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Technology-enabled financing of sustainable infrastructure: A case for blockchains and decentralized oracle networks

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A R T I C L E I N F O

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A B S T R A C T

The capital required to maintain infrastructure in good repair falls short globally. This is commonly referred to as the "infrastructure finance gap". To address climate change, transitioning from conventional to sustainable infrastructure further imposes financing challenges. This study employs the Model approach to justify and predict how blockchain technologies can leverage infrastructure data to close the finance gap by introducing new financing mechanisms. A semisystematic literature review was carried out for infrastructure finance, sustainable infrastructure and smart cities finance mechanisms, as well as blockchains and oracles. Conventional infrastructure finance via debt and equity lacks benchmarks that reflect the risk-return characteristics of the asset class. Performance-based financing addresses this issue by integrating performance data in valuations. However, a lack of trust in data veracity remains. Blockchains provide trust and transparency in data and transactions. They utilize oracles to access off-chain information for on-chain decision-making. With smart contracts and decentralized oracle networks, a general approach is presented where data from internet-of-things inform on-chain transactions, delivering performance benchmarks that accurately reflect the risk-return characteristics in an infrastructure investment. Capital can then be more readily deployed, thus closing the finance gap. An end-to-end example of financing sustainable stormwater infrastructure, Open Storm, is also presented.

1. Introduction

Infrastructure comprises the physical and institutional assets that sustain a society's essential services, economic growth, and its members' well-being (Thacker et al., 2019). In its most recent report, the American Society of Civil Engineers (ASCE) gave the United States infrastructure a C- rating, stating that it "…shows general signs of deterioration and requires attention. Some elements exhibit significant deficiencies in conditions and functionality, with increasing vulnerability to risk" (American Society of Civil Engineers, 2021, page 3). For United States infrastructure to achieve a state of good repair by 2029, the costs is estimated at $5.9 trillion USD, where about 44 % is yet to be covered (American Society of Civil Engineers, 2021). This translates to an annual deficit of $259 billion USD from 2020 to 2029. It should be noted that the added cost in infrastructure to adjust for climate change was not included in the American Society of Civil Engineers' assessment, and has been argued to add 4 % to 25 % of future capital needs (Hallegatte et al., 2019). The deficit between infrastructure needs and actual investments is commonly known as the infrastructure finance gap (Hillman and Tippett, 2021). This capital shortfall is also observed globally. The World Economic Forum estimated that the annual deficit in infrastructure investments would be $5 trillion USD (Boehm et al., 2021). In addition, the Global Infrastructure Hub, a G20 Initiative, estimated the global infrastructure investment needs to be $94 trillion USD between 2016 and 2040, an average of approximately $3.76 trillion USD of investments per year (Global Infrastructure Hub, 2017). Of the capital that has been committed, 83 % is attributed to public (i.e., government) investments and 17 % to private sector participation (World Bank Group, 2017). In order to address the infrastructure finance gap, this study focuses on why current financing approaches do not cover the shortfall and how technology innovation such as blockchains, as well as private sector participation, can serve as solutions.

Infrastructure projects, where the public sector traditionally has been the predominant investor, exhibit several features that make participation from private sector investors challenging. Significant upfront, illiquid, long-term capital is required for development and construction, leading to a high barrier for entry for private sector investors (Weber et al., 2016). The long service and economic life of an

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infrastructure asset require on-going operations and maintenance budgets increasing investment risks (Gatzert and Kosub, 2016). These capital investments need to be funded to service debt obligations to bonds and loans, as well as – project dependent – dividend payouts, to equity investors, either from tax revenues, fees, or alternative revenue sources. The extended operating expense (OPEX) horizon and sizable capital expenditures (CAPEX), along with debt service requirements and internal rate of return (IRR) expectations of invested capital make risk-adjusted financing of infrastructure critical. Furthermore, conventional infrastructure financing structures often take years to execute and incur high transaction costs (Jansen and Tuijp, 2021; Jin et al., 2016). With high risks of market failure on one hand, and infrastructure being regarded as a public good on the other, government provisions, support for loss guarantees, and other risk-mitigating mechanisms such as regulations have been central to the provision of core economic infrastructure (Chen and Bartle, 2017).

Together with an increasing interest in infrastructure financing and funding mechanisms (National Academies of Sciences and Medicine, 2022), blockchain is being considered as a technology to lower the transaction costs, increase data transparency and transaction efficiency (Ahluwalia et al., 2020; Santana and Albareda, 2022). As a distributed ledger technology (DLT), blockchains can facilitate direct, peer-to-peer transactions without an intermediary or central decision maker such as a bank. It prevents double spending and validates transactions while keeping immutable public records of activities on-chain (Nakamoto, 2008). Despite positive sentiment and expectations towards the potential benefits of blockchain (Mnif et al., 2021), its adoption has been slower than expected and implementations on a larger scale are still rare (Balzarova et al., 2022; Gartner, 2021). Common barriers include regulatory uncertainty (Cowden and Tang, 2022), a steep technological learning curve (Oberhauser, 2019), as well as unfavorable user experience (Glomann et al., 2020). In addition, factors such as cryptocurrency instability (Iwamura et al., 2019), introduction of new organizational governance models (Batubara et al., 2018), and the question as to whether blockchain can deliver true decentralization in decision-making (Chu and Wang, 2018) present barriers to adoption. Nonetheless, the limits on conventional financing for delivering infrastructure have resulted in predictions that blockchain adoption is inevitable and will play a major role in major industry sectors (Bhushan et al., 2020). One of the most visible practical implementations in the area of financing infrastructure is Project Genesis, a blockchain-based tokenization of green bonds that allows retail investors to buy into environmentally sustainable projects, while being provided with transparent data that the project delivers on the intent of the bond financing (BIS Innovation Hub, 2021).

The expectations of blockchain technology adoption are particularly relevant with the sustainability of infrastructure becoming central to the discussion and priorities on climate transitioning and resilience (United States White House Briefing Room, 2021). The United States Federal Sustainability Plan emphasizes the need for Federal agency policy, programs, operations, and infrastructure to adopt adaptive and resilient strategies for future climate impacts (President Executive Order 14057, 2021). The United Nations 17 Sustainable Development Goals (SDGs) are urgent calls to action for peace and prosperity on the planet. Among which SDGs 6 Clean Water and Sanitation, SGD 9 Industry, Innovation, and Infrastructure, SDG 11 Sustainable Cities and Communities, argue for universal access to sustainable infrastructure services, where clean water and sanitation, and affordable green energy are central tenets (Adshead et al., 2019; Delanka-Pedige et al., 2021). A survey on municipalities showed that transitioning towards sustainable infrastructure is also a goal among municipal leaders in planning for climate change but the financing structures are not sufficient for meeting such as transition (Cousins and Hill, 2021). To reconcile sustainability and infrastructure, innovative financing mechanisms that account for climate and sustainability are required (Cousins and Hill, 2021; United Nations Environment Programme Finance Initiative, 2021). Tao et al. (2022) have shown a recent uptick in the number of environmental finance research. A key challenge is that the financing of sustainable infrastructure such as smart stormwater systems, electric and autonomous vehicle transportation, and energy-efficient buildings have more barriers as compared to their traditional counterparts. The generally higher perceived technology risks associated with more environmentally conscious solutions, which lead to higher upfront costs, tend to be barriers for financing (Fernandez, 2022; Meltzer and Constantine, 2018). Increasing the financial attractiveness of sustainable infrastructure for investors by reducing project performance risks requires further investigation. Risk premiums should be lowered such that sustainable infrastructure projects are hedged against their downside risks, benefiting both the investor and investee (Codosero Rodas et al., 2019; Li and Liao, 2018). More accurate and trusted data via internet-of-things (IoT) and blockchains should benefit both the investor and investee. IoT data provides better insight into the performance of the asset, which informs valuation and thus the risk-return characteristic of the sustainable infrastructure project. This transparency will lower investment risks for the investor, and thus lower the cost of capital for the investee that seeks to build and maintain sustainable infrastructure. Similar phenomenon has been observed in carbon risk disclosure's effect on cost of bank loans as well as the green bond market (Bhutta et al., 2022; Hyun et al., 2020; Zhu and Zhao, 2022). Ultimately, IoT and blockchains will induce better investment conditions for both the investor and investee to bring infrastructure to fruition.

A substantial body of research exists on the opportunities for blockchain applications in smart cities in general and in the operations of energy systems, yet there is a knowledge gap at the intersection of sustainability, infrastructure financing, and blockchain-enabled investment mechanisms. Adams and Tomko (2018) state that research is needed before the promises of blockchains as an enabler of traceability and environment governance can become reality because these projects remain conceptual and proponents have "glossed over detailed discussions" (Adams and Tomoko, 2018, page 18:2). For sustainable infrastructure and smart cities to be financed through blockchain, a justification of this integration, and an understanding of the technical tools as well as the premise and limitations to enable adoption, are required. The current study addresses three central research questions: (1) What are the emerging areas of research in infrastructure finance, sustainable infrastructure and smart city finance mechanisms, and blockchain technology applications? (2) How does blockchain enable sustainable infrastructure and smart city financing? (3) What are the implications of blockchain-based financing for sustainable infrastructure and smart cities? Smart cities and sustainable infrastructure will be discussed synonymously based on the value proposition of smart cities to improve performance data availability for decision-making in sustainable infrastructure. The research explores the opportunity to utilize blockchain technologies such as decentralized oracle networks (DON) for monitoring, reporting and verification (MRV) of sustainable infrastructure asset performance in pay-for-performance mechanisms, and reduce risks and cost of capital in sustainable infrastructure investments. To the authors' knowledge this is the first study to integrate decentralized oracle networks for financing sustainable infrastructure and contributes to the literature on sustainable infrastructure finance and investments.

2. Materials and methods

Establishing new theory based on distinct disciplines will be required to address the knowledge gap in current literature. This is carried out through building and combining select literature and sources of information. The research method to be employed is therefore aligned with that of a conceptual research article, which Jaakkola (2020) characterizes it as creating new theory by building on concepts and data tested through empirical research. Conceptual papers offer integrated frameworks and directions of future inquiry by unearthing new connections among constructs and providing logical associations between them (Gilson and Goldberg, 2015). As opposed to empirical research, there is no specific research design for conceptual papers. However, this study will use the Model methodology approach, which is characterized by identifying unexplored connections and justifying causal linkages between constructs to build a theoretical framework to predict relationships between disparate subjects (Jaakkola, 2020). Researchers are able to explore emerging phenomena where data is not readily available. The Model approach to address the research questions is shown in Fig. 1.

The literature review process recognizes the current knowledge on the risk and return characteristics of infrastructure finance, mechanisms in financing sustainable infrastructure and smart cities, and applications of oracles and blockchain in the existing literature. Since the three areas of study are drawn from a wide range of literature, a semi-systematic literature review is conducted to address research question 1. Semi-systematic literature reviews are used to scope an area of study and its gradual evolution over time (Snyder, 2019). This method captures theories and common challenges defined within a domain. Select search strings were used to identify relevant literature in the areas of study. The manuscripts and documents were evaluated according to the following criteria: (a) literature was limited to those published from 2013 to 2022; (b) unfitting titles and abstracts were excluded. The selection data sources, search strings, and process are shown in Fig. 2. Relevant professional expert reports from the National Academies of Sciences, Engineering, and Medicine, the Global Infrastructure Hub, EDHEC Infrastructure Institute, World Bank, and Quantified Ventures that do not typically show up in the academic databases Scopus and Web of Science search results were manually added to the literature review stack.

After the literature review process, the key insights and knowledge gaps are assessed via the Model research design to uncover the opportunities and value propositions that blockchain and oracle technologies present to improve the information for risk-return profiles of infrastructure assets and sustainable infrastructure and smart cities finance mechanisms without the use of empirical data. By making connections between disciplinary areas, the impact of blockchain and oracles on sustainable infrastructure financing is evaluated to address the implications for technology-enabled financing of sustainable infrastructure.

