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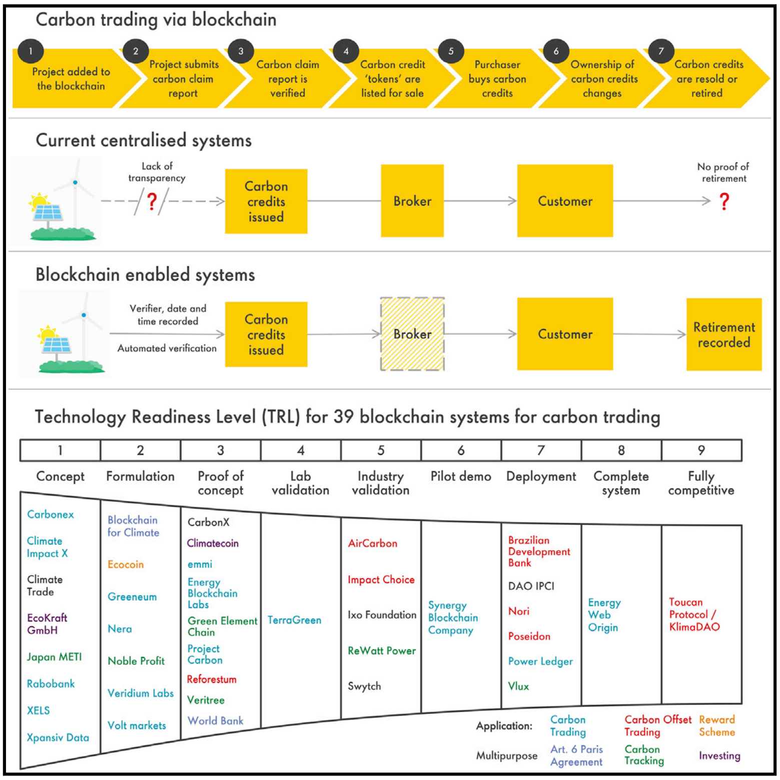
Article

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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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]

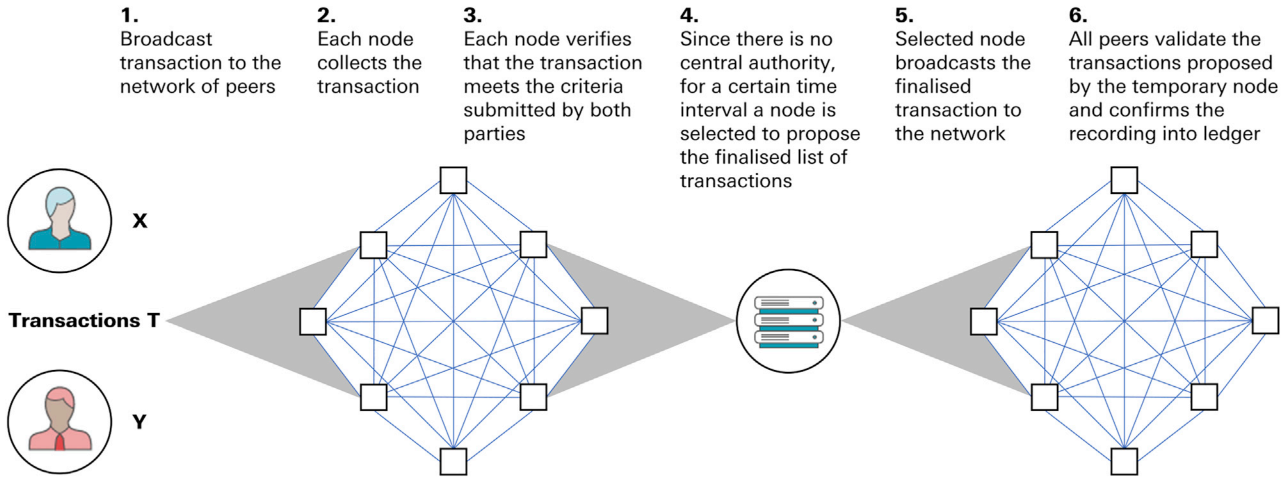

Figure 1. The steps required for a transaction to be added to a blockchain
Adapted from Shell[14] and Yaga et al.[15]

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.

