versa. Moreover, managing intellectual property, democratizing of science for significant decisions in the community, and opening up black boxes like algorithms or closed data.

But Janowicz et al. (2018) also express concerns for the implementation of BT for open science. For instance, retractions are normal processes in science due to mistakes, updated papers, plagiarism, and other reasons but in case of a blockchain data is immutable once it is stored; a reasonable handling for such a use case has to be found. Another critical concern is the question of how and to what extent financial incentives may lead to unintended behavior since quite a few projects are using monetary aspects as motivation for their users. There is a chance that the focus of researchers could shift from actual research and knowledge creation to an economic mindset what should not be a major driver in science. Finally, Janowicz et al. (2018) criticize the high number of blockchain-based concepts that barely contain precise details to understand their exact workings and value proposition. We also found several projects in our analysis that did not provide enough information to understand their intentions or applications technically so that we can confirm this statement.

5.3. Projects

In the following sections, we describe use cases of the six categories we defined along with associated projects. We do not aim to present every single project in detail as it would be far beyond the scope of this paper; moreover, several of them are similar and follow more or less the same goals. Also, we include some approaches and applications that are not focused on science but contain specific interesting functions or mechanisms that are promising if transferred to blockchain-based research workflows. Our analysis includes projects that are at concept, prototype, or deployed status; some of them are commercial. Regarding references, we preferred research papers or whitepapers. If these were not available, we referred to the related website or GitHub repository.

5.3.1. Social Research Platform/Repository

We classified most of the projects that we analyzed as *social research platforms/repositories*. Especially in this category, the concepts and applications often provide many overlapping functionalities and have similar goals. Potential use cases are to create open platforms, repositories, or marketplaces to support collaborations in science and to allow open access to research data hence improving the reproducibility of experiments, studies, and other kinds of research. Typically, they contain much more capabilities like communication methods, reputation and identity mechanisms, and incentive systems for their users. Further, the traceability of the BT serves as protection of the contributors and creates a trustworthy and transparent environment. Two exemplary open science platform projects are Frankl (2018) and Aletheia (2018).

Some blockchain-based projects also aim to open up the publishing process and to provide incentive mechanisms for peer-reviewers in order to be more transparent, trustworthy, and rewarding; they function similar to an open access journal. Examples are Publish and Evaluate Online (PEvO) (Wolf et al., 2016), EUREKA (EUREKA, 2019), and the concept of

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[27] https://www.information-age.com/blockchain-role-future-ip-123473412/

[28] https://blog.dennemeyer.com/blockchain-disrupt-ip-protection

an academic endorsement system (AES) (Anonymous, 2016) that was published anonymously. The AES paper criticizes specific aspects of the scientific system. Their approach involves, among other features, the possibility for researchers to individually endorse the work of others with a currency of the network. Steemit (2019), as a non-scientific application supports such a mechanism along with a reputation system so users can independently reward other users for their content/contributions. There are also existing projects that, in addition to features for collaboration, research management, and publishing, also provide funding methods for research, for example, Scienceroot (Günther and Chirita, 2018), the Open Science Network (OSN) (OSN, 2019), the Decentralized Research Platform (DEIP) (DEIP, 2018), and Orvium (Orvium, 2018).

In order to gain more trust and transparency in their fund granting for research, The National Research Council of Canada created a blockchain-based prototype that is named NRC-IRAD (NRC-IRAP, 2019) to proactively publish grants and contribution data in real-time. We think this approach also has great potential for other countries. It works as a public blackboard for researchers and their groups or organizations who can apply for certain government-funded research topics. Making research data workflows FAIR (findable, accessible, interoperable, and reusable/reproducible) with using a decentralized data infrastructure is the goal of DaMaHub (Data Management Hub) (DaMaHub, 2019). Their first implementations combine BT to transparently record and track all system transactions and IPFS for data searching and storage. In case of content dissemination, LBRY (not science-related) (LBRY, 2019) has an interesting approach as a community-operated digital marketplace in which content owners can set individual fees for their contents without any dependence on intermediaries; similar to WildSpark (Tabrizi and Konforty, 2017). Such a method transferred to science may allow researchers to publish, distribute, and potentially monetize their work individually. The system could also be expanded with a peer-review process to create a blockchain-based journal.