3. Literature review

3.1. Infrastructure finance

One of the earliest definitions of infrastructure, described by Jochimsen (1966), is “the sum of all material, institutional and personal assets, facilities, and conditions available to an economy based on the division of labor and its individual economic units that contribute to realizing the assimilation of factor remuneration, given an expedient allocation of resources” (translated from German in Weber et al., 2016, page 11). Infrastructure has become an attractive alternative investment class for institutional investors due to several commonly perceived characteristics such as low volatility in high-risk market environments, steady income, diversification from equity markets, and value as an inflation hedge (Duclos, 2019; Weber et al., 2016). However, given the wide range of industry types, organizational models, and regulations that compose infrastructure, the specific risk-return profiles of infrastructure must be considered. A recent World Bank survey of 6343 public infrastructure projects from 129 developing countries during the period from 1987 to 2020 shows adoption of a wide range of contractual forms from user charge tariffs and tolls (2211), fixed annuity (440), availability-based variable annuity (239), revenue share (85), fixed tariff purchase agreements (3167) and other hybrid mechanisms (World Bank Group, 2021).

Contrary to a simple sector-based analysis of investment characteristics, the risk-return profile of infrastructure depends on a multitude of factors (e.g., business models, partnership models, etc.) (Fig. 3). One of the most critical differentiators between assets is the unique contractual agreements of infrastructure projects that determine the risk-return profile of the investment (Weber et al., 2016). Fig. 3 illustrates the internal rate of return (IRR) of two similar physical assets, categorized in the same subsector, each at a different stage of their project life cycle with different embedded contractual structures. For an operational asset with an availability payment-based public-private partnership (PPP) structure that is not highly leveraged, and where the public participant is fiscally and politically stable, minimal market risk is assumed by the private party. The expected return would range from 5 % to 9 %. The other physical asset, although a monopoly and regulated, is subject to demand-side risk as the business model is user financed as opposed to budget financed. The increased risk leads to an expected return of 9 % to 14 %. While the two assets are physically identical and both operational, their risk-return characteristics vary.

Investors gain access to infrastructure through direct placement deals, listed and unlisted funds, which have not performed up to the commonly perceived characteristics due to misunderstood or mixed risk profiles of assets under management (Amenc et al., 2017; Blanc-Brude and Abhishek, 2020). Andonov et al. (2021) rejected the hypothesis that closed private fund investments in infrastructure deliver more stable and diversified cash flow than other alternative asset classes. PPPs tend to command a much higher price as compared to public procurement of infrastructure, resulting from large risk transfers, how the private sector treats risk, and the performance uncertainty of the public-private organizational contract (Makovšek and Moszoro, 2018). Existing infrastructure indices and funds aggregate financial vehicles based on industry sector. This does not distinguish between the contractual and regulatory characteristics that inform risks and returns, nor does it take into account factors that may distort the investment characteristics of the underlying infrastructure, leading to a deviation from expected infrastructure investment outcomes (Blanc-Brude, 2013). The structure and components of infrastructure indices can also be skewed, which leads to the question of whether such benchmarks can capture any general infrastructure qualities or valuations (Bianchi et al., 2017; Blanc-Brude, 2013).

The lack of accurate valuation of infrastructure assets has led to a mis-match between the available long-term source of capital and the infrastructure asset to be financed (Rossi and Stepic, 2015). Climate-resilient infrastructure has an additional layer of financing difficulty due to the higher upfront capital costs, higher perceived technology performance risks, as well as unaccounted costs of stranded assets from investing in climate-conscious solutions (Lindsay et al., 2021; Meyer and Schwarze, 2019). Thus, improving the transparency of infrastructure performance metrics is seen as an important advancement for innovations in infrastructure project financing and development (Herrmann and Spang, 2020; Lovell et al., 2022; Roelofs, 2019). The emergence of so-called cyberphysical systems and integration of IoT, with its value proposition to increase data availability on infrastructure performance improves the informational efficiencies and pricing strategies of conventional infrastructure (Liu and Fukushige, 2020; Teng et al., 2021). This information can then be incorporated in performance-driven models such as risk transfer finance, securitization against cash flows or asset valuation, and business-to-business market instruments.

3.2. Sustainable infrastructure and smart city finance mechanisms

The common practice of differentiating sustainable infrastructure investments only by sector lacks a comprehensive viewpoint of the asset class. It is necessary to analyze and demarcate individual infrastructure finance mechanisms in order to understand the unique risk-return characteristics with increased accuracy as well as avoid

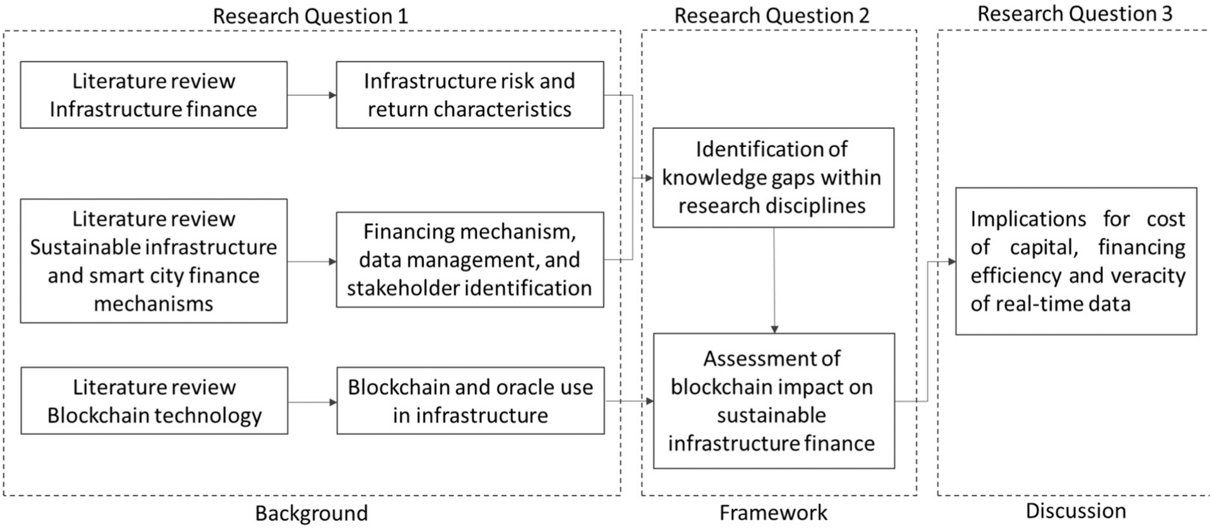

Fig. 1. The Model approach followed in this study to explain and predict relationships between infrastructure finance, sustainable infrastructure and smart cities finance mechanisms, and blockchains and oracles to provide insights in technology-enabled financing of sustainable infrastructure.

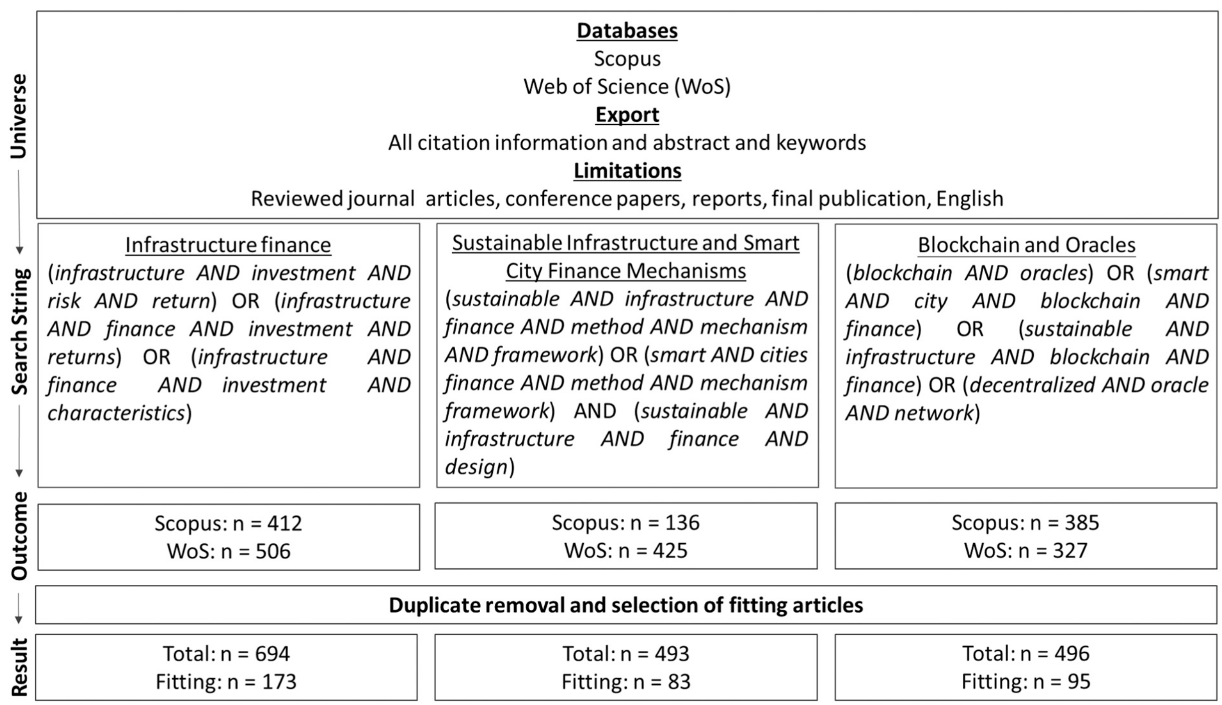

Fig. 2. Semi-systematic quantitative literature review for three distinct areas of study: infrastructure finance, sustainable infrastructure and smart cities finance mechanisms, blockchain and oracles. n is the number of literatures from Scopus and Web of Science and does not include professional expert reports.

greenwashing[1] (Weber et al., 2016). The performance of smart cities projects and sustainable infrastructure needs to be monitored, reported, and verified for investment decision-making (Akomea-Frimpong et al., 2021; Calvert et al., 2018; United States Environmental Protection Agency, 2022). The integration of ESG metrics and sustainable outcomes data in the financing of infrastructure has been explored in asset valuations and investment returns (Lu et al., 2015). New business and financing mechanisms have been proposed to implement sustainable financing, including through green bonds (Baker et al., 2018; Bhutta et al., 2022), "performance-based" models such as environmental impact bonds (EIBs) (Brand et al., 2021; Salzman et al., 2018), green asset-backed securitization (Agliardi, 2021), sustainability-linked loans or bonds (Kölbel and Lambillon, 2022), and new PPP structures (Ajith et al., 2022; Cheng et al., 2021; Hoeft et al., 2021). Performance-based models (also known as pay-for-success models) that measure outcomes have become the favored financing model for smart cities and sustainable infrastructure as it provides transparency and asset-specific risk allocations preferrable to all parties involved (Lindsay et al., 2021). Performance-based financing integrates real assets with digital infrastructure assets, such as IoT sensors and communication infrastructure (Adriaens et al., 2021; Uckelmann et al., 2011).

Sustainable infrastructure finance mechanisms rely on regular

[1] Greenwashing: misrepresenting practices or initiatives as sustainable (Saxton et al., 2019).

