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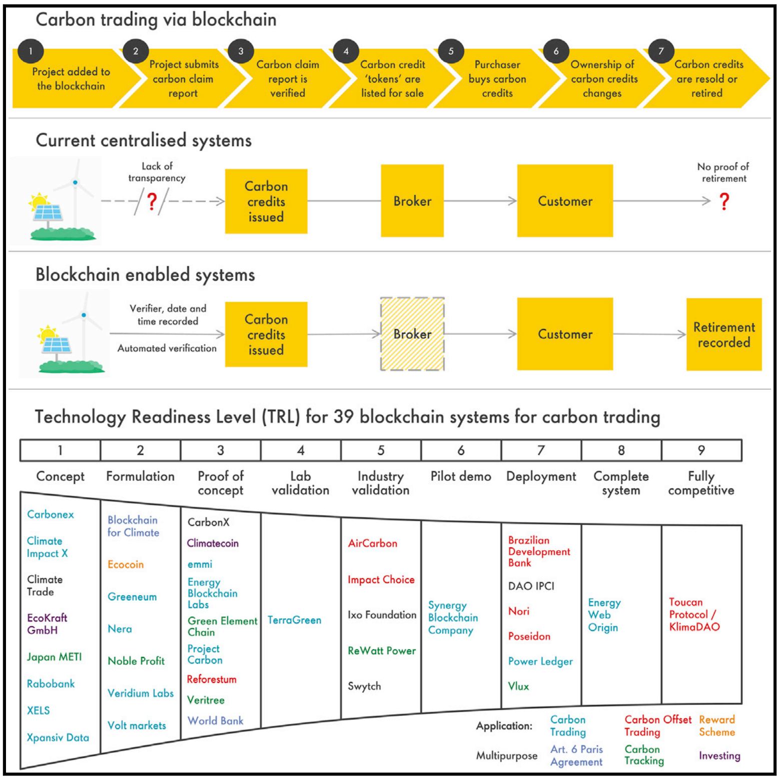
One Earth

Blockchain solutions for carbon markets are nearing maturity

Graphical abstract



Highlights

- Blockchain technology offers many improvements to carbon markets
- We assess the technology readiness level for 39 organizations developing blockchain solutions
- The market is currently immature; most solutions are at or before proof of concept
- Key technical, infrastructural, and regulatory barriers are identified

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In brief

Blockchain has a reputation of being over-hyped and under-delivering. In theory, it has the potential to offer significant improvements to carbon markets that strengthen climate change mitigation efforts. However, empirical knowledge on whether blockchain solutions can enable transparent and effective carbon markets remains limited. Here, we attempt to objectively assess the blockchain solutions developed for carbon markets in order to understand what benefits they offer, and this reveals that there are now commercially viable solutions already creating an impact in the market. Although blockchain is a tool to improve carbon offset tracking and trading, it is no panacea.

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One Earth

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Article

Blockchain solutions for carbon markets are nearing maturity

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SCIENCE FOR SOCIETY Carbon markets are rapidly spreading across the globe, and where compliance schemes are missing, the voluntary carbon market can step in. These markets put a price on carbon and enable a liquid market—a free market with low transaction costs and high flexibility—to avoid, reduce, or remove carbon from the atmosphere. These markets are not without criticisms, however, and many are advocating for higher quality carbon offsets, greater stringency, and greater supply chain transparency. The underlying technology behind cryptocurrencies, the blockchain, is often touted as a way to overcome those criticisms, but the extent to which they can exert a significant impact remains unclear. An overview of blockchain-powered carbon-market projects from 39 organizations shows that there are now technologically ready solutions, such as the Toucan Protocol or the work of the Energy Web Foundation, which can indeed improve carbon offset tracking and trading along supply chains. Nevertheless, several barriers prevent a widespread maturity of blockchain solutions for carbon markets, not least of which is a lack of regulatory certainty that is stifling development in larger (and more conservative) companies.

SUMMARY

Carbon markets could hasten climate change mitigation by driving investment towards efficient decarbonization activities, but they face problems around trust, transparency, and uptake. Blockchain offers a foundational technology upon which new carbon markets can be built which address these shortcomings. This sector is still nascent, fragmented, and clouded by technology hype, all of which obscures objective judgement of its performance and suitability. Here, we survey the current blockchain ecosystem, identifying 39 organizations that are developing blockchain solutions for carbon markets across four use cases: emissions-trading schemes, voluntary carbon markets, Article 6 of the Paris Agreement, and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). We develop and apply a technology readiness level (TRL) scale, and we find that most projects are still proofs of concept (TRL $\leq$ 3); however, one system has now reached maturity (TRL 9). Addressing the common barriers that face developers could allow more blockchain solutions to mature and potentially facilitate globalized carbon markets with greater efficiency, transparency, and accessibility.

INTRODUCTION

Climate change is the greatest example of market failure ever seen.[1] Carbon markets are critical in helping the world attain net-zero greenhouse-gas emissions.[2] They guide financial capital towards activities that decarbonize most efficiently, as they create flexibility over where and when decarbonization happens.[3,4] If one party wishes to reduce emissions but another finds it easier to do so, carbon markets allow them to trade, so that mitigation occurs at lower cost.

Carbon markets are now valued at over $100 billion,[2] placing a price on one-fifth of global emissions.[5] However, this is achieved through a patchwork of carbon taxes and trading schemes, with inconsistent coverage and unlinked prices. The willingness to pay of private investors to fund climate change mitigation outstrips current investments due to a lack of trust and access to current markets.[6]