Matryx (McCloskey et al., 2019) follows a novel approach and aims to incentivize the collaboration in science to foster the creation of innovative ideas and projects. Besides providing a marketplace for buying and selling digital assets, it also uses a blockchain-based tournament system in which, for example, a user can create an individual challenge with a particular bounty that gets paid off as a reward to the user who solves the problem. An exceptional topic is focused by Space Decentral (2018) that is a DAO whose aim it is to let the network's community in control for deciding how the science space programs on the platform will continue; functions as crowdfunding, sharing of research data, and peer-reviewing are integrated.

ScientificCoin (2018) is a crowdfunding platform that attempts to determine the potential/risk of scientific projects by several different factors in a mathematical algorithm and expert evaluation. Target groups are researchers that are searching for funds and investors. But it also opens up a way of receiving valuable feedback on research projects, which can help to identify and improve planning or methodical shortcomings. Another extraordinary blockchain-based network is Coegil (2019), which connects decision-makers with the expertise of many people (participants of the network) to eventually being able to make decisions of high quality. Transferred to science, we see the possibility in such a kind of system to get valuable feedback for research works by experts; especially young PhD students can benefit by that in preparation of their first publications.

The project bloxberg (Vengadasalam et al., 2019) provides a blockchain network that consists of several research organizations that form a consortium and administrating the ecosystem. They aim to foster, among other things, sharing of data, collaboration, peer-reviewing, handling of research claims, and publishing with the help of a secure global environment. The bloxberg system also allows using it as a base structure to develop new applications on it. ARTiFACTS (Kochalko et al., 2018) uses this infrastructure to build a research platform that provides indexing functionalities and a dashboard that displays multiple statistics on the stored content of a researcher. So, it is capable of creating a transparent data trail for research objects and determining several scientific metrics; the developers also plan to extend their system with a blockchain-based digital identity network.

A further blockchain infrastructure that focuses especially on the validation of data integrity in biomedical studies is TrialChain (Dai et al., 2018). This idea is also interesting for other scientific areas because data integrity plays a central role in all kinds of studies/experiments. One more noteworthy and ambitious approach is Project Aiur (Project Aiur, 2018), which envisions building an open platform for validated knowledge without access barriers, publication bias, and information overload while all research is reproducible. To achieve their vision, they aim to combine a repository and a community-governed artificial intelligence that is capable of automating knowledge validation.

5.3.2. Reproducibility

Blockchain projects with a focus on *reproducibility* in science or the potential of improving the replication rate are subject in this category. Furlanello et al. (2017) proposed their PROBO-network, which is an approach to enhance scientific reproducibility with BT. In general, they want to solve the issue of rewarding time and expertise of scientists that are replicating research results by establishing a monetary-based incentive for them. To achieve that a researcher (proponent) publishes, for instance, a timestamped study with all supporting data in the PROBOS-blockchain and deposits a pre-determined amount of probos tokens to broadcast a request to the network, where clients (verifiers) can evaluate the quality of the study and verify its reproducibility; verifiers getting rewarded by the deposited tokens of the proponent (Furlanello et al., 2017). Especially in the medical sector reproduction of results is vital, for example, to produce reliable drugs for living test subjects and the global market but also to build upon promising and robust basics to prevent resource wasting with irreproducible research.

Forecasting and prediction markets like Gnosis (2017), Hivemind (2019), and Peterson et al. (2018) are another kind of promising blockchain-based projects. These markets involve people with expertise who predict or confirm specific outcomes based on existing information, representing a concept of collective intelligence. Such systems are usable in many application fields, for instance, in science to support reproducibility. Among other things, its participants can forecast or confirm the replication probability of experiment results. That procedure is suitable to obtain information in a short time to optimally allocate limited resources into reproduction projects (Dreber et al., 2015). The incentive for the users of these platforms usually is of a monetary nature because they get a pre-deposited coin/token reward for correct predictions and confirmations from the creators of requests.