Infrastructure I	Operational Availability-based Finance No market risk	• Assets with regulated, long-term availability-based PPP contracts – no/minimal market risk (demand or price) • Grantor of revenue is a recognized public body in stable country • Low or medium leverage
Infrastructure II	Operational User-based Finance Market risk	• Monopoly, regulated, but exposed to market risk (e.g., user financed) • Revenues yield from day one – possibly high leverage • Regulatory risk owing to periodic regulatory changes and/or unstable government

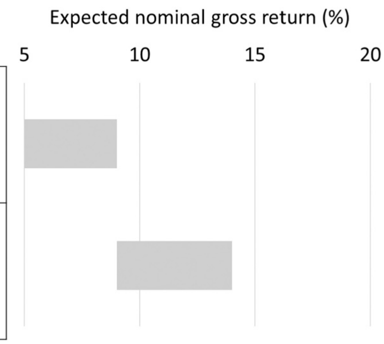

Fig. 3. Physically identical Infrastructure I and Infrastructure II have different risk-return characteristics based on project life-cycle stage and contractual agreements. Adapted from Weber et al. (2016).

updates of information on the status and use of the physical assets. Appropriate benchmarks are required to establish accurate and precise performance indices for them to be included in the financing mechanism (Codosero Rodas et al., 2019; Sengupta et al., 2018). Data from IoT enables performance-based mechanisms, unlocking new cash flows, increase operational efficiency and thus reduces costs (e.g., Sugrue and Adriaens (2022)). Gonzalez-Ruiz et al. (2019) employed the mezzanine debt mechanism in PPPs, capturing financial value by converting debt into equity shares contingent upon meeting sustainability criteria, to finance a wastewater treatment plant. Tirumala and Tiwari (2022) introduce a financing-facility based mechanism that pools low-cost funds from investors at the national or local level to support projects that meet the UN Sustainable Development Goals for the Ocean. Monetary provisions from the facility engage either large impact projects or individual projects through concessional financing, credit enhancements, or "blue" bonds issuances. Brand et al. (2020) uses stochastic hydro-financial watershed modeling to estimate cost savings from hedging against environmental risk with sustainable infrastructure that informs the financial terms of an environmental impact bond. The study also discusses risk reduction techniques for investors such as extending the bond length, using bond guarantees, or cost sharing among stakeholders. Chitikela and Simerl (2017) highlights the flexibility and efficient conductibility of renewing water infrastructure by performance contracting. Performance contracting is a budget-neutral approach to asset renewal as the savings incurred after the asset renewal can be used to service the outstanding debt. Hence, performance of the renewed infrastructure is used as a debt service criterion. Performance benefits can also achieve favorable conditions on the cost of financing using sustainability-linked bonds (Giráldez and Fontana, 2022). Other information used to indicate performance achievement include metrics such as stormwater runoff reduction and forest restoration (Brand et al., 2021). Ferrarez et al. (2020) provides 42 additional sustainability indicators, categorized across the environmental, economic, and social dimensions of infrastructure.

A seminal performance-based finance mechanism for sustainable infrastructure is shown in Fig. 4, depicting how The District of Columbia Water and Sewage Authority (DC Water) utilized the Environmental Impact Bond (EIB) to build sustainable infrastructure for managing its sewage and stormwater. The finance mechanism provides transparency on performance risk for the private sector investors by linking returns directly with the reduction percentage of stormwater runoff, increasing the bankability of the sustainable infrastructure and delivering the much-needed infrastructure for the municipality. The EIB is a 30-year tax-exempt municipal bond that was placed with two institutional investors and has a required tender on the fifth year (Fig. 4). The bond was issued at $25 million USD with a coupon of 3.43 % paid semiannually. On year five, contingent on the percentage of stormwater runoff reduction, a provision of $3.3 million USD would be exchanged between the investors and DC Water. If the sustainable infrastructure reduced stormwater runoff greater than 41.3 % of the measured baseline, DC Water will make a one-time payment of $3.3 million USD to the investors. If stormwater runoff was reduced by less than 18.6 % of the

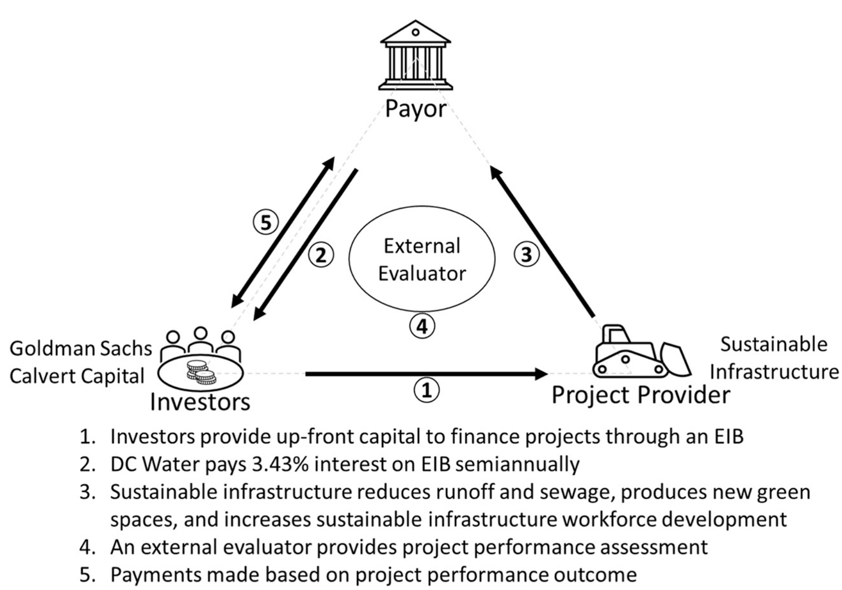

Fig. 4. A visual representation of the performance-based financing mechanism. Adapted from Quantified Ventures (2021).

measured baseline, the investors would make the payment to DC Water. Reductions that fall between 18.6 % and 41.3 % would not result in any additional payment on either side. The EIB would then only be serviced with the basic principal and the 3.43 % interest. The finance mechanism stakeholders include: the project provider who delivers the infrastructure, investors in the project, payors (including users), and external third-party evaluators. The investors provide up-front capital to initiate or scale a sustainable infrastructure project. The project provider carries out construction of the infrastructure asset after receiving the up-front capital. The payor of the project makes fixed or variable interest payments to the investors. External evaluators quantify and verify the sustainable infrastructure performance. According to the measurements, an additional payment accrued from cost savings or other revenue generations to the investors can be triggered when overperformance occurs. In the case of underperformance, payors of the project can invoke a clawback from the investors, hedging against performance risks. This mechanism, as with all other performance-based funding and financing structures, is dependent on the veracity, timeliness, and transparency of data, which has led to the opportunity for blockchain and oracles.

3.3. Blockchain and oracles

The idea of blockchains rose to prominence as the underlying technology of Bitcoin, the world's largest cryptocurrency. Nakamoto (2008) introduced the technology as peer-to-peer timestamped transactions that are aggregated by hashing the transactions into a continuous, proof-of-work record, addressing the double-spend problem without a financial institution. Blockchains are viewed as a promising technology for smart cities and sustainable infrastructure because they enable network participants to exchange data, allow for transparent communication, and afford new decentralized transaction models. Given that conventional practices in the IoT era, such as cloud-based computation and storage, may be at risk as a single-point of failure or have privacy concerns, the integration of blockchain and IoT has led to innovative decentralized applications that includes smart finance, smart cities, and smart energy grids (Chen et al., 2022; Marsal-Llacuna, 2020).

Blockchain-based solutions in data aggregation and performance tracking for smart cities include applications for security, city services and management (Bagloee et al., 2021; Bhushan et al., 2020). Woo et al. (2021) describe the application of blockchain technology for building energy performance MRV and to verify carbon credit market disclosures. Several studies have proposed the use of blockchain technology to finance infrastructure through tokenization. Tokenization is the process of digitizing and representing real-world assets or financial instruments on the blockchain (Bongini et al., 2022; OpenZeppelin, 2017; Uzsoki, 2019). Moseley (2018) proposed utilizing security tokens (i.e., financial securities on the blockchain) for debt financing of infrastructure. By representing bonds on the blockchain as security tokens, the blockchain-based digital bond could be used as an alternative instrument for the financing of the project by lowering transaction costs and increasing investment vehicle liquidity. Tian et al. (2020) describe the opportunity for blockchain to tokenize infrastructure equity as an alternative to traditional debt financing, improving transaction efficiencies. Project Genesis has released two blockchain-based green bond tokenization platforms to allow retail investors to participate in financing infrastructure and receive information on the green performance returns (BIS Innovation Hub, 2021).

Although blockchains are adept at native cryptocurrency token accounting and transactions, the cited studies above do not focus on the mechanisms or effects of utilizing real-time data from off-chain environments. The blockchain by itself is siloed from the outside world and its capabilities are limited (Mühlberger et al., 2020). Oracles have been introduced to overcome this limitation. Oracles are the bridges that connect off-chain computational resources and data to the mainchain infrastructure, such as smart contracts where execution of transactions are conditional to real-world events (Omar et al., 2021; Poblet et al., 2020). Breidenbach et al. (2021) introduced the concept of hybrid smart contracts, a general framework for augmenting existing smart contract capabilities by integrating off-chain computing resources through oracles. However, the off-chain computational resources and data vary in the degree to which they are trusted and may be viewed as central points of vulnerability (Sheldon, 2020). The process of creating trust is commonly known as trust minimization. Trust minimization is defined as the ability to "reduce the adverse effects of systemic corruption or failure" (Breidenbach et al., 2021, page 65). Trust minimization can be implemented at two locations of the data pipeline: the web servers from which data is drawn (i.e., data source) and the oracles. To increase reliability and trust at the data source, machine learning algorithms for data anomaly detection and data signing for authentication have been implemented (Al-amri et al., 2021; Yasskin, 2022). Active machine learning models that provide nonlinear classification boundaries have been suggested for anomaly detection in complex environmental data sets (Russo et al., 2020). The Robust Random Cut Forest algorithm has been used to detects anomalies on streaming data such as industrial and infrastructure control systems by simultaneously adapting to changing input signals and handling duplicates or near-duplicates that could mask the presence of outliers (Bartos et al., 2019). Neural network-based machine learning algorithms, autoencoder and the long short-term memory encoder decoder, have shown to be superior to conventional machine learning techniques such as regression and support vector machine for detecting anomalies in IoT-based vertical plant wall for indoor climate control (Liu et al., 2020). Signing data can authenticate data integrity. Current internet communication protocols (e.g., https) cannot prove provenance of data sent over the internet. As a result, the data being passed to a smart contract after receiving it from a web server cannot be authenticated. DECO is a privacy-preserving and data authentication protocol which allows users to prove data provenance and verify statements about data with zero-knowledge (ZK) via data signing (Zhang et al., 2020).

Trust minimization may also be implemented in oracles. Decentralized oracle networks (DON) working in tandem with hybrid smart contracts achieve trust minimization by means of decentralization, cryptographic tools, and cryptoeconomic guarantees (Breidenbach et al., 2021). In a committee-based format, DONs may use redundancy (i.e., combining data from multiple data sources) to address source faults as well as voting to reach consensus on the validity of the incoming data. Common usage of DONs have been providing decentralized price feeds to Decentralized Finance (DeFi) applications (Kaleem and Shi, 2021). Park et al. (2021) describes a framework for a privacy-preserving oracle system that converts signed data in a legacy web server into a zero-knowledge succinct noninteractive argument of knowledge (zk-SNARK) proof for use in hybrid smart contracts. The data on-chaining process is verified and automated through hybrid smart contracts while data owner privacy remains protected. Adler et al. (2018) introduced a decentralized oracle, Astraea, based on a voting mechanism that decides the truth or falsity of propositions, making adversary oracle manipulation difficult. Cai et al. (2022) improves upon Astraea by implementing peer prediction-based scoring with non-linear staking. The scoring scheme is designed so voters maximize their expected score by honest reporting of data.