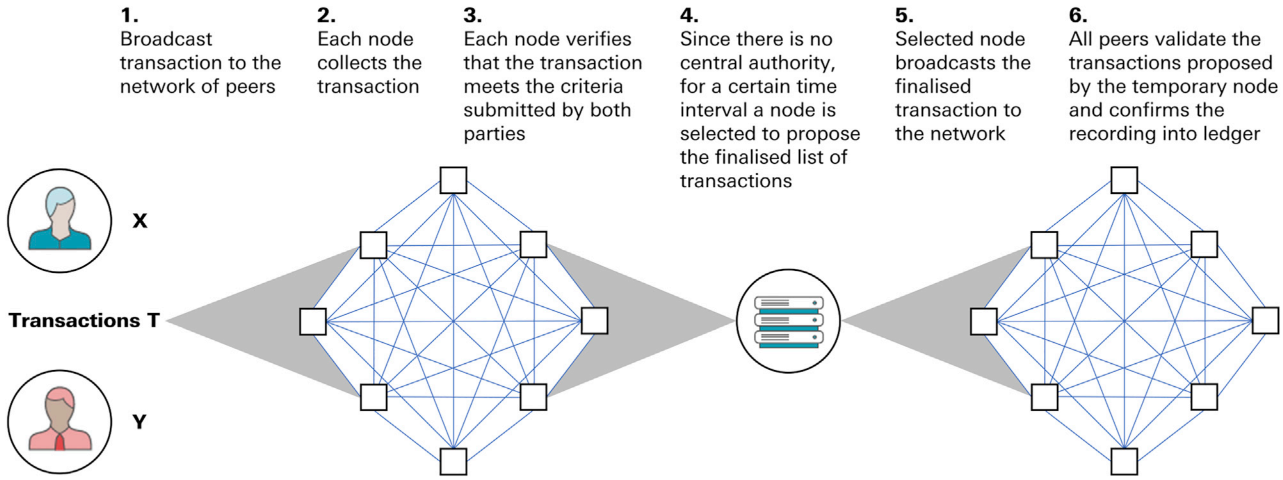

Figure 1. The steps required for a transaction to be added to a blockchain
Adapted from Shell[14] and Yaga et al.[15]

Blockchain technology has been suggested as means to increase the efficiency, accessibility, and integrity of carbon markets.[7,8] The United Nations supported research into the topic,[9] resulting in a surge of media attention around the potential of blockchains for carbon markets[10–12] and the formation of dozens of start-up companies.

A public blockchain is an immutable, tamper-proof, shared ledger of state changes of a digital asset.[13] This means it is a permanent, publicly held record of information that nobody owns or can edit, yet anybody can view or add to. It can (for example) hold details of transactions and ownership of assets, much like a bank ledger, except that everybody knows and agrees upon who owns what at any point in time, and the entire transaction history can be viewed publicly. Figure 1 illustrates a simplified transaction between two entities in a blockchain system. For a glossary of terms, the technical fundamentals of blockchains, and two main blockchain platforms, please see Notes S1–S3.

Carbon trading is a market-based instrument used to mitigate climate change (see Note S4 for detail). First introduced as part of the 1997 Kyoto Protocol, there are now 64 emissions-trading systems and national carbon taxes in force or scheduled, covering around one-fifth of global greenhouse-gas emissions.[5] The European Union's Emission Trading System (EU ETS) is the largest carbon market in the world (see Note S5), covering 45% of EU greenhouse-gas emissions and delivering a 20% reduction by 2020 compared with 1990 levels.[16]

These are compliance carbon markets (CCMs), in which regions or nations regulate and trade allowances to emit carbon. Voluntary carbon markets (VCMs) are an alternative that enable companies and individuals to trade carbon credits as part of their net-zero transition strategies (see Note S6).[17] Voluntary carbon markets are much smaller than compliance markets, but demand for carbon offsets has increased 100-fold over the last decade.[18] Other notable implementations include Article 6 of the Paris Agreement,[19] an international cooperation between countries to reach their nationally determined contributions (see Note S7), and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which seeks "carbon neutral growth" of the aviation industry (see Note S8).[20]

The core problems with carbon markets include trust, transparency, and utilization. Trust in the legitimacy of the carbon savings being sold is a concern[6] due to weak regulation and evaluation of projects,[21,22] along with markets' vulnerability to gaming and fraud[21,23] and the potential for emissions leakage.[24] Poor industry accounting means the amount of carbon that has been offset is not accurately known. While offset generation data are publicly available, there is currently no database that aggregates this information.[18] Complex trading processes and high transaction costs lead to lack of participation in voluntary markets and thus low liquidity and irrational price formation.[5]

Blockchain is one potential solution to overcome these problems,[25,26] a foundational technology upon which transparent, trustworthy, and liquid carbon markets can be built. The similarities between digital currencies and carbon credits (both are fungible and can be created) mean the features that make blockchain successful as a currency can improve many aspects of carbon markets. Its immutable nature and publicly visible record enable robust accounting practices that avoid ambiguity over ownership and double counting of emissions reductions. Using a public blockchain ensures accessible record checking and therefore additional accountability on the parties involved, while also enabling faster and cheaper administration with real-time settlement. It has the potential to automate and apply credibility throughout the carbon-credit supply chain, once rules are established. Blockchain's interoperability with other systems without a third-party intermediary[27] has led to propositions that it be used in international carbon markets.[26,28,29] The fractionalization of carbon credits into units of less than 1 tCO_2 enables new business-to-consumer marketplaces, where retailers offer customers the opportunity to offset the carbon emissions in products they purchase.[30] Despite these benefits, blockchain can only tackle a subset of the problems facing carbon markets; technology alone cannot resolve the intricacies of political relations or issues around accountability.

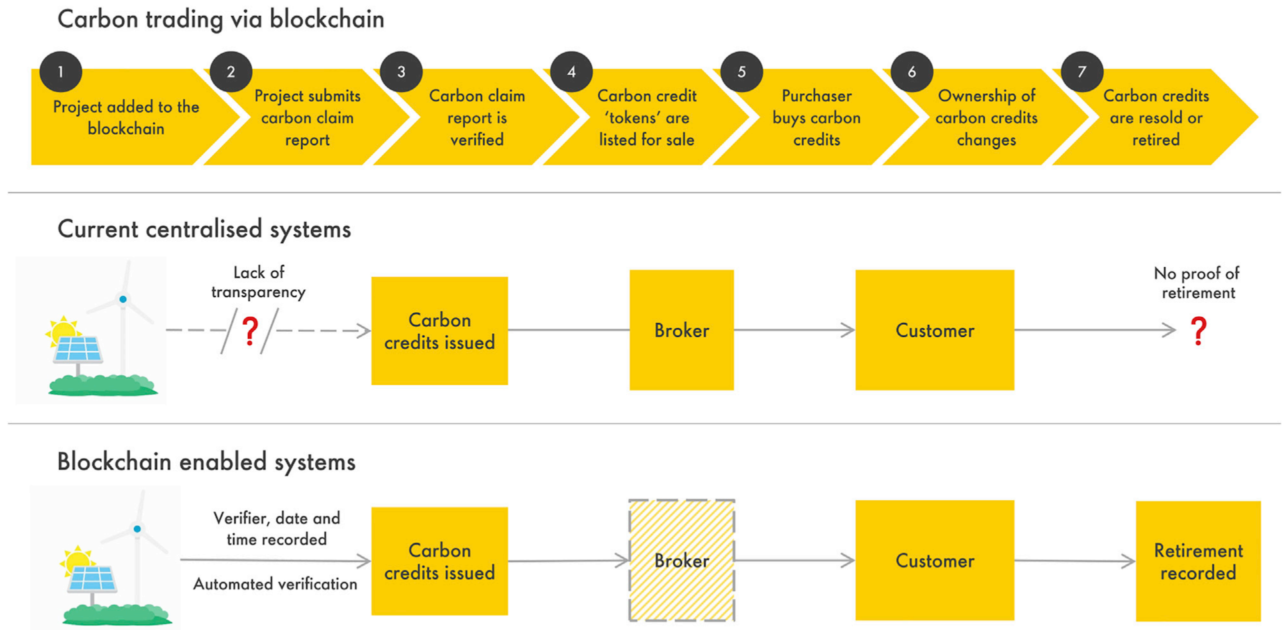

Figure 2. Schematic overview of carbon trading on a blockchain versus a centralized platform