The next blockchain-based project that we want to mention because of its unique approach is Dsensor (2015) even though it seems stopped or canceled. There was no actual news for over a year, and the announced whitepaper is overdue for 2 years, so we assume the project got aborted. It aimed to provide a computational consensus that uses relevant sensor data to determine whether a networks hypothesis is correct or not. So, if a result is measurable and the data access to necessary sensors exists, such a system would be capable of performing an automatic validation/reproduction of a specific outcome and at the same time recording it on a blockchain for securing data integrity.

5.3.3. Transparent Evidence

This category contains projects that intend to create *immutable proofs* on a blockchain to verify different aspects like the existence of particular information, submission of documents, or time of actions. These digital certifications allow, for example, to support legal procedures and to provide the required security/trust for open technical infrastructures. One project is OriginStamp (Gipp et al., 2015) that offers Proofs-of-Existence in the form of timestamps on the Bitcoin blockchain. So, a person can obtain evidence for being in possession of specific information at a certain time, for instance, documents, results, ideas, and all other kinds of digital assets. Further, CryptSubmit (Gipp et al., 2017) uses OriginStamp as a basis to combine the timestamp functionality with a scientific manuscript management system for journals and conferences. Thus, it creates a Proof-of-Submission that serves as evidence about submission and integrity of data to prevent fraud and theft of research (Cantrill, 2016; Degen, 2016; Dansinger, 2017). CryptSubmit also supports timestamped peer-reviews to enhance trust in the whole review process and can additionally serve as a basis for open peer-reviewing.

Online discussion and sharing platforms can also use BT to record all platform activities to secure the trustworthiness of messages and data. So, the first appearance of an idea or a micro-contribution gets registered and then is traceable to its originator. VirtualPatent (Breitinger and Gipp, 2017) is a project that proposes such an approach. It aims to function as a social media platform that immediately timestamps every message in the system to allow open discussions about, for example, novel ideas and drafts. PUBLISHsoft (2018) has a similar but commercialized concept and a different target group as it intends to notarize and trace journalistic news; the mechanism is transferable to research data likewise.

An approach that is focusing primarily on the peer-review process in science is Blockchain for Peer Review (BfPR, 2019) that aims to make the procedure more trustable. They envision to extract peer-review data from connected journal management systems to record them in a blockchain hence allowing the reviews to be independently validated. In the following, we describe two non-science related projects with noteworthy functionalities. The first project is Codex (Codex, 2018) that offers its users the possibility to register digital assets. Their platform got designed for art and collectibles (for example, wine and jewelry) where no centralized title registration exists. We see the potential to use such a decentralized register for scientific publications or datasets to prove their existence and affiliation. The second project is Sovrin (Sovrin Foundation, 2018), which is a blockchain-based identity management network. It provides, transferred to research, the technical opportunity to transparently link every contribution to the identities of its originators and therefore to create a scientific curriculum vitae.

5.3.4. Intellectual Property Protection

Since *intellectual property* is a typical output in research, it is important to *protect* it and the originators adequately, in special when knowledge gets patented and monetized. The projects in this category are focusing on notarization, licensing, and certifications of digital assets. These systems are usable in many application fields, but one of the most substantial is science. An already deployed and commercialized application is Bernstein (Barulli et al., 2017) that aims to be a notarization service powered by BT. Its underlying system can issue ownership certifications of digital assets that get stored in a hashed form on the Bitcoin blockchain; examples are licenses, research papers, and non-disclosure agreements (NDAs). Another blockchain-based project that is additionally providing the ability to create marketplaces to monetize an idea, patent, or different kinds of intellectual property is po.et (po.et, 2017). The Molecule Protocol (Molecule, 2019) is combining open science and BT to build a collaborative market-based platform for discovery and funding of pharmaceutical intellectual property. They intend to connect scientists, patients, and industry to advance drug development in its transparent, secure environment.