In infrastructure applications, Osterland and Rose (2021) utilizes oracles to maintain an audit certificate of a significant amount of data from German waterway transportation on the blockchain while tracing and proving the provenance of data. Zhang et al. (2021) present a framework to address the malpractices in infrastructure construction and development using blockchain and smart contracts, enabling around-the-clock services, integration of data analysis algorithms, and security and stability within the management system. Other common use cases of blockchain in construction projects are solving administration and transaction disputes (Mohammed et al., 2021).

4. Discussion and implications

Extending from the literature review, a blockchain-based approach utilizing DONs to inform sustainable infrastructure and smart cities finance is established. The approach provides the logical connection and justification for why blockchain is primed to facilitate performance-based sustainable infrastructure financing and how blockchains improve investment transparency and risk-return characteristics to increase the financial attractiveness of sustainable infrastructure assets.

4.1. Connections between infrastructure finance, sustainable infrastructure and smart city finance mechanisms, and blockchains and oracles

The infrastructure finance literature indicates the lack of accurate benchmarks and valuation metrics but the digital rendering of infrastructure can provide information on real-time infrastructure performance and governance (Ramu et al., 2022). A key requirement is the availability and transparency of data that captures performance of the asset (Adriaens et al., 2021). In sustainable infrastructure and smart cities finance mechanisms, the performance-based model provides asset-specific performance indicators and risk management profiles desirable to all stakeholders (Lindsay et al., 2021). For performance-based financing of sustainable infrastructure, evaluating project feasibility, selecting developers, and financing, operating, and MRV in the post-construction phase of a project lifecycle requires intricate coordination and consensus building from various actors. Currently, an external evaluator is required to assess performance against established and contractually agreed metrics. However, trust in institutions, evaluators, and rating providers has been a challenge due to recent performance lapses, security breaches, and cost, thus exposing limitations to these intermediaries (Jonsdottir et al., 2022; Nicole and Robert, 2013; Sadawi et al., 2021). Legacy accounting systems and mechanisms are deemed insufficient to avoid information asymmetry resulting from heterogeneity and fragmentation of data flows (Gatti, 2018; Sclar, 2015). High MRV costs and counterparty risks associated with greenwashing of infrastructure assets to fit the ESG narrative have impacted the financing and development of sustainable solutions (Baldi and Pandimiglio, 2022; He et al., 2021). A trust-preserving data and stakeholder management system is needed. The use of blockchain is well-suited for performance-based financing mechanisms as it provides trust and transparency for all parties involved in a project, "allowing mutually mistrusting entities to exchange financial value and interact without relying on a trusted third party" (Wüst & Gervais, 2018, page 45). However, the integration of sustainable infrastructure performance information with blockchain-based financial transactions is challenging. Conventional blockchain functionality are insular (i.e., blocked off from the outside world) and expensive to append and execute (Mühlberger et al., 2020; Zarir et al., 2021). Even with oracle technology, data availability can be switched on and off by a data provider or a centralized web server, negatively affecting the benefit of blockchains, such as decentralization (Sheldon, 2020). To create more robust systems, decentralizing the potential single points of failures is a key concern for blockchain use cases (Lockl et al., 2020; Rathore et al., 2019).

To facilitate performance-based financing for infrastructure, smart contracts will be required that can combine on-chain and off-chain modules in a decentralized approach. This can be realized via hybrid smart contracts and DONs, which are efficient blockchain-agnostic interfaces to off-chain resources (Fig. 5). As opposed to conventional smart contracts that only govern on-chain activities, hybrid smart contracts expand conventional smart contract functionality by integrating off-chain resources in a trusted and confidentiality-preserving fashion (Breidenbach et al., 2021; Cai et al., 2022). By combining the secure properties of smart contracts anchored on the mainchain with the off-chain capabilities of DONs, a bevy of opportunities arise for applications in sustainable infrastructure finance. Hybrid smart contracts constitute several modules: on-chain components and an off-chain nodes, and an "executable" that is running on the oracle nodes (Breidenbach et al., 2021). Executables are programs that run autonomously, continuously, and initiate adapters based on requests coming from a

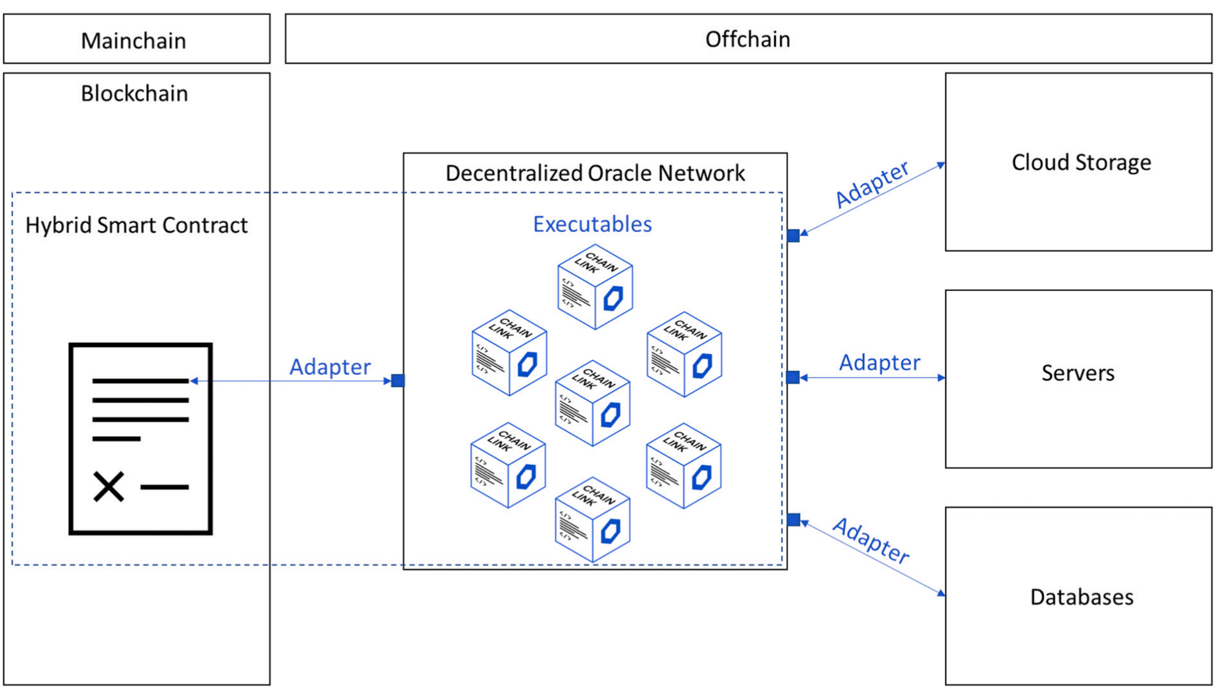

Fig. 5. Visualization of a decentralized oracles network pulling off-chain data on-chain to a hybrid smart contract (Adapted from Breidenbach et al. (2021)). The DON accepts requests from the hybrid smart contract and the executables initiate the adapters to query data from off-chain resources and pass the requested information back on to the blockchain (The hybrid smart contract request source code: https://github.com/smartcontractkit/chainlink/blob/develop/contracts/src/v0.8/ChainlinkClient.sol). The direction of data flow to service a hybrid smart contract request are indicated by the arrows. Chainlink® has authorized the use of the Chainlink/Link logo. Chainlink® reserves the right to revoke the use at any time if usage is deemed to misrepresent Chainlink®.

hybrid smart contract. They utilize adapters to communicate with external resources such as web servers. Once the oracle node receives the requested information from external resources, the information is then sent over another adapter back to the hybrid smart contract on-chain (Fig. 5). DONs can send data from external sources back on-chain with different trust models or transparency requirements depending on the specific use case (Shi et al., 2021; Yasskin, 2022; Zhang et al., 2020).

Carrying out performance-based financing (e.g., environmental impact bond or other performance-based contracts) on the blockchain with DON technology shifts the stakeholder relationships of Fig. 4 to Fig. 6. The investors provide up-front capital directly to the infrastructure project provider to initiate construction. The asset owner, typically a public utility or government entity, makes interest payments directly to the investors. The payment processes are done peer-to-peer without the need for financial intermediaries. With infrastructure IoT-based performance data accessed and verified through DONs, third-party external evaluators are reduced in their roles, or no longer required. The collected infrastructure performance measurements off-chain are used as inputs to the smart contract on-chain for automatic execution of payouts conditioned on cost savings and other revenue generated from overperformance or risk-hedging in underperforming circumstances (Fig. 6). All stakeholders, including the public, will have access to read and audit the smart contract agreements as well as the performance data. Introducing transparent data MRV and automated transaction mechanism may reduce the cost of capital and allow for optimized risk management among the stakeholders in the sustainable infrastructure. This increases the financial attractiveness of the sustainable infrastructure asset, bringing in much needed capital to close the finance gap.

4.2. Implications and illustrative application of DONs and hybrid smart contracts for sustainable infrastructure financing

By drawing on the risk and return expectations of the private investor on one hand, and performance-based infrastructure financing mechanism on the other, a general approach for blockchain-based financing of sustainable infrastructure is introduced. Fig. 6 conceptualizes how data from sustainable infrastructure can inform transactions among stakeholders on the blockchain through DONs and hybrid smart contracts. The general approach centers around performance-based mechanisms, which depend on veracity, transparency of performance metrics, and accountability of individual actors (Adriaens et al., 2021; Brand et al., 2021). Fig. 7 depicts a framework of how data flows from sustainable infrastructure to the DON and hybrid smart contracts (Step 4 in Fig. 6) as well as a corresponding end-to-end example.

4.2.1. General data flow from sustainable infrastructure IoT to DONs and hybrid smart contracts

In Fig. 7, the data flow starts with the collection of performance data from infrastructure assets (i.e., the physical layer), using IoT devices (i.e., the IoT sensing layer) for measurements such as stormwater levels or structural health of bridges (Bartos et al., 2018; Zhang et al., 2016). The data is transmitted and stored on web servers and databases (Bartos et al., 2018; Zhang et al., 2016). In the database/server layer, machine learning algorithms can be utilized for identifying data anomalies, filling data gaps, and enabling verification (Al-amri et al., 2021; Yasskin, 2022). Digital signatures can be added to confirm the precision and accuracy of data (Sporny et al., 2022; Zhang et al., 2020). Application programming interfaces (APIs) enable data queries from DON adapters, bridging web servers and databases to DONs and hybrid smart contracts. In the DON layer, the oracle nodes hosts executables and adapters that interact with web servers and databases as well as off-chain computation resources (Breidenbach et al., 2021). DONs minimize the need for on-chain storage and computation while increasing trust and reliability of data originating from off-chain sources. Once the off-chain data is provided to the hybrid smart contract (i.e., the blockchain layer), transactions can be executed based on agreed upon conditions such as those in Fig. 6. To augment the data flow framework, a corresponding end-to-end example is provided. This example illustrates the detailed components in each layer of the data flow for Open Storm, a stormwater management infrastructure. Open Storm is an open-source product available for research or commercial applications (http://open-storm.org/). Currently, Open Storm does not have blockchain-based applications thus the DON and blockchain layer in the example are theoretical designs while the layers below have been implemented. The theoretical finance example shows how a municipality such as the city of Ann Arbor, Michigan may utilize DONs and hybrid smart contracts to finance and carry out sustainable infrastructure for managing stormwater. The left side of Fig. 7 shows the data flow framework, and the right side is the corresponding Open Storm components.