The top panel shows the simplified steps required for a carbon trade to occur on a blockchain platform, whereby project owners create tokens for carbon-saving projects, which are then traded via the decentralized market. The middle and bottom panels illustrate the differences between carbon offsetting via centralized and blockchain platforms. The dashed border around brokers in the latter case indicates that they are not strictly necessary, but no current projects are observed with projects selling directly to customers.

There is no firm consensus on how blockchain could be used in practice for carbon markets, in the same way as it would have been difficult to envisage in 1990 how the internet would be used for financial markets. One plausible example would be an Internet of Things (IoT)-connected forest self-verifies the carbon it sequesters using sensor data and remote imaging. These savings could be issued on the ledger and automatically verified after hitting the requirements of a company's carbon-offset-verification criteria. They are then issued on a marketplace and are purchased, retired, or resold. A recent example is the Toucan Protocol, which takes credits from the Verified Carbon Standard (VCS), retires them, and mints a replica token on the blockchain known as a Base Carbon Tonne that can be transferred or sold as required.[31] Two parties can trade in the absence of trust without a third-party intermediary, as illustrated in Figure 2, giving reduced administration costs across the system (see Note S6 for issues faced around removing intermediaries).[32]

While numerous media and gray-literature articles consider the potential for blockchain and carbon trading and analyze the prospects of individual companies, there has been comparatively little academic work on the topic, and much of it is purely hypothetical.[32,33,39]. For example, recent work has either proposed ways to incorporate blockchain into carbon markets[34] and their verification systems[35–37] or assessed the suitability of blockchain for individual markets, such as Article 6 of the Paris Agreement[25,38] or carbon trading scheme pilots in China.[39]

Here, we complement existing work by providing an unbiased assessment of the market as a whole, rather than focusing on individual markets or technologies. We explore 39 organizations that are developing blockchain solutions to examine how blockchain technology could be implemented in carbon markets, covering four common use cases: emission-trading schemes, voluntary carbon markets, Article 6 of the Paris Agreement, and the aviation industry's CORSIA scheme (see Notes S5–S8 for details on each). We assess the current blockchain ecosystem by classifying all organizations working in the sector with a bespoke technology readiness level (TRL) scale, which follows the EU Horizon 2020 methodology. Results show that most projects are still at the proof-of-concept (TRL $\leq$ 3) level, with one project (KlimaDAO) having now reached maturity (TRL 9). Our work identifies the existing barriers to implementation and gives policy recommendations on how to overcome these and increase the speed of development of blockchain solutions with a clear competitive advantage over current systems.

RESULTS

Method summary

A mixed-methods approach was taken, combining a systematic literature reviewand semi-structured interviews with a quantitative assessment of companies using the TRL scale.

A literature review was undertaken to synthesize the advantages and disadvantages of the main proposed use cases and to identify the organizations designing blockchain solutions for carbon markets. The justification and selection criteria were as broad as possible: simply any technology for which we could find sufficient information. Interviews with market participants and carbon market experts supplemented the literature review. The market analysis used 118 sources and interviews with seven

Table 1. The technology readiness level scale created for evaluating blockchain solutions in carbon markets

TRL	Description	Criteria
1.	basic principles observed	clear use case explained in the organization's documentation
2.	technology concept formulated	technical details listed, including blockchain platform and consensus mechanism
3.	experimental proof of concept (PoC)	evidence of the creation of a (private) PoC[a]
4.	technology validated in lab	data published on the technology, either through GitHub, transaction data, or through published data
5.	technology validated in industry-relevant environment	2+ partnerships with external companies announced. This assumes that collaboration would only occur if the organization has proven their use case privately.
6.	technology demonstrated in relevant environment	media reports or public data released of partner PoC or pilot successfully using the technology
7.	system prototype demonstration in operational environment	proof of use in an operational supply chain as opposed to using a test environment
8.	system complete and qualified	If produced, the envisioned roadmap to production is completed. Security and quality have been verified by third parties. All code is publicly available in open-source projects and functional.
9.	actual system proven in operational environment (and competitive)	blockchain technology is fully implemented into the system and working competitively to other projects at full capacity

[a]If working pilot or transaction data existed on https://etherscan.io, then TRL 3 was completed.

stakeholders (typically with the chief executive officers [CEOs] of start-up companies) to identify 39 companies that are developing blockchain solutions for carbon markets. A full list of sources is given in Table S1, and overviews of the companies and use cases can be found in Table S2.

We use the TRL scale to measure the maturity of a technology. Initially developed by National Aeronautics and Space Administration (NASA) for space applications, it has been used extensively for military technology and public sector research[40] and more recently for blockchain projects.[41,42] Here, we use the EU Horizon 2020 methodology as a framework to develop a blockchain-specific TRL scale, which plots the progression of technologies from TRL 1 (nascent) through to TRL 9 (mature).[43] Technical blockchain experts (those detailed in the experimental procedures) were consulted to adapt the scale and produce clearly defined criteria to achieve each level, as listed in Table 1. For a project to be awarded a certain TRL, the criteria of all previous levels must be reached. For the TRL analysis, data were sourced from organization websites, whitepapers and media reports, and through interviews (see Table S1).

The technology readiness level of blockchain solutions

These solutions can be categorized into six specific use cases (see Table S3). Half of the identified companies are developing solutions for carbon trading, which includes both compliance markets and voluntary markets. As a further 25% of companies are developing solutions specifically for carbon-offset credits, these are included as a separate category. The majority of solutions are not tied to a specific market, giving products that could be applied to any carbon market. Some companies are working on multiple solutions, such as DAO IPCI, who are producing blockchain platforms for non-specific carbon trading, carbon offset trading, and Article 6.[44] Other use cases identified include using blockchain technology to crowd fund low-carbon and carbon-offsetting projects, and rewarding carbon-reducing consumer behavior, but these can be considered niche cases due to their small market share.