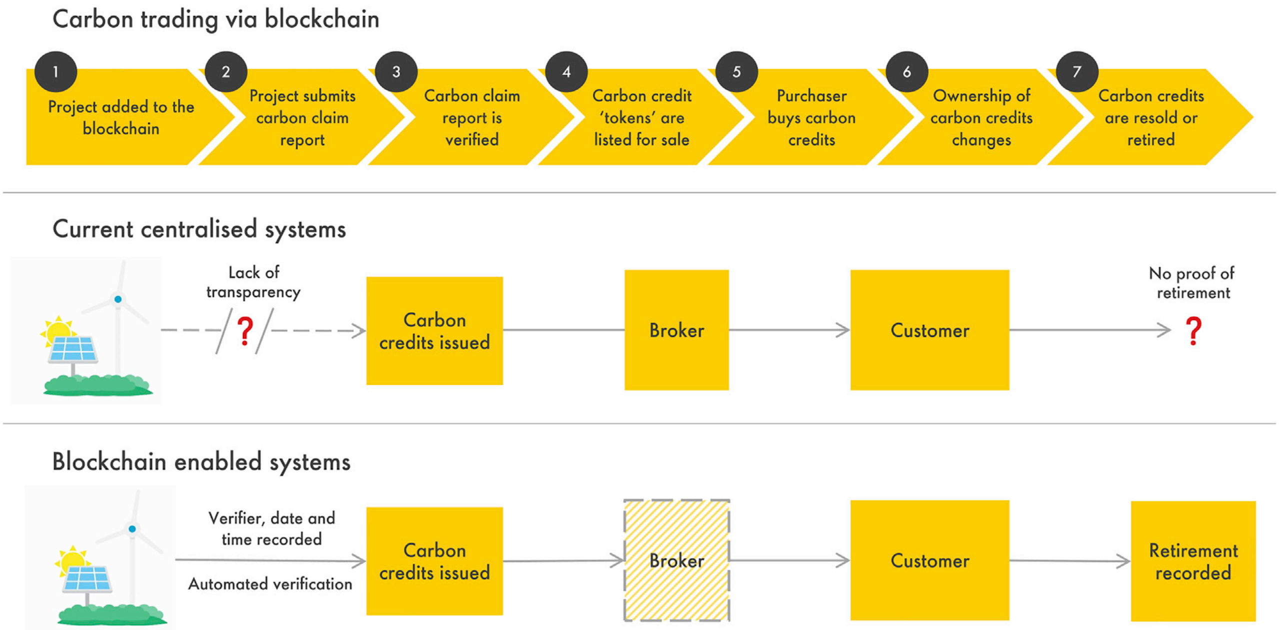

Figure 2. Schematic overview of carbon trading on a blockchain versus a centralized platform

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.