4.2.2. Open storm: an end-to-end example of data flow and performance-based financing on the blockchain

Using distributed valve controllers and adaptive feedback, Open Storm controls stormwater flows on a watershed scale to reduce flooding and improve water quality. Details of the sensing and control infrastructure are found in Bartos et al. (2018). Here we highlight the sustainable infrastructure components, measured metrics, and their integration with DONs and hybrid smart contracts for financing. The financing mechanism for Open Storm follows those shown in Fig. 6 as risk sharing is well-balanced among the stakeholders and performance of the sustainable infrastructure is transparent, increasing its financial viability to initiate capital investment and delivering the much-needed infrastructure. The private sector investors provide direct, up-front

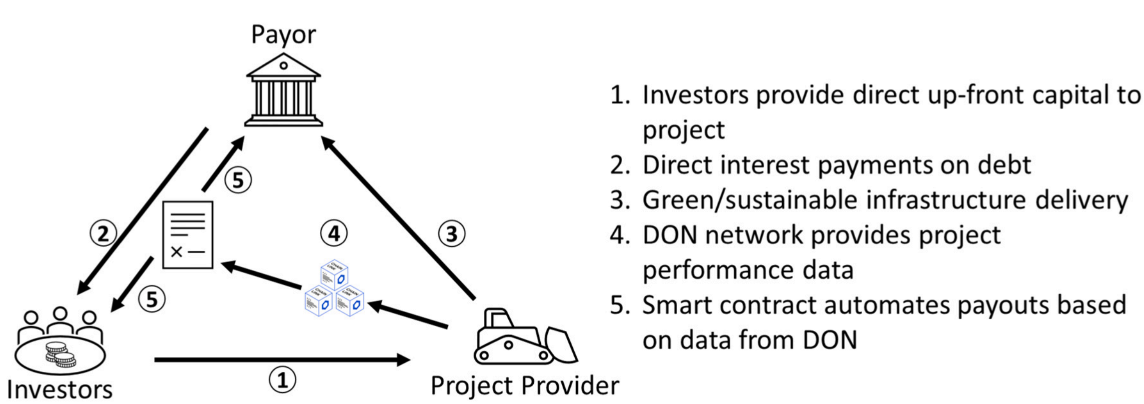

Fig. 6. General approach of the performance-based financing mechanism via the blockchain and decentralized oracle network (DON) technology. Chainlink® has authorized the use of the Chainlink/Link logo. Chainlink® reserves the right to revoke the use at any time if usage is deemed to misrepresent Chainlink®.

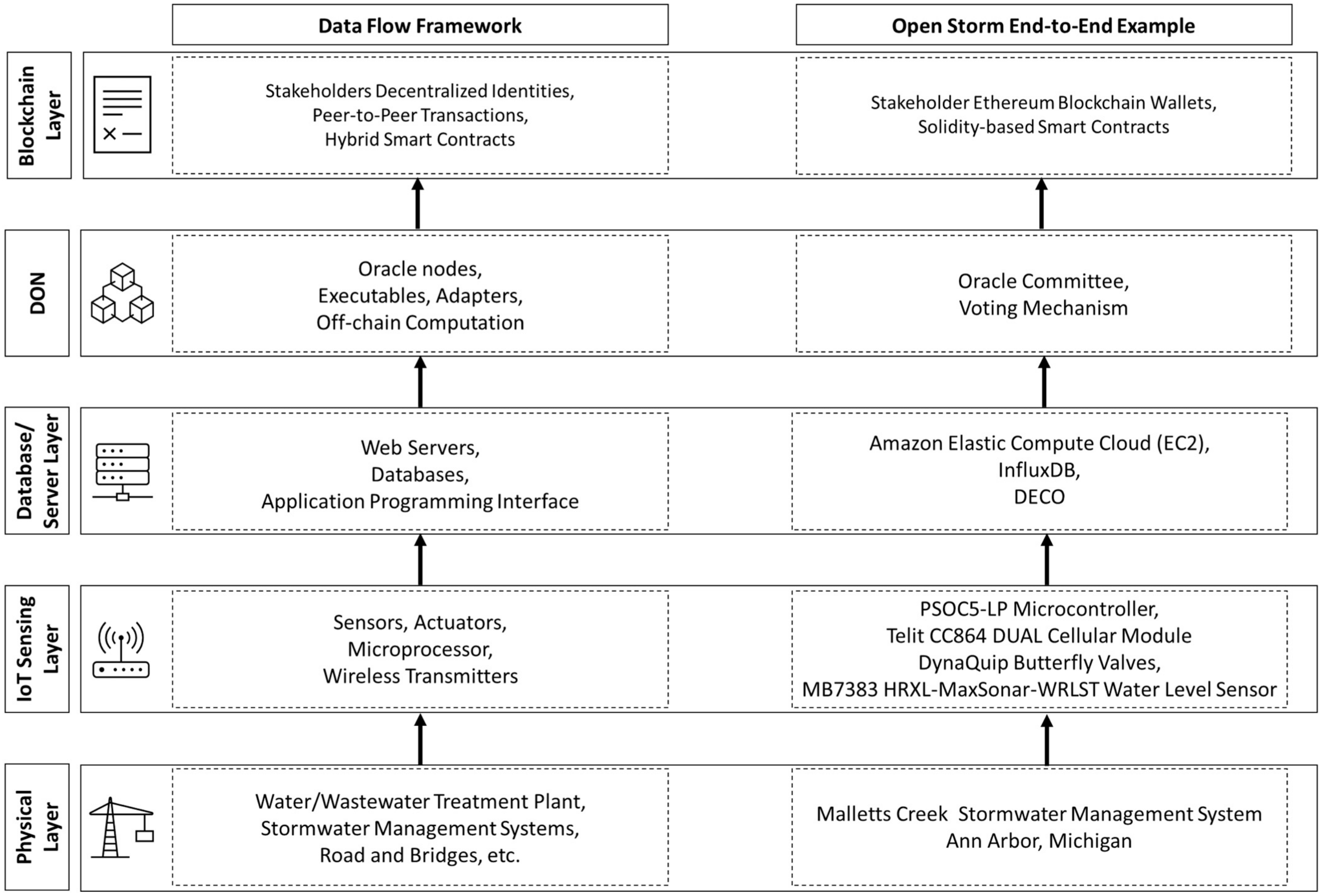

Fig. 7. Overview of the flow of data from the physical layer to the blockchain layer (left). An end-to-end example of blockchain-based financing of a stormwater management infrastructure, Open Storm (right). The arrows indicate data flow direction when data is requested on the blockchain.

capital to the project provider to implement Open Storm. Open Storm's performance risk for both the investors and the payor are made transparent and managed by linking payments directly with the reduction of peak stormwater flow and suspended solids concentration. Payments accrued from cost savings by using Open Storm, such as avoiding flood damages and reducing water treatment expenditures, can be made to the investors when positive performance occurs.

The stormwater sensing and control infrastructure is deployed in Malletts Creek in the city of Ann Arbor, Michigan. It aims to reduce flooding and improve water quality through adaptive and timely releases from retention basins when rainstorms occur. The sustainable infrastructure put into place are measurement sensors for retention basin water depth, automated samplers for water quality, and control systems of valves and gates. These sustainable infrastructure components are used in contrast to gray infrastructure (i.e., traditional steel and concrete pipelines). Gray infrastructure has been shown to be expensive, ineffective, deleterious in conveying and treating water during storm events, and also difficult to transition away from (Palmer et al., 2015; Suleiman, 2021).

The physical layer in Fig. 7 is Malletts Creek in Ann Arbor, Michigan that requires stormwater management infrastructure. The IoT sensing layer includes microcontrollers, sensors, actuators, and wireless transmitters. The PSOC5-LP microcontroller (Cypress Semiconductor, San Jose, California, USA) serves as the main processing unit that houses the operating system for controlling the attached sensors and actuators. Wireless telemetry is used to transmit and receive data from a web server by the sensor nodes. The cellular connectivity is implemented with the Telit CC864 DUAL cellular module (Telit, Irvine, California, USA). The sensors include the MB7383 HRXL-MaxSonar-WRLST water level sensors (MaxBotix Inc., Brainerd, Minnesota, USA) and SonTek-IQ (SonTek, San Diego, California, USA), a flow measurement device used to estimate suspended solids concentration. Butterfly valves (DynaQuip, St. Clair, MO, USA) are the actuating devices that control releases from retention basins by configuring the degree to which the valves open to modulate flows. The butterfly valves, as with the sensors, are operated with instructions received from a remote database hosted on a web server. The database/web server layer receives, stores and processes data. This layer functions as storage for sensor readings as well as a layer of communication between the sensors in the field (i.e., IoT sensing layer) and user applications (i.e., DON and blockchain layers). Currently Open Storm uses InfluxDB databases that are hosted on the Amazon Elastic Compute Cloud (EC2) web server. The field sensors can upload measurements to InfluxDB as well as query the database for commands on what tasks to carry out next. On the user application side, the stakeholders initiate data requests for water depth and water quality data to the web server. Applications running on the web server ask for the sensor readings from the database and pass these readings back to the user application. The user application may also write commands via the web server to the database to remotely control hardware in the field. Trust minimization tools such as machine learning algorithms for data anomaly detection and data signing for authentication to increase reliability in the data source can also be hosted in the database/web server layer.

In the blockchain and DON layers, the hybrid smart contract is a user application that can read from the Open Storm database via DONs and then trigger financial transactions on the blockchain based on those readings. Open Storm has demonstrated improvements in stormwater management performance compared to scenarios where Open Storm is not used (Bartos et al., 2018). Following a storm event, approximately 19 million liters were removed during the storm window and retained in the basin. Peak flows at the watershed outlet were 0.28 m^3/s during the storm where measurements would have been almost 0.60 m^3/s if the control valves in the basin had not been in place. The increased stormwater residence time in the basin allowed for settling of suspended solids in the water, lowering concentrations from 110 mg/L to 60 mg/L. These measurements can be requested and sent to the hybrid smart contract via DONs. The DON committee can hold a vote on the validity of the incoming data, adding reliability and trust to the off-chain data. The outcomes from the Open Storm infrastructure can trigger payments from the city of Ann Arbor, Michigan's blockchain wallet to the private sector investor's blockchain wallet given that the positive performance metrics coded in the hybrid smart contract are met. The positive performance payments increase the returns of the private investor for taking on sustainable infrastructure project development risks with their initial upfront capital. Ultimately, the infrastructure finance gap can be closed by having asset risk-return characteristics align with all stakeholders through the trusted and transparent measurements of the sustainable infrastructure performance.

4.2.3. *Decentralized identities of stakeholders*

By executing performance-based financing of sustainable infrastructure on the blockchain, all stakeholders in the infrastructure project would be represented with a decentralized identity (DID) on the blockchain containing a unique ID, a public cryptographic key, and other relevant descriptions (Avellaneda et al., 2019; Davie et al., 2019). A decentralized trust web is established through the verifiable credentials of decentralized identifiers (Davie et al., 2019). DIDs contains a stakeholder's unique characteristics such as location, banking information, and healthcare records without centralized, third-party custody (Rivera et al., 2017). DIDs make centralized governing authorities handling financial transaction, personal credentials and information redundant, improving trust and communications in a cost-effective way (Li et al., 2019; Sporny et al., 2021). In the Open Storm example (Fig. 7), the city of Ann Arbor, Michigan, the private investors, the project provider, and the hybrid smart contract would each be represented on the blockchain with a DID, making peer-to-peer financial transactions possible. The DIDs are currently implemented as blockchain wallets.

5. Conclusions

The capital shortfall to build and maintain infrastructure, also referred to as the infrastructure finance gap, is prevalent around the world. To account for sustainable infrastructure that mitigate and adapt to climate change increases the difficulty of closing the finance gap. The reluctance of private investors to deploy capital into the infrastructure asset class is largely due to a lack of accurate investment benchmarks as well as a mismatch between the risk-return expectations. Conventional infrastructure investment characteristics and their performance benchmarks often deviate from the common thesis of infrastructure as a market-decoupled, stable-yield generating asset. This, in turn, increases the already-elevated risk premium of sustainable infrastructure, further lowering their financial attractiveness. This paper argues for the use of blockchain technology and decentralized oracle networks for a more trusted and transparent approach to better reflect investment risks and returns, inducing successful financing of sustainable infrastructure.