A concept named Coalition of Automated Legal Applications Intellectual Property (COALA IP) (De Filippi et al., 2016) aims to be a free community-driven protocol for establishing an open global standard in intellectual property licensing to form a consistent framework and to eliminate the dependence on central organizations. Also interesting for researchers and their contributions is Vaultitude (Vaultitude, 2018) which is a large-scale project whose team is cooperating with international authorities and law firms to establish a blockchain supported Proof of Authorship for the digital assets of their users. The projects Bookchain (Scenarex, 2019), Attribution Ledger (Prescient, 2019), and ChainPrint (ChainPrint, 2017) are concentrating on protecting and publishing intellectual property, mainly documents, books, and creative works. So, their target groups are authors, publishers, and partially printing houses, but also researchers may use such services if they want to disseminate papers, studies, or other writings. In all three cases, the uploaded data gets recorded via blockchain to create an immutable trail of information to provide trust and security before and after the publication process.

5.3.5. Resource Sharing

Resources are limited; researchers are peculiarly aware of that when some experiments are not feasible due to a local lack of materials, workforce, equipment, or funds. In this regard, a blockchain can serve as a distributor to *share digital resources* like storage space. Specific projects for sharing storage space, for example, to save all kind of research data securely in a blockchain environment, are Storj (Tardigrade) (Storj Labs, 2018), Filecoin (Protocol Labs, 2017), Sia (Vorick and Champine, 2014), SAFE network (MaidSafe, 2019), and Swarm (Swarm, 2019) in which all individuals can participate by providing unused capacities of their computer systems. Despite that network users are storing the information of data owners, they cannot access/read them, only the owners can do that; the projects use different methods for this, among other things, encryption and file splitting. Information in the form of data is also a valuable resource that is digitally shareable. The Ocean Protocol (Ocean Protocol, 2019) pursues such an approach and helps marketplaces to buy and sell mainly artificial intelligence data/services while incentivizing data reusing and sharing with a blockchain-based incentive system. This data can get used as learning material for artificial intelligences, but also can support researchers in their projects.

Besides sharing storage space and data, there are also approaches to share computing power in a blockchain network. We think a method of that kind is promising to enable, for instance, researchers to execute specific demanding computing tasks such as complex simulations. A project that aims to provide exactly this functionality hence to operate like a distributed "supercomputer" is Golem (Golem, 2016). Their approach works with various nodes (providers) which are offering their unused computing power as a resource in exchange for monetary tokens. In general, other network participants (requestors) can use that provided performance to calculate, for example, algorithms, photogrammetry reconstructions, renderings of movies/CGI, and machine learning applications in an associated sandbox environment. The Golem network supports the distribution and monetization of software as well.

5.3.6. Customizable Infrastructure

Customizable infrastructures are serving as a fundament on which developers can build their designed blockchain-based networks. In contrast to custom-built blockchains, the source code gets already provided, and less know-how is needed for their realization. So, this approach saves time and funds, but it is limited in its possibilities because the underlying systems usually prescribe certain aspects like the consensus model and the basic structure of the network. Most of the projects in this category are focusing on private permissioned blockchains that have mainly companies as their target group, but still, universities and research groups can benefit from these infrastructures. Exemplary science and academic-related use cases are data tracking and auditing, education/training of students, project management, distribution of digital assets, timestamping, and the issuance of certifications. Further, it is possible to use customizable infrastructures to partly build similar applications like the projects we mentioned in the sections 5.3.1–5.3.5 but with the advantage that they can get adapted to specific demands. Also, completely new solutions are realizable.

In every case, the requirements of a project need to get evaluated to decide whether the possibilities of a provided customizable infrastructure are sufficient to fulfill them or a custom blockchain application is necessary. If the estimated quality is satisfying, there is no necessity to incur the additional effort for a new development. We found several projects that aim to provide such an infrastructural framework to build blockchains or blockchain-based applications, for example, Hyperledger (Androulaki et al., 2018) from IBM, Openchain (Openchain, 2015), Multichain (Greenspan, 2015), Blockstack (Ali et al., 2019), and DCore (DECENT, 2019). In summary, we see customizable infrastructures as a perfect introduction to the BT to test its potential and suitability for diverse application scenarios and to gather the first experience in their development.