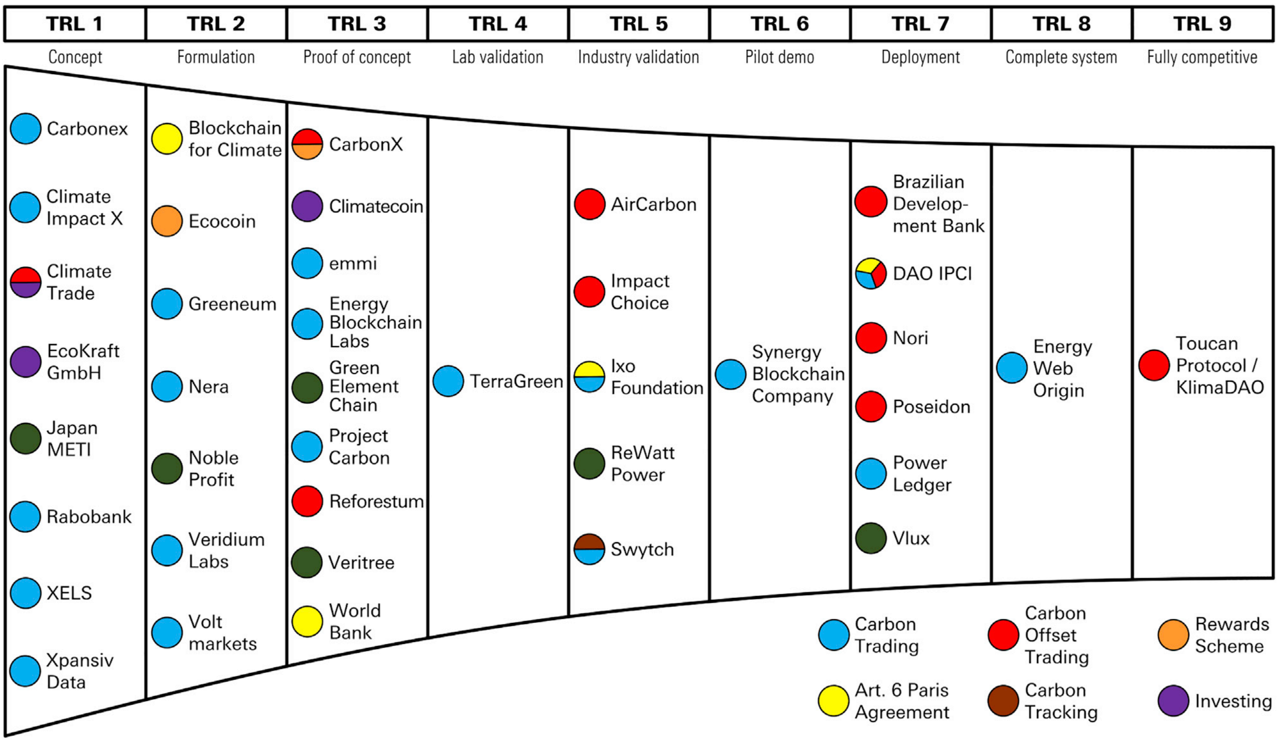

Figure 3. The technology readiness level of blockchain solutions in carbon markets
The color of each icon indicates the use case of each project. A full list of sources is given in Table S1.