The study first reviewed existing literature in infrastructure finance, sustainable infrastructure and smart cities finance mechanisms, and blockchain and oracle technology. Rationale and justifications for the adoption of blockchain and oracles in the financing of sustainable infrastructure were subsequently discussed. The discussion reconciled the three disparate areas of literature by addressing the need for accurate investment benchmarks and the lack of trust in centralized entities with the combination of performance-based financing, IoT sensors, DONs, and hybrid smart contracts. IoT sensors are able to relay sustainable infrastructure performance data via DONs to hybrid smart contracts for financial transactions on-chain. The combination introduced a general approach that ensures accuracy, trust and transparency in data used for financing of sustainable infrastructure. The data flow from IoT sensors to hybrid smart contracts was also mapped out. Data is collected from the physical world of infrastructure by sensors. The readings from the sensors are transmitted to databases hosted on web servers. Hybrid smart contracts initiate requests for data that are needed for financial decision-making. DONs receive the requests, pull the requested data from the web server, and send the data back to the hybrid smart contract. An end-to-end example of performance-based financing of a stormwater management infrastructure, Open Storm, was presented to augment the general data flow framework.

By ensuring accuracy, trust, and transparency in sustainable infrastructure performance data, risk and return expectations are well-balanced among project stakeholders. Performance risks in sustainable infrastructure are reduced through the integration of DONs and hybrid smart contracts, which improve auditability and verifiability in performance-based financing. The financial attractiveness of sustainable infrastructure investments increases with the advent of accurate benchmarks and transparent risk management mechanisms. Capital can be deployed with a trusted and accurate depiction of the underlying asset, closing the infrastructure finance gap.

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CRediT authorship contribution statement

Kenneth Hsien Yung Chung: Conceptualization, Methodology, Formal analysis, Visualization, Investigation, Writing – original draft. **Dan Li:** Conceptualization, Visualization, Writing – review & editing. **Peter Adriaens:** Supervision, Writing – review & editing.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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References

Adams, B., Tomko, M., 2018. A critical look at cryptogovernance of the real world: challenges for spatial representation and uncertainty on the blockchain (short paper) 10th international conference on geographic information science (GIScience 2018), Dagstuhl, Germany. http://drops.dagstuhl.de/opus/volltexte/2018/9346.

Adler, J., Berryhill, R., Veneris, A., Poulos, Z., Veira, N., Kastania, A., 2018. Astraea: a decentralized blockchain oracle, 30 July-3 Aug. 2018. In: 2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData).

Adriaens, P., Tahvanainen, A., Dixon, M., 2021. Smart infrastructure finance. In: Wendt, K. (Ed.), Green and Social Economy Finance: A Review, 1st ed. Taylor & Francis Group. https://doi.org/10.1201/9780429329326.

Adshead, D., Thacker, S., Fuldauer, L.I., Hall, J.W., 2019. Delivering on the sustainable development goals through long-term infrastructure planning. Glob. Environ. Chang. 59, 101975 https://doi.org/10.1016/j.gloenvcha.2019.101975.

Agliardi, R., 2021. Green securitisation. J. Sustain. Financ. Invest. 1–16 https://doi.org/10.1080/20430795.2021.1874214.

Ahluwalia, S., Mahto, R.V., Guerrero, M., 2020. Blockchain technology and startup financing: a transaction cost economics perspective. Technol. Forecast. Soc. Chang. 151, 119854 https://doi.org/10.1016/j.techfore.2019.119854.

Ajith, V., A.S, R., Mohan, R., Vinodini Ramesh, M., 2022. Empowering communities in addressing drinking water challenges using a systematic, participatory and adaptive approach and sustainable PPP model. Technol. Forecast. Soc. Chang. 185, 121970 https://doi.org/10.1016/j.techfore.2022.121970.

Akomea-Frimpong, I., Jin, X., Osei-Kyei, R., Kukah, A.S., 2021. Public–private partnerships for sustainable infrastructure development in Ghana: a systematic review and recommendations. Smart Sustain. Built Environ. https://doi.org/10.1108/SASBE-07-2021-0111 ahead-of-print(ahead-of-print).

Al-amri, R., Murugesan, R.K., Man, M., Abdulateef, A.F., Al-Sharafi, M.A., Alkahtani, A. A., 2021. A review of machine learning and deep learning techniques for anomaly detection in IoT data. Appl. Sci. 11 (12).

Amenc, N., Blanc-Brude, F., Chreng, A., Tran, C., 2017. The rise of “Fake Infra”: the unregulated growth of listed infrastructure and the dangers it poses to the future of infrastructure investing. https://edhec.infrastructure.institute/paper/the-rise-of-fake-infra/.

American Society of Civil Engineers, 2021. 2021 report card for America's infrastructure executive summary. https://infrastructurereportcard.org/wp-content/uploads/2020/12/2021-IRC-Executive-Summary-1.pdf.

Andonov, A., Kräussl, R., Rauh, J., 2021. Institutional investors and infrastructure investing. Rev. Financ. Stud. 34 (8), 3880–3934. https://doi.org/10.1093/rfs/hhab048.

Avellaneda, O., Bachmann, A., Barbir, A., Brenan, J., Dingle, P., Duffy, K.H., Maler, E., Reed, D., Sporny, M., 2019. Decentralized identity: where did it come from and where is it going? IEEE Commun. Stand. Mag. 3 (4), 10–13. https://doi.org/10.1109/MCOMSTD.2019.9031542.

Bagloee, S.A., Heshmati, M., Dia, H., Ghaderi, H., Pettit, C., Asadi, M., 2021. Blockchain: the operating system of smart cities. Cities 112, 103104. https://doi.org/10.1016/j.cities.2021.103104.

Baker, M., Bergstresser, D., Serafeim, G., Wurgler, J., 2018. Financing the Response to Climate Change: The Pricing and Ownership of U.S. Green Bonds. National Bureau of Economic Research Working Paper Series, No. 25194. https://doi.org/10.3386/w25194.

Baldi, F., Pandimiglio, A., 2022. The role of ESG scoring and greenwashing risk in explaining the yields of green bonds: a conceptual framework and an econometric analysis. Glob. Financ. J. 52, 100711 https://doi.org/10.1016/j.gfj.2022.100711.

Balzarova, M., Dyer, C., Falta, M., 2022. Perceptions of blockchain readiness for fairtrade programmes. Technol. Forecast. Soc. Chang. 185, 122086 https://doi.org/10.1016/j.techfore.2022.122086.

Bartos, M., Wong, B., Kerkez, B., 2018. Open storm: a complete framework for sensing and control of urban watersheds [10.1039/C7EW00374A]. Environ. Sci.: Water Res. Technol. 4 (3), 346–358. https://doi.org/10.1039/C7EW00374A.

Bartos, M.D., Mullapudi, A., Troutman, S.C., 2019. Rrcf: implementation of the robust random cut Forest algorithm for anomaly detection on streams. J. Open Source Softw. 4 (35), 1336. https://doi.org/10.21105/joss.01336.

Batubara, F.R., Ubacht, J., Janssen, M., 2018. Challenges of blockchain technology adoption for e-government: a systematic literature review. In: Proceedings of the 19th Annual International Conference on Digital Government Research: Governance in the Data Age, Delft, The Netherlands. https://doi.org/10.1145/3209281.3209317.

Bhushan, B., Khamparia, A., Sagayam, K.M., Sharma, S.K., Ahad, M.A., Debnath, N.C., 2020. Blockchain for smart cities: a review of architectures, integration trends and future research directions. Sustain. Cities Soc. 61, 102360 https://doi.org/10.1016/j.scs.2020.102360.

Bhutta, U.S., Tariq, A., Farrukh, M., Raza, A., Iqbal, M.K., 2022. Green bonds for sustainable development: review of literature on development and impact of green bonds. Technol. Forecast. Soc. Chang. 175, 121378 https://doi.org/10.1016/j.techfore.2021.121378.

Bianchi, R., Drew, M., Whittaker, T., 2017. Is “Listed Infrastructure” a fake asset class? https://edhec.infrastructure.institute/paper/is-listed-infrastructure-a-fake-asset-class/.

BIS Innovation Hub, 2021. A vision for technology-driven green finance. https://www.bis.org/publ/othp43.htm.

Blanc-Brude, F., 2013. Towards efficient benchmarks for infrastructure equity investments. https://risk.edhec.edu/publications/towards-efficient-benchmarks-infrastructure.

Blanc-Brude, F.G., Abhishek, 2020. Unlisted infrastructure performance contribution, attribution & benchmarking. https://edhec.infrastructure.institute/wp-content/uploads/2020/11/performance_attribution_072020.pdf.

Boehm, S., Lebling, K., Levin, K., Fekete, H., Jaeger, J., Nilsson, A., Wilson, R., Geiges, A., Schumer, C., 2021. State of Climate Action 2021: Systems Transformations Required to Limit Global Warming to 1.5°C.

Bongini, P., Osborne, F., Pedrazzoli, A., Rossolini, M., 2022. A topic modelling analysis of white papers in security token offerings: which topic matters for funding? Technol. Forecast. Soc. Chang. 184, 122005 https://doi.org/10.1016/j.techfore.2022.122005.

Brand, Matthew W., Gudiño-Elizondo, N., Allaire, M., Wright, S., Matson, W., Saksa, P., Sanders, B.F., 2020. Stochastic hydro-financial watershed modeling for environmental impact bonds [10.1029/2020WR027328]. Water Resour. Res. 56 (8), e2020WR027328 https://doi.org/10.1029/2020WR027328.

Brand, M.W., Quesnel Seipp, K., Saksa, P., Ulibarri, N., Bomblies, A., Mandle, L., Allaire, M., Wing, O., Tobin-de la Puente, J., Parker, E.A., Nay, J., Sanders, B.F., Rosowsky, D., Lee, J., Johnson, K., Gudino-Elizondo, N., Ajami, N., Wobbrock, N., Adriaens, P., Gibbons, J.P., 2021. Environmental impact bonds: a common framework and looking ahead. Environ. Res. Infrastruct. Sustain. 1 (2), 023001 https://doi.org/10.1088/2634-4505/ac0b2c.

Breidenbach, L., Cachin, C., Chan, B., Coventry, A., Ellis, S., Juels, A., Koushanfar, F., Miller, A., Magauran, B., Moroz, D., Nazarov, S., Topliceanu, A., Zhang, F., Tram`er, F., 2021. Chainlink 2.0: next steps in the evolution of decentralized oracle networks. https://chain.link/whitepaper.

Cai, Y., Irtija, N., Tsiropoulou, E.E., Veneris, A., 2022. Truthful decentralized blockchain oracles [10.1002/nem.2179]. Int. J. Netw. Manag. 32 (2), e2179 https://doi.org/10.1002/nem.2179.

Calvert, T., Sinnett, D., Smith, N., Jerome, G., Burgess, S., King, L., 2018. Setting the standard for green infrastructure: the need for, and features of, a benchmark in England. Plan. Pract. Res. 33 (5), 558–573. https://doi.org/10.1080/02697459.2018.1531580.

Chen, C., Bartle, J.R., 2017. Infrastructure financing: a guide for local government managers. https://digitalcommons.unomaha.edu/pubadfacpub/77.

Chen, Y., Lu, Y., Bulysheva, L., Kataev, M.Y., 2022. Applications of blockchain in industry 4.0: a review, 2021// Inf. Syst. Front.. https://doi.org/10.1007/s10796-022-10248-7.

Cheng, Z., Wang, H., Xiong, W., Zhu, D., Cheng, L., 2021. Public–private partnership as a driver of sustainable development: toward a conceptual framework of sustainability-oriented PPP. Environ. Dev. Sustain. 23 (1), 1043–1063. https://doi.org/10.1007/s10668-019-00576-1.