Figure 3 shows the results of the TRL analysis. The market is immature, with more than half of the solutions currently in the lowest three levels: at initial proof-of-concept stage or below. The median value is TRL 3, and there is no correlation between use case and TRL, with the exception of carbon-investing solutions being the most underdeveloped with a mean TRL of 1.67. The results show the accumulation of projects at TRL 3, 5, and 7, suggesting that specific barriers cause progress to stall at these levels (see the section "Funding sources and blockchain technologies used" for discussion). A single project has reached the criteria for TRL 9, KlimaDAO, which at the time of writing has retired 12.7 $MtCO_2$ through speculative buying of Base Carbon Tonnes (BCTs) that each represent the retirement of 1 Voluntary Carbon Unit (VCU).[45] Contrary to the traditional actions of a carbon market, this has motivated speculative crypto-investors into this realm through desire to "stake" KLIMA tokens (locking these tokens up for a fixed period in order to receive additional tokens in return).[46]

The organizations developing blockchain solutions

We find little correlation between TRL and the age of a company, or the time it has spent on blockchain development (see Figures S1 and S2). Most organizations are young, with the median year of formation being 2017. The median year for commencing blockchain development is the same as the foundation year, suggesting that most companies formed specifically for this use case.

Half of the blockchain solutions are being developed by privately held companies, as shown in Figure 4. This shows most of the companies that are struggling to develop from TRL 3 to TRL 4 are non-profit organizations, whereas the opposite can be seen in the accumulation of privately held companies at TRL 5. This could indicate financial barriers to reaching the lab-validation stage, as discussed in the section "Funding sources and blockchain technologies used." Most organizations developing solutions were founded in Europe, North America, and Asia. Blockchain solutions are concentrated in the more technologically developed countries, with five of the eight Asian organizations originating in Japan, Singapore, or China. It should be noted that only one project was founded in South America, and no organizations originate from Africa.

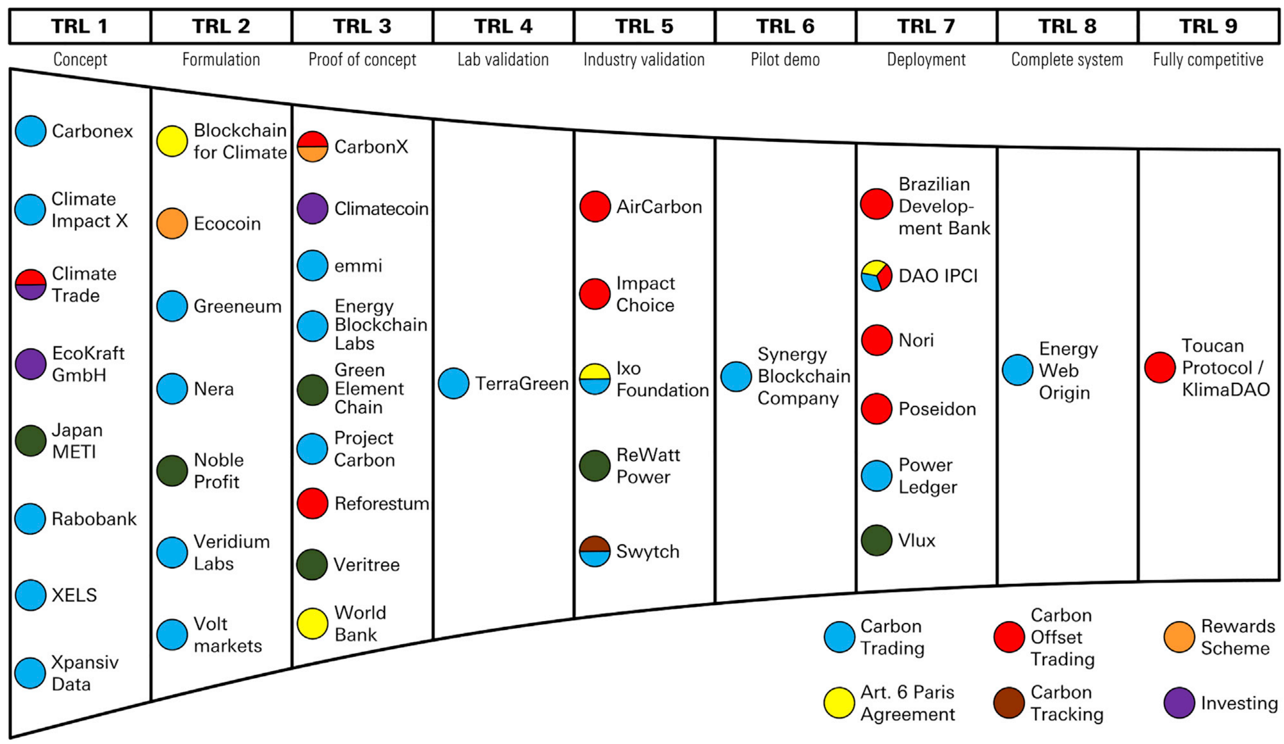

Figure 3. The technology readiness level of blockchain solutions in carbon markets
The color of each icon indicates the use case of each project. A full list of sources is given in Table S1.

Most of the organizations are small, with under 50 employees (see Figure S3). The exceptions are the three oldest organizations who are not solely focused on carbon markets or blockchain (Japan METI, The World Bank, and the Brazilian Development Bank). There is a weak correlation between the number of employees and the development level of each organization, with half of companies in TRL 1–3 having fewer than 10 employees compared with only a quarter of those in TRL 5–8.

Funding sources and blockchain technologies used

Figure 5 shows the funding method used for each organization. A variety of funding sources are seen in the highest TRLs, but private investment and initial coin offerings (ICOs) dominate, each used by 45% of projects. ICOs are a crowd-funding method used by blockchain companies whose solution contains a token (cryptocurrency) to gain capital. Those interested in the project can exchange conventional money (fiat currency) or Ether for a pre-determined quantity of the new cryptocurrency token that is being developed, in the hope that the token will increase in price in the future. The volatility of cryptocurrencies has given these a negative reputation (see Discussion).

Figure 5 also shows that most companies are developing their blockchain solution using the Ethereum platform, reflecting its relative maturity. Furthermore, Energy Web Origin is a fork of Ethereum, Polygon is a "decentralized scaling platform" for Ethereum, and Blockchain for Climate are planning on using "Ethereum 2.0." A fifth of solutions are using the IBM technology stack that is built on Hyperledger Fabric; however, these solutions are not present at the higher technology readiness levels. A similar number of organizations have taken the approach of building their own unique blockchain platform, with many of these also utilizing another platform in some way. Five platforms are present in the highest TRLs (Energy Web Origin, Ethereum, Stellar, and two native platforms), suggesting there is no platform monopoly at present.