5.4. Summary and Discussion

Our review shall serve as a snapshot of the current research situation of the BT for open science with an additional view outside the box to other applications that offer useful functionalities for that scope. During the last 7 months in that we collected and analyzed practical projects, we noticed that the market is unstable. A few of them disappeared, got canceled with official statements of their developers, or are subjectively dead based on long-time inactivity. In total, more new approaches were announced in these months, so the trend we identified shows a steadily increasing number of active blockchain projects for open science. That development is also retroactively observable over the past few years.

For section 5, we diligently analyzed 35 relevant research publications (gray literature excluded) and overall 60 blockchain-based projects (see **Supplementary Material**) with different application areas and classified them into six categories to structure them corresponding to their orientation. Considering the acquired knowledge, we agree that the BT has a great potential to foster open science in various aspects. Examples are a new level of trust into systems and their transparency, traceability of digital assets, higher reproducibility, innovative citizen science projects, creative incentive methods, and a generally improved research quality. Especially the realizable openness of blockchain applications and the tamper-proof recording of all transactions in a system make this technology to a suitable trustless infrastructure for open science.

In the end, a blockchain alone represents a database with a unique bulk of characteristics but without a specific sense. An integrated application like Bitcoin or Ethereum gives a purpose and functionality to it. So, we differentiate between the blockchain and application layer (includes the front-end), which need to correspond with each other to use the technology as an advantage. Therefore, in open science projects, both layers should get designed in harmony following the open principles to provide a cornerstone for a transparent and trustable environment; the prevention of non-transparency and possibilities for malicious behavior is fundamental.

If a researcher integrates BT continuously within the whole research cycle, it can be useful in every phase, also partially for experimenting if it comes to tests of algorithms or evaluation of sensorial data. As shown, there are many varieties of using the technology in science to achieve a win-win situation for all stakeholders. In combination with sophisticated application design and development, it is also able to enable new usage models regarding research management, peer-reviewing, funding, and publishing. However, the expectations must be realistic; BT is not a cure for all existing problems in science or an all-in-one solution.

During our analysis, some questions and concerns arose in terms of various projects and other aspects that should get examined in future works. Below, we will briefly describe these uncertainties; more details to the most relevant topics will follow in section 6 to answer our third research question. Many projects are introducing own incentive methods that are often of monetary nature; examples are bounty systems or coin/token rewards for specific actions. On one side, we question if it is a suitable approach to integrate such financial aspects in the research process. Would that shift the intention to create knowledge and progress in science to an economic focus? On the other side, we agree to establish new incentives for the invested time and expertise of scientists who are reproducing and confirming results/studies and peer-reviewing submitted research work for conferences and journals. Further concerns are about how to deal with bugs in already deployed hence immutable SCs, and how different nations are assessing proofs issued from a blockchain in their juristic processes.

The literature and projects also showed that a standard is missing that sets a framework for how blockchains can communicate with external software through APIs, and how data is exchanged to ease the development and integration of the BT into existing workflows. The current situation makes it difficult to identify serious blockchain-based applications. The enthusiasm around this technology led to many new project announcements in the last few years, but in the area of open science, most are in concept or prototype status as our analysis showed hence are not suitable for full integration. To prevent the waste of resources, we advise making sure only to actively use blockchain applications that are at a mature state and already providing the desired functionalities. Due to the unstable market, projects can disappear from 1 day to another, specifically because most of the time, startups are developing them that usually do not have a financial buffer.

A couple of the analyzed projects aim to make intermediaries in science obsolete. These would primarily be publishers. However, the publishers can also use the BT for their good. It provides the potential for them to partially automate distribution and peer-review processes via SCs, and to decrease their costs to manage the steadily increasing amount of knowledge and number of publications. As a synergy effect, these aspects can also be positive for researchers, for instance, through fewer publication fees and faster feedbacks. Further, publishers can open up their operations to transparently show how peer-reviewing and other activities function in order to improve their trustworthiness.

Funding bodies as one stakeholder group in science are using, among various factors, metrics for their decisions on how to distribute their financial resources to researchers and their projects. The problem is that indicators of the same researchers and publications are often differing from one research platform to another due to the circumstance that they use different databases to calculate their key figures. We think the basic technical structure of a blockchain is an excellent opportunity to create a shared, transparent storage. So, it can provide the same data for every science platform to calculate precise metrics like the impact factor of a researcher or a publication.