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

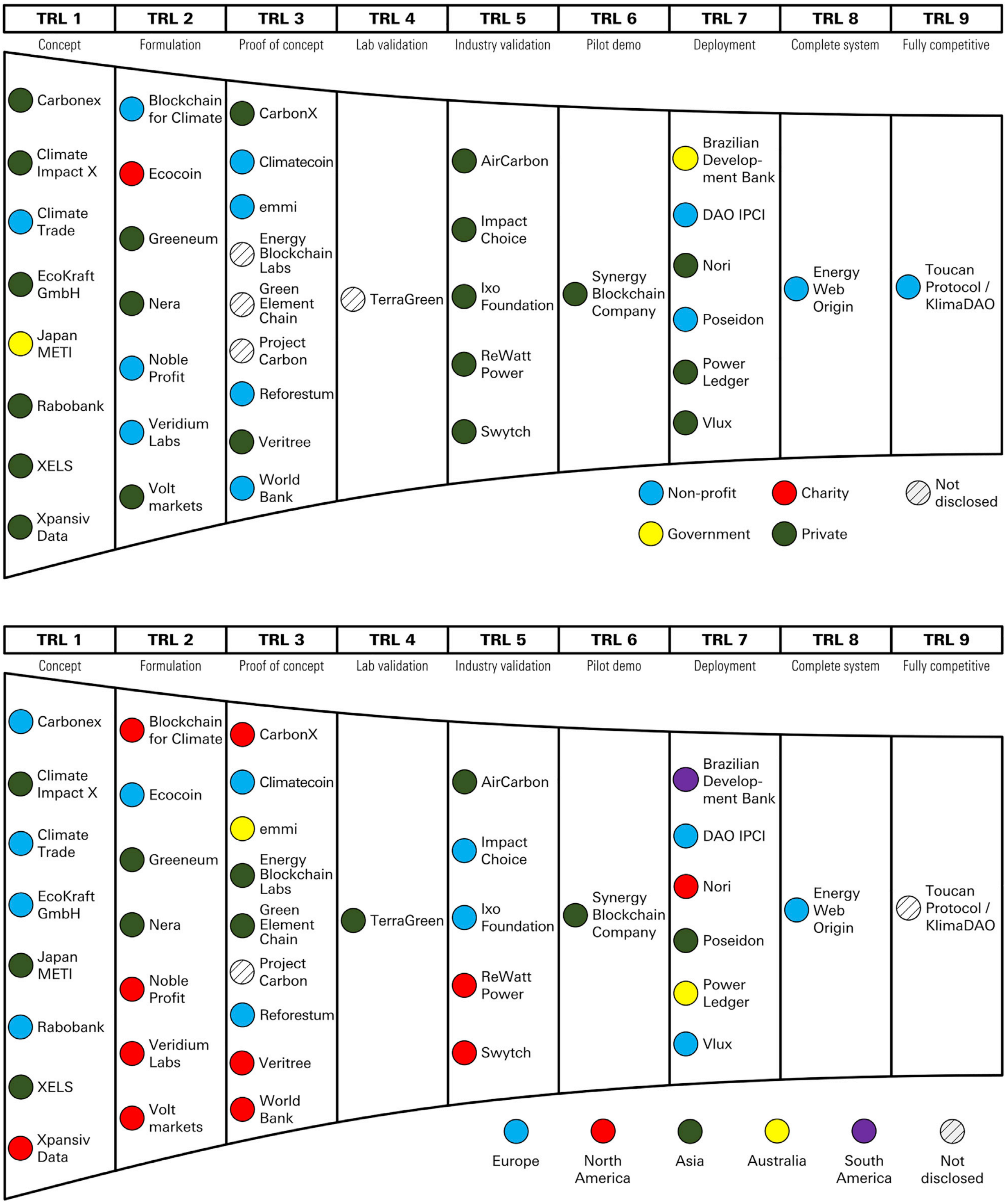

Figure 4. Characteristics of the organizations developing blockchain solutions in carbon markets