Chitikela, S.R., Simerl, J.J., 2017. Municipal water and wastewater infrastructure management and the sustainable utility?A performance contracting (PC) review. World Environ. Water Resour. Congr. 2017, 211–222. https://doi.org/10.1061/9780784480632.015.

Chu, S., Wang, S., 2018. The Curses of Blockchain Decentralization, 30 July-3 Aug. 2018. arXiv. https://doi.org/10.48550/ARXIV.1810.02937.

Codosero Rodas, J.M., Cabezas Fernández, J., Naranjo Gómez, J.M., Castanho, R.A., 2019. Risk premium assessment for the sustainable valuation of urban development land: evidence from Spain. Sustainability 11 (15). https://doi.org/10.3390/su11154191.

National Academies of Sciences, E.collab, Medicine, 2022. Equitable and Resilient Infrastructure Investments. The National Academies Press. https://doi.org/10.17226/26633.

Cousins, J.J., Hill, D.T., 2021. Green infrastructure, stormwater, and the financialization of municipal environmental governance. J. Environ. Policy Plan. 23 (5), 581–598. https://doi.org/10.1080/1523908X.2021.1893164.

Cowden, B., Tang, J., 2022. Institutional entrepreneurial orientation: beyond setting the rules of the game for blockchain technology. Technol. Forecast. Soc. Chang. 180, 121734 https://doi.org/10.1016/j.techfore.2022.121734.

Davie, M., Gisolfi, D., Hardman, D., Jordan, J., Donnell, D.O., Reed, D., 2019. The trust over IP stack. IEEE Commun. Stand. Mag. 3 (4), 46–51. https://doi.org/10.1109/MCOMSTD.001.1900029.

Delanka-Pedige, H.M.K., Munasinghe-Arachchige, S.P., Abeysiriwardana-Arachchige, I.S. A., Nirmalakhandan, N., 2021. Wastewater infrastructure for sustainable cities: assessment based on UN sustainable development goals (SDGs). Int J Sust Dev World 28 (3), 203–209. https://doi.org/10.1080/13504509.2020.1795006.

Duclos, C., 2019. Infrastructure investment as a true portfolio diversifier. J. Priv. Equity 23 (1), 30–38. https://doi.org/10.3905/jpe.2019.1.096.

Fernandez, V., 2022. Environmental management: implications for business performance, innovation, and financing. Technol. Forecast. Soc. Chang. 182, 121797 https://doi.org/10.1016/j.techfore.2022.121797.

Ferrarez, R.P.F., Vargas, R.V., Alvarenga, J.C., Chinelli, C.K., de Almeida Costa, M., de Oliveira, B.L., Haddad, A.N., Soares, C.A.P., 2020. Sustainability indicators to assess infrastructure projects: sector disclosure to interlock with the global reporting initiative. Eng. J. 24 (6), 43–61. https://doi.org/10.4186/ej.2020.24.6.43.

Gartner, 2021. Hype cycle for blockchain 2021. https://blogs.gartner.com/avivah-litan/2021/07/14/hype-cycle-for-blockchain-2021-more-action-than-hype/.

Gatti, S., 2018. 3 - Project characteristics, risk analysis, and risk management. In: Gatti, S. (Ed.), Project Finance in Theory and Practice, Third edition. Academic Press, pp. 63–103. https://doi.org/10.1016/B978-0-12-811401-8.00003-9.

Gatzert, N., Kosub, T., 2016. Insurers' investment in infrastructure: overview and treatment under solvency II. In: Courbage, C. (Ed.), The Geneva Papers: 40 Years at the Cutting Edge of Research in Insurance Economics. Palgrave Macmillan UK, pp. 74–101. https://doi.org/10.1007/978-1-137-57479-4_4.

Gilson, L.L., Goldberg, C.B., 2015. Editors' comment: so, what is a conceptual paper? Group Org. Manag. 40 (2), 127–130. https://doi.org/10.1177/1059601115576425.

Giráldez, J., Fontana, S., 2022. Sustainability-linked bonds: the next frontier in sovereign financing. Cap. Mark. Law J. 17 (1), 8–19. https://doi.org/10.1093/cmlj/kmab033.

Global Infrastructure Hub, 2017. Global infrastructure outlook. https://www.oxfordeconomics.com/recent-releases/Global-Infrastructure-Outlook.

Glomann, L., Schmid, M., Kitajewa, N., 2020. Improving the Blockchain User Experience - An Approach to Address Blockchain Mass Adoption Issues from a Human-Centred Perspective. Advances in Artificial Intelligence, Software and Systems Engineering, Cham, 2020//.

Gonzalez-Ruiz, J.D., Arboleda, A., Botero, S., Rojo, J., 2019. Investment valuation model for sustainable infrastructure systems. Eng. Constr. Archit. Manag. 26 (5), 850–884. https://doi.org/10.1108/ECAM-03-2018-0095.

Hallegatte, S., Rentschler, J., Rozenberg, J., 2019. Lifelines : the resilient infrastructure opportunity. World Bank. https://openknowledge.worldbank.org/handle/10986/31805.

He, Q., Wang, Z., Wang, G., Xie, J., Chen, Z., 2021. The dark side of environmental sustainability in projects: unraveling greenwashing behaviors. Proj. Manag. J. https://doi.org/10.1177/87569728211042705, 87569728211042705.

Herrmann, P., Spang, K., 2020. What About Coordination, Transparency and Anticipation in Projects? A Systematic Review of "Controlling" of Projects, Especially of Public Infrastructure Projects, 2020//. Eurasian Business Perspectives, Cham.

Hillman, J., Tippett, A., 2021. Financing global infrastructure: the role of the private sector. https://www.cfr.org/blog/financing-global-infrastructure-role-private-sector.

Hoeft, M., Pieper, M., Eriksson, K., Bargstädt, H.-J., 2021. Toward life cycle sustainability in infrastructure: the role of automation and robotics in PPP projects. Sustainability 13 (7). https://doi.org/10.3390/su13073779.

Hyun, S., Park, D., Tian, S., 2020. The price of going green: the role of greenness in green bond markets [10.1111/acfi.12515]. Account. Finance 60 (1), 73–95. https://doi.org/10.1111/acfi.12515.

Iwamura, M., Kitamura, Y., Matsumoto, T., Saito, K., 2019. Can we stabilize the price of a CRYPTOCURRENCY?: understanding the design of bitcoin and its potential to compete with central bank money. Hitotsubashi J. Econ. 60 (1), 41–60. http://www.jstor.org/stable/45124706.

Jaakkola, E., 2020. Designing conceptual articles: four approaches. AMS Rev. 10 (1), 18–26. https://doi.org/10.1007/s13162-020-00161-0.

Jansen, K., Tuijp, P., 2021. A survey of institutional investors' investment and management decisions on illiquid assets. J. Portf. Manag. 47 (3), 135. https://doi.org/10.3905/jpm.2020.1.202.

Jin, Y., Li, B., Roca, E., Wong, V., 2016. Water as an investment: liquid yet illiquid! Appl. Econ. 48 (9), 731–745. https://doi.org/10.1080/00036846.2015.1085646.

Jochimsen, R., 1966. Theorie der Infrastruktur : Grundlagen der marktwirtschaftlichen Entwicklung. J.C.B. Mohr.

Jonsdottir, B., Sigurjonsson, T.O., Johannsdottir, L., Wendt, S., 2022. Barriers to using ESG data for investment decisions. Sustainability 14 (9). https://doi.org/10.3390/su14095157.

Kaleem, M., Shi, W., 2021. Demystifying Pythia: A Survey of ChainLink Oracles Usage on Ethereum. Financial Cryptography and Data Security. FC 2021 International Workshops, Berlin, Heidelberg, 2021//.

Kölbel, J., Lambillon, A.-P., 2022. Who Pays for Sustainability? An Analysis of Sustainability-Linked Bonds.

Li, Z., Liao, Q., 2018. Economic solutions to improve cybersecurity of governments and smart cities via vulnerability markets. Gov. Inf. Q. 35 (1), 151–160. https://doi.org/10.1016/j.giq.2017.10.006.

Li, Y., Yang, W., He, P., Chen, C., Wang, X., 2019. Design and management of a distributed hybrid energy system through smart contract and blockchain. Appl. Energy 248, 390–405. https://doi.org/10.1016/j.apenergy.2019.04.132.

Lindsay, M., Ulrich, C., Mooring, P., 2021. DC water's pioneering environmental impact bond a success, 2020//. https://www.quantifiedventures.com/dc-water-eib-results.

Liu, J., Fukushige, M., 2020. Efficiency and pricing of water supply and sewerage services in Japan. Util. Policy 62, 100984. https://doi.org/10.1016/j.jup.2019.100984.

Liu, Y., Pang, Z., Karlsson, M., Gong, S., 2020. Anomaly detection based on machine learning in IoT-based vertical plant wall for indoor climate control. Build. Environ. 183, 107212 https://doi.org/10.1016/j.buildenv.2020.107212.

Lockl, J., Schlatt, V., Schweizer, A., Urbach, N., Harth, N., 2020. Toward Trust in Internet of things ecosystems: design principles for blockchain-based IoT applications. IEEE Trans. Eng. Manag. 67 (4), 1256–1270. https://doi.org/10.1109/TEM.2020.2978014.

Lovell, K., Watson, J., Hiteva, R., 2022. Infrastructure decision-making: opening up governance futures within techno-economic modelling. Technol. Forecast. Soc. Chang. 174, 121208 https://doi.org/10.1016/j.techfore.2021.121208.

Lu, Z., Peña-Mora, F., Wang, X.R., Shen, C.Q., Riaz, Z., 2015. Social impact project finance: an innovative and sustainable infrastructure financing framework. Procedia Eng. 123, 300–307. https://doi.org/10.1016/j.proeng.2015.10.094.

Makovšek, D., Moszoro, M., 2018. Risk pricing inefficiency in public–private partnerships. Transp. Rev. 38 (3), 298–321. https://doi.org/10.1080/01441647.2017.1324925.

Marsal-Llacuna, M.-L., 2020. The people's smart city dashboard (PSCD): delivering on community-led governance with blockchain. Technol. Forecast. Soc. Chang. 158, 120150 https://doi.org/10.1016/j.techfore.2020.120150.

Meltzer, J.P., Constantine, C., 2018. Blending climate funds to finance low-carbon, climate-resilient infrastructure. https://www.brookings.edu/research/blending-climate-funds-to-finance-low-carbon-climate-resilient-infrastructure/.

Meyer, P.B., Schwarze, R., 2019. Financing climate-resilient infrastructure: determining risk, reward, and return on investment. Front. Eng. Manag. 6 (1), 117–127. https://doi.org/10.1007/s42524-019-0009-4.

Mnif, E., Mouakhar, K., Jarboui, A., 2021. Blockchain technology awareness on social media: insights from twitter analytics. J. High Technol. Manag. Res. 32 (2), 100416 https://doi.org/10.1016/j.hitech.2021.100416.

Mohammed, A., Almousa, A., Ghaithan, A., Hadidi, L.A., 2021. The role of blockchain in improving the processes and workflows in construction projects. Appl. Sci. 11 (19) https://doi.org/10.3390/app11198835.

Moseley, M., 2018. Blockchain, smart contracts and infrastructure. https://www.gihub.org/articles/blockchain-smart-infrabonds/.

Mühlberger, R., Bachhofner, S., Castelló Ferrer, E., Di Ciccio, C., Weber, I., Wöhrer, M., Zdun, U., 2020. Foundational Oracle Patterns: Connecting Blockchain to the Off-Chain World. Business Process Management: Blockchain and Robotic Process Automation Forum, Cham, 2020//.

Nakamoto, S., 2008. Bitcoin: a peer-to-peer electronic cash system. https://bitcoin.org/en/.