We also think, as mentioned in some literature, that the adoption rate of the BT will decide about its future development both in science and in all other application fields. So, the number of users is a key factor; a network without participants does not make sense. Most of the projects we analyzed had, from a subjective point of view, a non-existent or small community, so we opine that the technology needs a push explicitly for its usage in open science; maybe a big publisher, stakeholder, or a norm? Overall, it is still a fairly new technology, so it is not yet possible to say for sure how the masses will interact with it and what behavior will emerge.

In this section, we answered our second research question and gave a picture about the current research state of BT for open science along with its possibilities and uncertainties that we identified during our review.

6. CHALLENGES AND RESEARCH POTENTIALS

In this section, we describe in the context of our third research question challenges and research potentials that we identified during our analysis. Future works should address them in order to eliminate technological and legal insecurities and to enhance the usability of the BT for open science and beyond. We focused on some of the most relevant and promising topics in our view, which got not or insufficiently investigated yet. They shall provide an impulse in the form of starting points for further research; as a positive side effect, addressing these issues can partially also foster other non-scientific areas.

We want to point out that the challenges presented in this section are very complex and profound, so we do not expect them to get resolved in the near future. For example, the correctness problem of software which is fundamental to smart contracts (see section 6.1) is around since the early days of programming, and till today a solution is not yet in sight. Therefore, the following topics are an outlook into vital pillars that need to be considered in the course of a broad integration of BT.

6.1. Risks and Validation of Smart Contracts

Trustworthiness is a key element of BT and one of its main drivers, so developers should design all aspects in their applications in a way to support and provide that property. In this regard, we see SCs that get used in many projects as critical because they can offer various possibilities for malicious behavior and are prone to crucial coding errors in their development. The ability to use Turing-complete programming languages opens up not only numerous use cases and functionalities but also increases the complexity and thus the potential for human mistakes and the number of backdoors/exploits. These can cause, for example, crashes of the processes or vulnerabilities of the program itself that may allow hackers to steal the resources that a digital contract manages (Bigi et al., 2015; Atzei et al., 2017). The novelty of SCs justifies the circumstance that the common knowledge about their design, implementation, programming, and validation is not well developed yet.

One approach to counteract vulnerabilities of SCs is to limit the expressiveness of the underlying programming language (Dannen, 2017). Another possibility is the several commercial providers of audit services that have got founded in the last years. They are checking SCs to make sure they fulfill their purpose without eventual weak points. Examples are Runtime Verification[29] and Securify[30]. In that sense, we see research potential in investigating ways to automate the formal verification of SCs through software to quickly eliminate the possibility of specific attacks (Bigi et al., 2015; Luu et al., 2016). A further approach can be a modular construction kit to be able to build digital contracts piece by piece for reliable, simple applications. Hence no great coding skills are required, and the creation process gets eased, similar to OpenZeppelin[31]. Also, standards can generally improve the design procedure and security. There is still much to do on this topic to enable an efficient and secure large-scale use of SCs for all application areas.

6.2. Missing Standardization and Frameworks

Established standards and frameworks for technologies can be vital and bring several advantages with them like time-saving, error prevention, and increased security. Through our analysis, we have concluded that these are largely absent in BT. So far, blockchain developers have taken a pioneering role and mostly programmed their applications in different languages without technical specifications. Thus, many unique application structures emerged that have their advantages and disadvantages as well as security risks and vulnerabilities. Standards for BT can help to foster its adoption, interoperability, make systems more secure, in particular, build trust (Deshpande et al., 2017). Also, they enhance the accessibility into the general development of blockchain applications. In terms of software communication, standardized APIs can make the design of new interfaces redundant in most cases.

There is still a lot of potential in researching suitable standards and frameworks for the BT, for example, to ease the design and development of blockchain-based software, or to integrate a blockchain into research workflows. Also interesting are unified methods of how academic publishers can use this technology to improve certain of their processes and benefit from it. In our opinion, infrastructural frameworks like Hyperledger will play an even more prominent role in the future in creating a variety of new applications. One general goal of standards and frameworks must be to facilitate the entry into blockchains in order to address non-experts and break down access barriers. Altogether, both topics offer a lot of promising research possibilities, and we think they will be a cornerstone of the BT in the future.