DISCUSSION

There are clear benefits to implementing blockchain technology in carbon markets; however, our TRL analysis suggests that large-scale deployment of market solutions is not an imminent prospect. Issues remain before the technology can flourish, which is to be expected given the infancy of blockchain.

The state of carbon market applications for blockchain

It is clear that the market is immature and still developing. Four-fifths of projects commenced since 2017, and half of all blockchain solutions are yet to progress beyond proof-of-concept stage. This is not surprising, considering that the first concept of a blockchain was only released a decade ago[47] and the oldest blockchain platform with smart contracts (essential for carbon markets) was released in 2015.[48]

The funding source for blockchain solutions could have impacted on their speed of development. Using the crowd-funding method of an ICO is the riskiest form of investment strategy, due to the widely fluctuating exchange rate from Ether to fiat currency. For example, receiving investment via an ICO worth the equivalent of £1,000,000 in Ether (the cryptocurrency used in

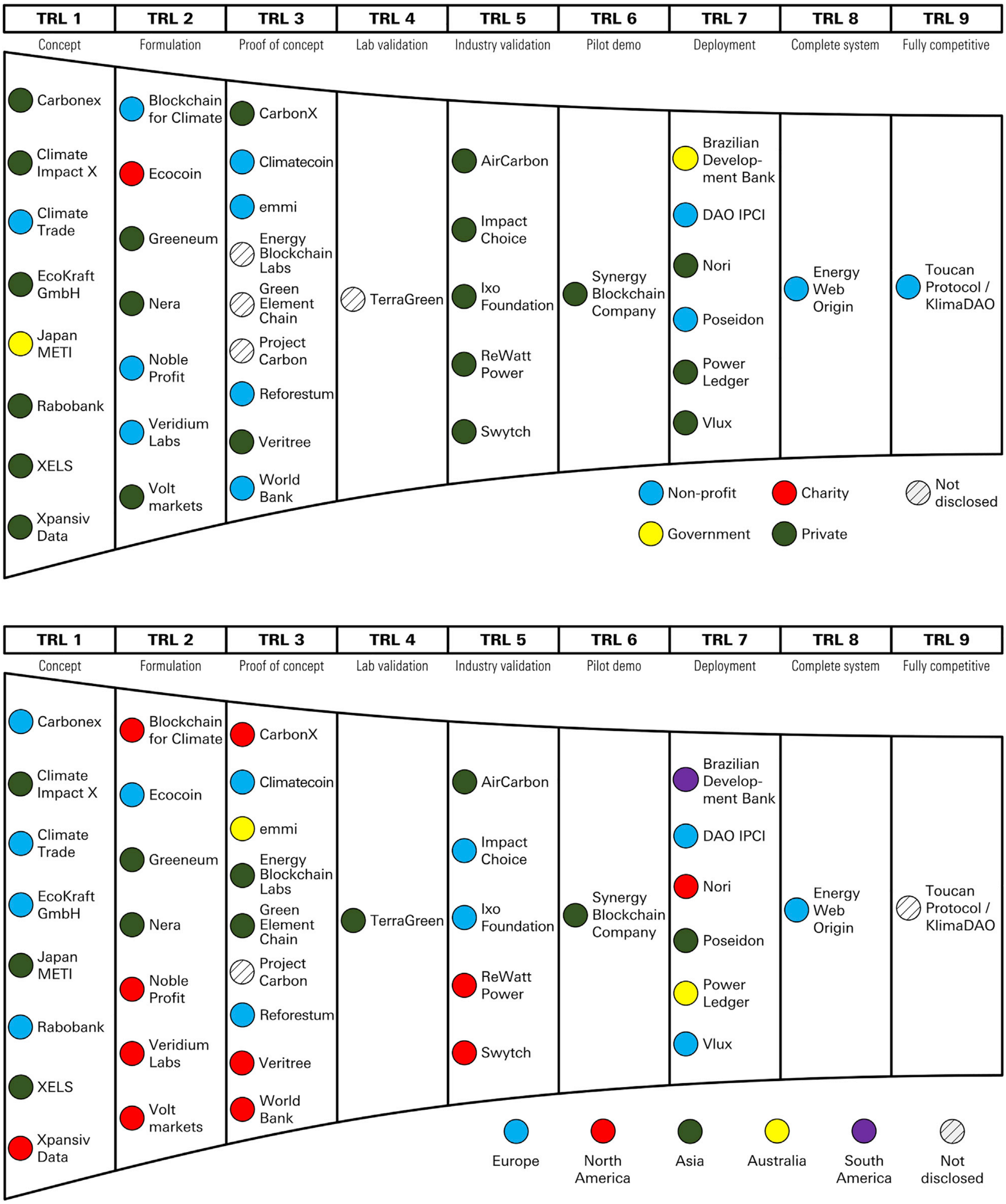

Figure 4. Characteristics of the organizations developing blockchain solutions in carbon markets

The top panel shows the type of organization, and the bottom panel shows its location, both as a function of TRL. A full list of sources is given in Table S1. Note that KlimaDAO was "built by a distributed pseudo-anonymous team"[45] and so has unknown origin.