Nicole, G., Robert, H., 2013. Trust and the global financial crisis. In: Handbook of Advances in Trust Research. Edward Elgar Publishing. https://doi.org/10.4337/9780857931382.00019.

Oberhauser, D., 2019. Blockchain for environmental governance: can smart contracts reinforce payments for ecosystem services in Namibia? [Technology and code], 2020// Front. Blockchain 2. https://www.frontiersin.org/article/10.3389/fbloc.2019.00021.

Omar, I.A., Hasan, H.R., Jayaraman, R., Salah, K., Omar, M., 2021. Implementing decentralized auctions using blockchain smart contracts. Technol. Forecast. Soc. Chang. 168, 120786 https://doi.org/10.1016/j.techfore.2021.120786.

OpenZeppelin, 2017. Tokens. https://docs.openzeppelin.com/contracts/2.x/tokens.

Osterland, T., Rose, T., 2021. Oracle-based Process Automation in DLT Dominated Ecosystems With an Application to German Waterway Transportation 2021 2nd Asia Service Sciences and Software Engineering Conference, Macau, Macao. https://doi.org/10.1145/3456126.3456132.

Palmer, M.A., Liu, J., Matthews, J.H., Mumba, M., D'Odorico, P., 2015. Water security: gray or green? Science 349 (6248). https://doi.org/10.1126/science.349.6248.584-a, 584-584.

Park, J., Kim, H., Kim, G., Ryou, J., 2021. Smart contract data feed framework for privacy-preserving Oracle system on blockchain. Computers 10 (1). https://doi.org/10.3390/computers10010007.

Poblet, M., Allen, D.W.E., Konashevych, O., Lane, A.M., Diaz Valdivia, C.A., 2020. From Athens to the blockchain: oracles for digital democracy [original research]. Front. Blockchain 3. https://www.frontiersin.org/article/10.3389/fbloc.2020.575662.

President Executive Order 14057, 2021. Catalyzing clean energy industries and jobs through federal sustainability. Retrieved from. https://www.fedcenter.gov/programs/eo14057/.

Quantified Ventures, 2021. DC water's pioneering environmental impact bond a success. https://www.quantifiedventures.com/dc-water-eib-results.

Ramu, S.P., Boopalan, P., Pham, Q.-V., Maddikunta, P.K.R., Huynh-The, T., Alazab, M., Nguyen, T.T., Gadekallu, T.R., 2022. Federated learning enabled digital twins for smart cities: concepts, recent advances, and future directions. Sustain. Cities Soc. 79, 103663 https://doi.org/10.1016/j.scs.2021.103663.

Rathore, S., Wook Kwon, B., Park, J.H., 2019. BlockSecIoTNet: blockchain-based decentralized security architecture for IoT network. J. Netw. Comput. Appl. 143, 167–177. https://doi.org/10.1016/j.jnca.2019.06.019.

Rivera, R., Robledo, J.G., Larios, V.M., Avalos, J.M., 2017. How digital identity on blockchain can contribute in a smart city environment. In: 2017 International Smart Cities Conference (ISC2).

Roelofs, P., 2019. Transparency and mistrust: who or what should be made transparent? [10.1111/gove.12402]. Governance 32 (3), 565–580. https://doi.org/10.1111/gove.12402.

Rossi, E., Stepic, R., 2015. European infrastructure project finance market. In: Rossi, E., Stepic, R. (Eds.), Infrastructure Project Finance and Project Bonds in Europe. Palgrave Macmillan UK, pp. 25–51. https://doi.org/10.1057/9781137524041_3.

Russo, S., Lürig, M., Hao, W., Matthews, B., Villez, K., 2020. Active learning for anomaly detection in environmental data. Environ. Model Softw. 134, 104869 https://doi.org/10.1016/j.envsoft.2020.104869.

Sadawi, A.A., Madani, B., Saboor, S., Ndiaye, M., Abu-Lebdeh, G., 2021. A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. Technol. Forecast. Soc. Chang. 173, 121124 https://doi.org/10.1016/j.techfore.2021.121124.

Salzman, J., Bennett, G., Carroll, N., Goldstein, A., Jenkins, M., 2018. The global status and trends of payments for ecosystem services. Nat. Sustain. 1 (3), 136–144. https://doi.org/10.1038/s41893-018-0033-0.

Santana, C., Albareda, L., 2022. Blockchain and the emergence of decentralized autonomous organizations (DAOs): an integrative model and research agenda. Technol. Forecast. Soc. Chang. 182, 121806 https://doi.org/10.1016/j.techfore.2022.121806.

Saxton, G.D., Gomez, L., Ngoh, Z., Lin, Y.-P., Dietrich, S., 2019. Do CSR messages resonate? Examining public reactions to firms' CSR efforts on social media. J. Bus. Ethics 155 (2), 359–377. https://doi.org/10.1007/s10551-017-3464-z.

Sclar, E., 2015. The political economics of investment utopia: public–private partnerships for urban infrastructure finance. J. Econ. Policy Reform 18 (1), 1–15. https://doi.org/10.1080/17487870.2014.950857.

Sengupta, R., Hebb, T., Mustafa, H., 2018. In: Seeking Greener Pastures: Exploring the Impact for Investors of ESG Integration in the Infrastructure Asset Class, pp. 89–113. https://doi.org/10.1007/978-3-319-66387-6_4.

Sheldon, M.D., 2020. Auditing the blockchain Oracle problem. J. Inf. Syst. 35 (1), 121–133. https://doi.org/10.2308/ISYS-19-049.

Shi, P., Wang, H., Yang, S., Chen, C., Yang, W., 2021. Blockchain-based trusted data sharing among trusted stakeholders in IoT [10.1002/spe.2739]. Softw. Pract. Experience 51 (10), 2051–2064. https://doi.org/10.1002/spe.2739.

Snyder, H., 2019. Literature review as a research methodology: an overview and guidelines. J. Bus. Res. 104, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039.

Sporny, M., Longley, D., Sabadello, M., Reed, D., Steele, O., Allen, C., 2021. Decentralized identifiers (DIDs) v1.0. core architecture, data model, and representations. https://www.w3.org/TR/did-core/.

Sporny, M., Longley, D., Chadwick, D., 2022. Verifiable credentials data model v1.1 W3C. https://www.w3.org/TR/vc-data-model/.

Sugrue, D., Adriaens, P., 2022. Maritime transport efficiency to inform demand-driven user fees for harbor infrastructure. J. Waterw. Port Coast. Ocean Eng. 148 (1), 04021049 https://doi.org/10.1061/(ASCE)WW.1943-5460.0000695.

Suleiman, L., 2021. Blue green infrastructure, from niche to mainstream: challenges and opportunities for planning in Stockholm. Technol. Forecast. Soc. Chang. 166, 120528 https://doi.org/10.1016/j.techfore.2020.120528.

Tao, H., Zhuang, S., Xue, R., Cao, W., Tian, J., Shan, Y., 2022. Environmental finance: an interdisciplinary review. Technol. Forecast. Soc. Chang. 179, 121639 https://doi.org/10.1016/j.techfore.2022.121639.

Teng, S.Y., Touš, M., Leong, W.D., How, B.S., Lam, H.L., Máša, V., 2021. Recent advances on industrial data-driven energy savings: digital twins and infrastructures. Renew. Sust. Energ. Rev. 135, 110208 https://doi.org/10.1016/j.rser.2020.110208.

Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., O'Regan, N., Rozenberg, J., Watkins, G., Hall, J.W., 2019. Infrastructure for sustainable development. Nat. Sustain. 2 (4), 324–331. https://doi.org/10.1038/s41893-019-0256-8.

Tian, Y., Lu, Z., Adriaens, P., Minchin, R.E., Caithness, A., Woo, J., 2020. Finance infrastructure through blockchain-based tokenization. Front. Eng. Manag. 7 (4), 485–499. https://doi.org/10.1007/s42524-020-0140-2.

Tirumala, R.D., Tiwari, P., 2022. Innovative financing mechanism for blue economy projects. Mar. Policy 139, 104194. https://doi.org/10.1016/j.marpol.2020.104194.

Uckelmann, D., Harrison, M., Michahelles, F., 2011. An architectural approach towards the future internet of things. In: Uckelmann, D., Harrison, M., Michahelles, F. (Eds.), Architecting the Internet of Things. Springer, Berlin Heidelberg, pp. 1–24. https://doi.org/10.1007/978-3-642-19157-2_1.

United Nations Environment Programme Finance Initiative, 2021. Principle for responsible banking guidance document. https://www.unepfi.org/publications/principles-for-responsible-banking-guidance-document/.

United States Environmental Protection Agency, 2022. Environmental benefits of clean water state revolving fund green infrastructure projects. https://www.epa.gov/cwsrf/environmental-benefits-clean-water-state-revolving-fund-green-infrastructure-projects.

United States White House Briefing Room, 2021. FACT SHEET: president biden and G7 leaders launch build back better world (B3W) partnership. Retrieved from. https://www.whitehouse.gov/briefing-room/statements-releases/2021/06/12/fact-sheet-president-biden-and-g7-leaders-launch-build-back-better-world-b3w-partnership/.

Uzsoki, D., 2019. Tokenization of Infrastructure: a blockchain-based solution to financing sustainable infrastructure. https://www.iisd.org/publications/tokenization-infrastructure-blockchain-based-solution-financing-sustainable.

Weber, B., Staub-Bisang, M., Alfen, H.W., 2016. Infrastructure as an asset class : investment strategy, sustainability, project finance and PPP. John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/umichigan/detail.action?docID=4526802.

Woo, J., Fatima, R., Kibert, C.J., Newman, R.E., Tian, Y., Srinivasan, R.S., 2021. Applying blockchain technology for building energy performance measurement, reporting, and verification (MRV) and the carbon credit market: a review of the literature. Build. Environ. 205, 108199 https://doi.org/10.1016/j.buildenv.2021.108199.

World Bank Group, 2017. Who sponsors infrastructure projects? Disentangling public and private contributions. https://library.pppknowledgelab.org/documents/5719.

World Bank Group, 2021. Private participation in infrastructure. https://ppi.worldbank.org/en/customquery.

Yasskin, J., 2022. Signed HTTP exchanges. Internet engineering task force. https://wicg.github.io/webpackage/draft-yasskin-http-origin-signed-responses.html.

Zarir, A.A., Oliva, G.A., Jiang, Z.M., Hassan, A.E., 2021. Developing cost-effective blockchain-powered applications: a case study of the gas usage of smart contract transactions in the ethereum blockchain platform. ACM Trans. Softw. Eng. Methodol. 30 (3), 28 https://doi.org/10.1145/3431726.

Zhang, Y., O'Connor Sean, M., van der Linden Gwendolyn, W., Prakash, A., Lynch Jerome, P., 2016. SenStore: a scalable cyberinfrastructure platform for implementation of data-to-decision frameworks for infrastructure health management. J. Comput. Civ. Eng. 30 (5), 04016012 https://doi.org/10.1061/(ASCE)CP.1943-5487.0000560.

Zhang, F., Maram, D., Malvai, H., Goldfeder, S., Juels, A., 2020. DECO: liberating web data using decentralized oracles for TLS. In: Proceedings of the 2020 ACM SIGSAC Conference on Computer and Communications Security. Association for Computing Machinery, pp. 1919–1938. https://doi.org/10.1145/3372297.3417239.

Zhang, Y., Wang, T., Yuen, K.-V., 2021. Construction site information decentralized management using blockchain and smart contracts [10.1111/mice.12804]. Comput. Aided Civ. Inf. Eng. https://doi.org/10.1111/mice.12804 n/a(n/a).

Zhu, B., Zhao, Y., 2022. Carbon risk and the cost of bank loans: evidence from China. Technol. Forecast. Soc. Chang. 180, 121741 https://doi.org/10.1016/j.techfore.2022.121741.