6.3. Incentive Systems for Science

We noticed that several of the blockchain projects in our evaluation are using diverse monetary incentive systems that function through the issuance of digital coins/tokens for research contributions or specific actions like peer-reviewing. We question these incentive methods due to the current instability and speculative nature of cryptocurrencies. The worth of blockchain issued coins/tokens can vary significantly in a short period; there is also a chance of a total loss. Market development of cryptocurrencies is reviewable on Coinmarketcap. Moreover, it is not clear from where the funds are to come. Some projects propose the researchers themselves as funding bodies, but it is questionable whether they will independently reward others for their scientific contributions. Also, such a monetary incentive depends substantially on the amount of funds. Further, we see the chance that financial inducements can shift the focus of scholars from qualitative knowledge creation to a quantitative performance mentality in which they aim to achieve publications as fast as possible to profit economically.

We think there is plenty of research potential in analyzing blockchain-based incentive systems that are reliable and sustainable on the one hand and motivating for scientists on the other. In our view, exciting research questions are how to influence creative performance positively by extrinsic work stimuli, and whether BT can contribute something meaningful to that goal. A further approach is to evaluate existing incentive systems for their improvability with that technology. Currently, incentives in science mainly revolve around metrics such as the number of citations, the impact factor, and the resulting reputation. Another possibility for research is to work on inducements for the increasing quantity of micro-contributions that should also be appropriately getting acknowledged. Overall, there are several starting points worth to investigate to use the technologies' potential regarding the creation of new and enhancing of existing incentive systems for science.

6.4. Scientific Metrics

The primary information sources of scientific metrics are research platforms, for instance, ResearchGate, Mendeley[32], Altmetric[33], Web of Science[34], and Google Scholar. Each of them uses its own database, which consists mainly of research profiles, publications, and their references to other research work. One exemplary metric is the number of citations that is, among other things, an element to calculate the impact factor of research papers and researchers. In that regard we compared, as short examples, the overall quantity of citations of two researchers (Jöran Beel from the Trinity College Dublin in Ireland and Melanie Swan from the Purdue University

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[29] https://runtimeverification.com/smartcontract/

[30] https://securify.chainsecurity.com/

[31] https://openzeppelin.org/

[32] https://www.mendeley.com

[33] https://www.altmetric.com/

[34] http://wokinfo.com/

in Indiana, United States) and of the Bitcoin Whitepaper between ResearchGate and Google Scholar - date: 20th July 2019 (see **Table 2**).

The comparison showed significant discrepancies, and we noticed that they are even bigger with other platforms. Scientific metrics can, for instance, serve as a factor that funding bodies use for their decisions. As exemplarily demonstrated, a problem of this decision-making method is the crucial deviation of the indicators from one to another research platform triggered by utilization of different calculation formulas and a separated database per system. In concrete terms, the decision of a funding body to support a specific researcher or group can turn out differently depending on the examined network because of the non-identical values of the metrics. We think BT is a suitable possibility to noticeably improve the informative value and reliability of the scientific key figure system.

A blockchain as a shared database can provide the same data source to calculate normed metrics, so all research platforms expel identical values. Open questions are, for example, how to handle retractions in an immutable environment or who fills the infrastructure with information and manages it. However, such a working system as a fundament also opens the doors for potential novel metrics of which we think can also get usefully connected to incentive methods for researchers. Altogether, the research possibilities of the BT for scientific key figures are great because, in particular, its characteristics are suitable to build a shared database and beyond that to enhance metrics or to create new ones.

TABLE 2 | Exemplary comparison of citation metric on two different scientific platforms.