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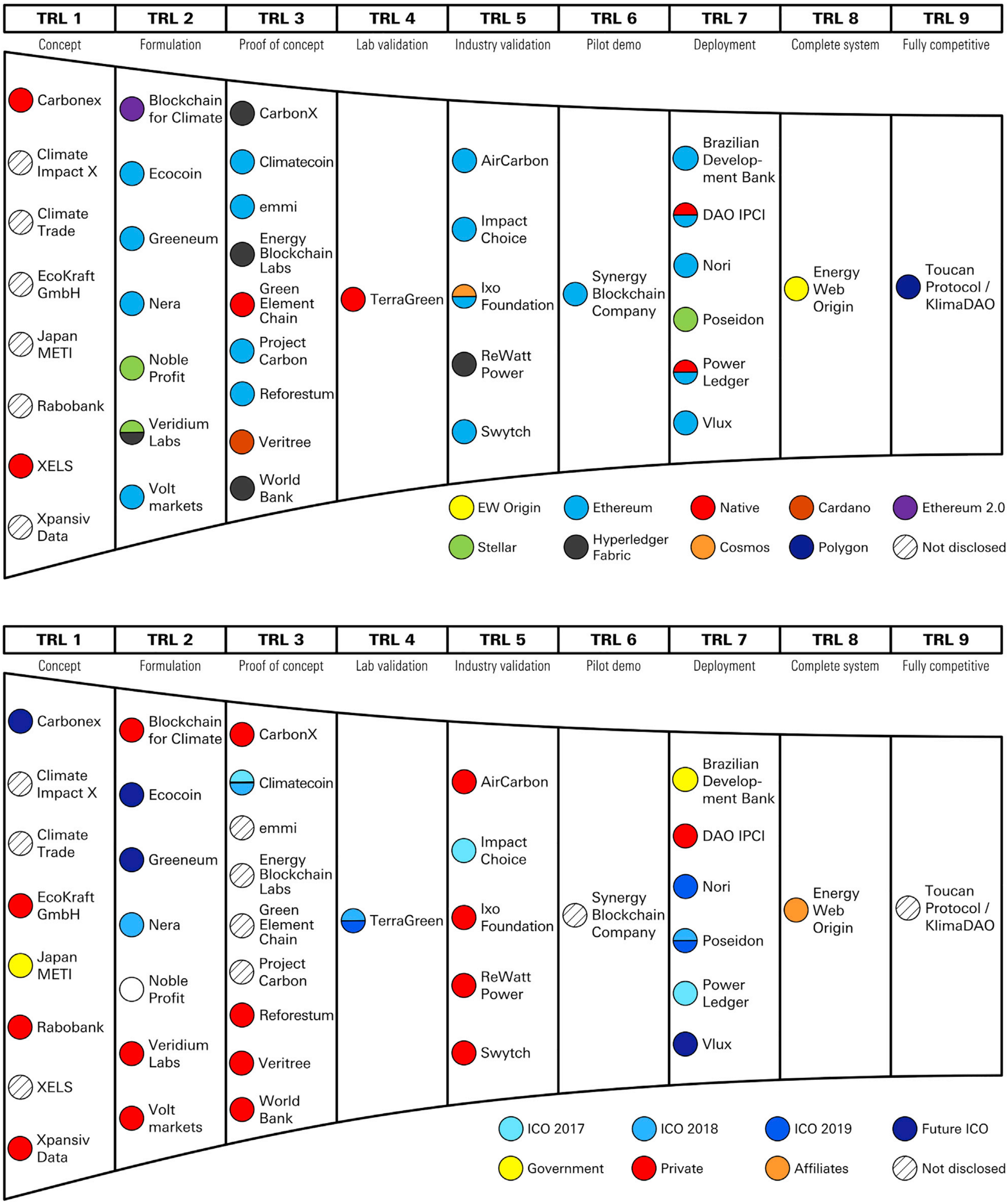

Figure 5. Characteristics of the funding source and technology used for blockchain solutions in carbon markets

The top panel shows the source of funding used in each project, and the bottom panel shows the blockchain platform used, both as a function of TRL. A full list of sources is given in Table S1.

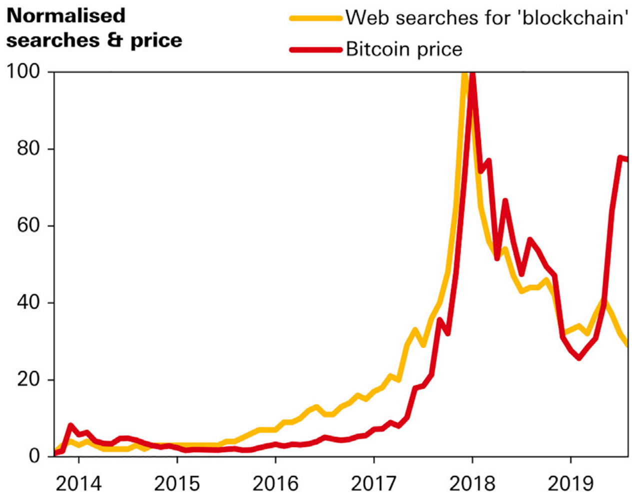

Figure 6. The relationship between interest in blockchain and the value of Bitcoin

Both metrics were normalized to a maximum value of 100 to allow for comparison. Data were sourced from Google[52] and Coindesk.[53]

the Ethereum network) on 14th January 2018 would have been worth less than £100,000 on 14th January 2019.[49] This funding strategy was confirmed as a detrimental factor to the development of the Nera solution by Carbon Grid Protocol.[50]

The noticeable outliers to this conclusion are Power Ledger and Poseidon, who both hosted ICOs and are still among the most developed solutions, at TRL 7. This could be explained, however, with Poseidon developing successful partnerships with users who may have funded pilot projects.[30] Power Ledger completed their ICO between August and October 2017[51] so would have therefore benefitted from the 6-fold increase in Ether price from August 2017 to January 2018[49] if they had transferred Ether into fiat currency before the exchange rate crashed.

Rationale for developing blockchain applications

The rationale for creating these solutions could fall into two categories: (1) problems with carbon markets are identified, all options are explored, and it is concluded that blockchain technology is the most viable option; or (2) blockchain technology is explored and carbon markets are identified as a good use case.

The second rationale is more likely to be stimulated by willingness to profit from the extensive publicity surrounding blockchain technology. It is also less likely to have exhausted other possible solutions to the problems of carbon markets, suggesting that blockchain technology may have been "shoehorned in," where there may be other market options not tested that better solve the problem.

Figure 6 shows the normalized number of Google searches for the term "blockchain" in comparison with the price of Bitcoin (the largest cryptocurrency). The clear association between these suggests that, at least in the run up to the 2018 boom, interest in the technology peaks as the price of the asset increases. More recently, the chart seems to suggest that the original use case of bitcoin as a store of value (i.e., Bitcoin) may have progressed to the slope of enlightenment, whereas the wider blockchain sector is less advanced. The majority of projects identified were developed during this period of rapid price increase, and after the price crash, the issuance of new blockchain solutions reduced from 12 in 2017 to two in 2018. This casual inference suggests that most of the blockchain solutions may fit in the second category.

The Gartner Hype Cycle model tracks the development of technological innovations through successive stages.[54] Gartner plotted blockchain technology towards the end of the "peak of inflated expectations" stage and 5–10 years away from the "plateau of uncertainty" stage during their August 2018 review.[55] The dramatic reduction in Bitcoin price and company formation during 2018 suggests that blockchain technology may have transitioned into the "trough of disillusionment" phase. Further evidence for this can be seen by the disparity of 2019 in Figure 6: Bitcoin price begins to recover, but the instances of blockchain searches continues to decrease. If many blockchain projects were formed under the "supplier proliferation stage" of the Hype Cycle model, this supports the conclusion that many projects were created under the second category.

Common barriers

TRL 4: Scalability and skills shortage

Many companies have yet to transition from TRL 3 to TRL 4. It is unlikely that this is due to unwillingness to release information about their solution, as three organizations at this level use GitHub (a public software development platform), and The World Bank presented their solution at COP25 in 2019.[56] It is also unlikely to be a legal issue as large organizations, who will have their own legal representatives, such as the Brazilian Development Bank and Energy Web Foundation, have successfully completed this requirement.

The inability to provide evidence suggests that there are technical issues inhibiting the proper functioning of the proof of concepts. This could be due to the "Scalability Trilemma": the difficulty in developing a blockchain technology that is simultaneously decentralized, secure, and scalable, due to the conflicting trade-offs involved in each objective.[57,58]

It could also point to a skill gap for software engineers in the blockchain sector. Blockchain has been the fastest growing freelance skill demanded by companies,[59] with the median salary for blockchain developers rising by 62% per year,[60] suggesting demand for skills is outstripping supply.

TRL 6: System integration

As there is no accumulation of solutions at TRL 4, there appears to be no issue with finding external partnerships once a working proof of concept exists. However, enabling the blockchain solution to successfully operate with their systems is more difficult.[56] TRL 6 represents the first level where all aspects of the system are required to work together, so other factors may stifle the development of the blockchain solution. This issue was highlighted in our interviews for one of these companies, whose pilot project was stalled by the immaturity of commons-based economics in energy systems where individuals both produce and consume energy (Anonymous G). As many blockchain technology solutions are also linked with other emerging technologies, such as IoT-connected smart devices, this is likely a major barrier to large-scale deployment.[61]

This could be overcome by establishing research facilities to allow "plug and play" testing of emerging technologies. Individual emerging technologies could be isolated and tested with other

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proven technologies. For instance, a micro-grid could be set up to create voluntary carbon credits and include various renewable energy sources, storage, smart metering, and digital technologies (IoT, artificial intelligence [AI], and blockchain). The micro-grid would contain proven technologies, and each one could be replaced individually to test new innovations. Starting with a blockchain solution and allowing more novel components to be introduced and debugged incrementally could increase the efficiency of development and reduce the costs of other equipment procurement for pilot projects. It could also be used to allow multiple start-ups to collaborate and test their equipment together in the same test environment, increasing overall productivity.[62]

This approach has been used previously to stimulate research in wave-energy converters and tidal-energy turbines at the European Marine Energy Centre (EMEC) in Orkney, Scotland. "Test berths" are provided with pre-leased and pre-consented areas of seabed with pre-installed subsea cables and grid connection equipment, reducing installation time, equity, and risk of investment.[63]

TRL 8: Regulatory concerns

Only two blockchain solutions have achieved TRL 8 (a complete system) or above thus far. This marks the completion of the testing phase and the beginning of real-world adoption. Similar to TRL 6, this means blockchain development can be hampered by the way the current system operates. In contrast to TRL 6, the completed roadmap typically requires significant scaling up of production and includes external factors, such as industry regulation and modifying industry standard practices, to interact with other companies. Power Ledger opines on this issue: "changing the rules of the game when you weren't invited to play is a tough thing to do."[64] They had demonstrated the technical capability of their energy-trading platform in Busselton Lifestyle Village in New Zealand and later successfully trialled the platform with Origin Energy in Australia.[65] However, once it came to deploying their peer-to-peer trading platform on a larger scale, the lack of regulation proved too risky for partners in an industry that is usually so highly regulated.

Similarly, the success of DAO IPCI is dependent on the success of Article 6 of the Paris Agreement, which is still not ready to be implemented.

Recommendations

We identify several factors that hinder the development of current industry solutions. These are focused on particular stages of maturity, regarding scalability and skills (TRL 4), integrating systems (TRL 6), and industry regulation (TRL 8). To alleviate these, we recommend that:

- Robust, tailor-made blockchain developer education programs should be established to alleviate the industry skill shortage.
- Research facilities should be established to allow "plug and play" functionality for all emerging technologies, for example, taking advantage of the Horizon 2020 research and innovation program in Europe.
- Key industry coalitions should broadcast clear guidelines on industry best practice, for example, avoiding ICOs as a funding method and promoting open-source use of Ethereum to enable skill sharing to reduce the industry skill shortage.
- The International Civil Aviation Organization (ICAO) should explore the viability of using blockchain technology in CORSIA, given the clear advantages it could bring and the blockchain expertise within the organization.
- Working groups should be established in different jurisdictions to provide policy advocacy, reducing the risk to investors. Inspiration could be taken from the EU Blockchain Observatory and Forum who help to fulfill this role for the European Commission.[66]
- Market "pull" strategies should be considered, whereby governments could create an enabling ecosystem to help move "stalled" applications through the bottlenecks identified earlier. Such moves are being seen in blockchain for peer-to-peer energy trading.[67]

Legal research is required to determine the applicability of blockchain technology in current regulation and legislation, for example, ascertaining whether the immutability of a public blockchain can be compliant with EU General Data Protection Regulation (GDPR), as there is no precedent of its applicability[7].

A prominent criticism of Bitcoin (which is often widely conflated with blockchain in general) is high energy consumption[68,69] and thus greenhouse-gas emissions from maintaining the network.[8] The choice of consensus mechanism impacts the energy required for the blockchain to agree on one state, with proof-of-stake and proof-of-authority systems (e.g., Cardano or Energy Web Chain) using much less energy than proof-of-work that is used by Bitcoin and Ethereum (see Note S3). Nonetheless, the resulting emissions should be subtracted from the carbon credits before they are surrendered to avoid over-estimating their overall environmental benefits.

This paper considers the roles that blockchain technology could play in emissions-trading schemes, but further research is required on its potential to link schemes together to facilitate a global carbon market, how these could be linked to the eventual implementation of Article 6 and CORSIA, and the potential nesting of voluntary schemes within countries' nationally determined contributions (NDCs). The creation of a global carbon price would remove the fundamental problem of carbon leakage, but the apathy and heterogeneity of major national governments may prove an insurmountable barrier.[70–72] Perhaps through the application of blockchain to carbon markets, there is a role for other organizations to create an effective and materially significant global carbon market.

Conclusions

This paper's contribution is an objective, academic review of blockchain solutions for carbon markets. In surveying the entire market, we find the current ecosystem is diverse, fragmented, and relatively immature. Most solutions are defined as early-stage proofs of concept (TRL 1–3), and we identify bottlenecks at TRLs 4, 6, and 8, which indicate critical issues around scalability, systems integration, and regulation that must be overcome. We identify a single project that has achieved widescale deployment (TRL 9), which notably takes an unorthodox approach of linking a carbon credit to a token that speculatively rises in price via staking rather than a traditional commodity market. Regardless, this sector has seen rapid development in recent years. The biggest movement over the last 2 years is the entry of large consortia, such as Rabobank, Climate Impact X, and Project Carbon, with established companies moving into the space that was until recently only occupied by small start-ups. Blockchain carbon market solutions could follow other application areas by transitioning from excessive competition between small-scale companies transitions towards the clustering of larger companies and consortia, better able to overcome the challenges of developing a solution to maturity.[73]

We identify clusters of use cases for blockchain in carbon markets and explore through case studies areas in which this could overcome the problems of existing markets. There are obvious benefits to implementing blockchain technology in carbon markets, notably transparency, traceability, and enabling the trust of technological solutions, such as satellite imagery. However, blockchain should not be seen as a panacea, and in some cases, it is arguably a solution looking for a problem. Other technological solutions may be better equipped to overcome the downsides of centralized carbon markets (e.g., secure multi-platform computing),[74,75] and these could and should be explored further.