Researcher/ Research Object	Citations-Research Gate	Citations-Google Scholar	Deviation
Jöran Beel	1,482	2,344	≈37%
Melanie Swan	2,138	5,401	≈60%
Bitcoin Whitepaper	5,631	6,598	≈15%

6.5. Legal Uncertainties

Some research has already been done on blockchain-based cryptocurrencies (Ponsford, 2015; Gikay, 2018), SCs, and DAOs (Savelyev, 2017; Dell'Erba, 2018) in connection with legal issues and topics, but there is still a lot of demand for further work and clarification (Werbach, 2018). Several blockchain projects we analyzed are relying, for instance, on timestamps to prove different aspects like the existence of specific information at a certain time or want to issue certificates to verify the ownership of digital assets. A concrete example is the timestamping of a dashcam recorded video (Gipp et al., 2016) that shows a car accident to confirm the moment of the crash and the authenticity of the video along with other details that can be important for the decision of a legal process. The question is, what is the legal status and acceptance when such blockchain-based evidence gets used in a lawsuit? In the case of that uncertainty, we see it as problematic that a few analyzed projects work with promises which are not juridically secured.

Further, SCs are also legally unspecified. For example, what happens if resources managed by them are no longer tangible or lost due to incorrect programming; which party is to blame and how does compensation work? SCs or DAOs can barely cover all possible real-world case constellations within their program code. In this respect, is there a technical or non-technical way to deal with unforeseen events? More questions are how juristic systems should treat SCs compared to traditional ones, and what possibilities exist to secure the contracting parties (Savelyev, 2017)? A general challenge is the different laws and courts in every country or state (Dell'Erba, 2018), which mean that a solution that functions in a particular location is unlikely to work in all other places. So, most likely, there will not be a global consensus, but countrywide specifications would eliminate many legal uncertainties. With the increasing importance of BT and its growing adoption, we believe that juridical topics are playing a major role in the future and should be addressed to support further developments.

7. CONCLUSIONS

This paper contains an analysis about how the BT can foster open science, a review of the state-of-the-art, and an evaluation of relevant research potentials and challenges for that subject. We identified the requirements for an open scientific ecosystem and compared them with the properties of BT to verify whether they fit together. In that way, we answered our first research question and determined the technology as a reliable and appropriate infrastructure for open science. Nevertheless, we regard BT as just one building block among others and we believe that the ideas behind open science can only be implemented if all pieces are put together in a meaningful way and complement each other. Concerning our second research question, we collected and reviewed topic related literature and blockchain projects to describe the current situation. We illustrated the possibilities of the technology by many practical examples to show its capabilities for scientific workflows. Some of the analyzed projects already offer functionalities that can optimize research processes, but most of them need additional development time to implement their aimed features. For our third research question, we identified several existing challenges and research potentials. With this, we intend to draw attention to various promising and essential research topics that should get addressed to support the further development of the BT for open science.

The combination of well-known characteristics like hashing, decentralization, and immutability makes the BT unique and explains the increasing interest of science and industry in it. Due to the limited literature, open questions, and the number of projects in concept or prototype status, we noticed that the usage of blockchains in the perspective of open science is in an early development phase. Nevertheless, the technology can already make valuable contributions to that area, for example, by improving current workflows of researchers, establishing trust in technical systems and enabling new collaborations as well as mitigating existing problems. One of them is the reproducibility crisis in which BT is not a standalone solution, but in our view, a supportive part of it. But many projects need more time to mature for being beneficial. However, there is still much to do in terms of standardization, governance models, beginner-friendliness, interfaces, security and legal issues, and educational work to fully exhaust the potential of the technology.

So long as the adoption of the BT grows, we expect it to get more mature continuously. In this regard, the addressing of the identified challenges will play a vital role in the future. The current situation is comparable to a greenfield in which no specific constraints exist, and researchers have many opportunities to implement new innovative blockchain-based systems and application scenarios. Altogether, after our review, we summarize that the capabilities of the BT for open science are by far not exhausted yet. We conclude that the technology can have a significant positive impact on scientific work and its open ecosystems but that primarily depends on the technology's acceptance of the scientific community and all other associated stakeholders, which is currently unpredictable.

AUTHOR CONTRIBUTIONS

SL has elaborated the entire content of the document, carried out the analysis, and contributed ideas to the topic. The writing of the manuscript was mainly done by SL supported by SS. MS and BG provided critical feedback and helped with the finalization.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbloc.2019.00016/full#supplementary-material

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