Blockchain should be seen as a foundational technology upon which the framework for transparent, trustworthy, and liquid carbon markets can be built. It is not a technology that can remove the intricacies of political relations, as highlighted with the accountability difficulties with Article 6 of the Paris Agreement. That said, it has the potential to automate and apply credibility to many parts of the carbon-credit supply chain (especially when used in conjunction with AI and IoT) once the rules have been finalized.

Blockchain is a very timely topic seeing remarkable growth, but it is one clouded by a lack of understanding and much speculation. We try to overcome this by providing objective, peer-reviewed overview of the ecosystem. This paper aims to set the groundwork for future studies, including a more comprehensive review of each carbon market sub-type. It could aid future work by laying the groundwork for more detailed assessments of specific use cases, protocols, or companies. Just as Andoni concluded with energy sector applications,[76] blockchain could well be disruptive for carbon markets, but many challenges must be overcome to advance the variety of solutions currently under development. By setting a baseline, we hope to provide clearer targets for companies to work towards, raise awareness of the technologies and solutions, and help to overcome existing barriers to implementation and increase the speed of development of blockchain solutions that have a clear competitive advantage over current systems.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to the lead contact, Iain Staffell (i.staffell@imperial.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

This paper analyses existing, publicly available data. The complete list of resources consulted are given in Table S1. This paper does not report original code. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

Systematic literature review

The literature was examined to determine the current issues facing carbon markets and the niches that blockchain technology could fill to improve them. Peer-reviewed publications were used where possible, but these are sparse due to the infancy of the technology. Therefore, government and industrial reports, commercial whitepapers, and other gray literature were also consulted.

Journals, industry reports, and media outlets were then reviewed to identify blockchain solutions that are being developed by governments, non-governmental organizations (NGOs), established companies, and start-ups. The "snowballing" technique was applied,[77] particularly with the literature produced by Andoni et al.,[76] Montemayor and Boersma,[78] and Edeland and Mörk.[79]

Imperial College London's library search, Web of Science, and Google Scholar were used to find academic sources, and EBSCO was used for business and industry sources. Internet searches using the Google search engine and Medium were used to identify gray literature sources since 2015.

Technology readiness level scale

There is a precedent of TRLs being used for blockchain projects in the literature.[41,42] However, Alexopoulos[41] uses a bespoke system for categorizing projects rather than a widely used methodology, such as those from NASA or the European Commission, limiting the applicability of its results. Mazur[42] considered the TRL of blockchain technologies collectively, which allows blockchain to be compared with other emerging technologies but does not differentiate between existing blockchain projects and thus is less effective in providing policy recommendations for specific applications of the technology itself.

The EU Horizon 2020 methodology was chosen as the framework on which to build a blockchain-specific TRL scale. This common scale was chosen as it is applied to the 7 years, €80bn research and innovation programme, and adapting blockchain technology to fit a common scale allows for more rational decisions to be made regarding its implementation, reducing the impact of preconceived thoughts about the technology.

Data sourced from organization websites, technical whitepapers, partners, media reports, and direct contact were used to quantify each organizations' blockchain solution on the TRL scale shown in Table 1. A pilot study was conducted on a small subset of blockchain projects to test these criteria, and modifications were made where data collection proved infeasible.

Sources

We consulted 118 sources to assess the TRL of each blockchain solution and to identify metadata relevant to each solution and company. These sources are listed in full within Table S1 and were used to produce the table and figures in the results.

Interviews

Semi-structured interviews with company representatives were performed to collect and clarify additional data for the TRL. This method gave the flexibility to ask only the relevant questions needed to fill information gaps after the literature review. Each interview was structured to gather general information about the project and then questions were used to understand whether the projects had hit the criteria required to reach different TRL level. Representatives were contacted through a mixture of "cold calling" or through network connections supplied by Shell. In total, seven interviews were completed, typically with the CEOs of the start-up companies.

Limitations

Due to the infancy of blockchain technology, gray literature was required to supplement academic and industry publications, leading to uncertainty over the validity of sources. When gray literature was required, care was taken to choose reputable and established sources, such as national and international media rather than advocacy websites.

The blockchain projects we assess have a range of different aims, and so some nuances are missed in a broad study such as this, which spans across all projects. Further work should assess projects independently according to their use case (e.g., voluntary versus compliance and for profit versus non-profit).

To the best of our knowledge, this is only the second time that the TRL scale has been used for different implementations of blockchain technology and the first in academic literature. Therefore, as with any novel implementation, it is likely that the scale can be refined in future iterations. Héder also acknowledges that TRLs can be a source of confusion,[40] so the boundaries between levels were made as clear as possible to mitigate this shortcoming. Furthermore, TRL does not signify the quality of a technology and so cannot be used in isolation for picking winners. TRL is one of many potential frameworks for assessing maturity. As blockchain is a complex system rather than a discrete technology, it may be appropriate to repeat this work using other frameworks, such as the Systems Readiness Assessment (SRA) as used within the defense industry.[80]

Interviews with experts in carbon markets and blockchain and Shell employees could lead to an inherent bias. Efforts to reduce this were taken by interviewing from different areas of the business and by presenting results externally for feedback prior to publication.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.06.004.

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AUTHOR CONTRIBUTIONS

Conceptualization, A.S., S.B., T.V.L., and I.S.; methodology, A.S. and I.S.; investigation, A.S.; data curation, A.S.; writing—original draft, A.S.; writing—review and editing, A.S., S.B., T.V.L., and I.S.; visualization, A.S. and I.S.; supervision, S.B., T.V.L., and I.S.; project administration, I.S.

DECLARATION OF INTERESTS

The authors declare no competing interests in any of the organizations developing blockchain solutions for carbon markets that were analyzed for this study. Three of the authors are employed by Shell Global Solutions International B.V., a member of a global group of energy and petrochemicals companies, but they are writing in a personal capacity. The study was commissioned, conducted, written, and submitted independently by the authors. All statements and omissions remain the sole responsibility of the authors.

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