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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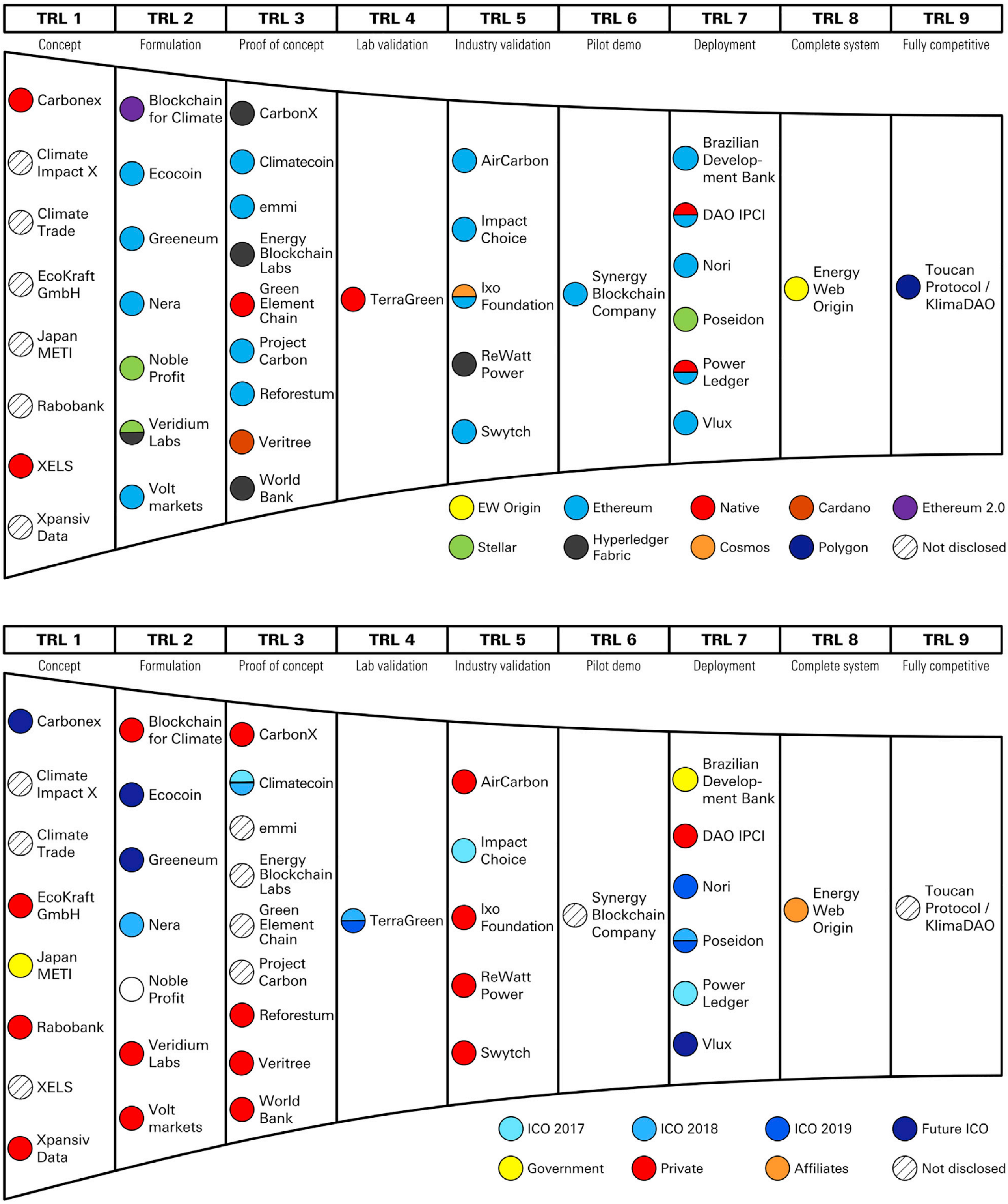

Figure 5. Characteristics of the funding source and technology used for blockchain solutions in carbon markets

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.

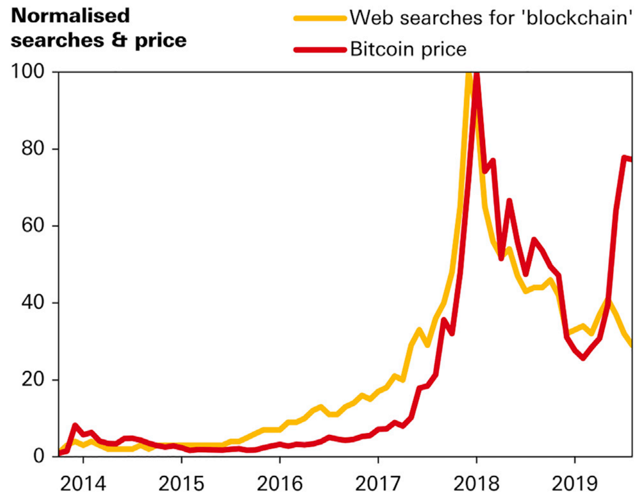

Figure 6. The relationship between interest in blockchain and the value of Bitcoin

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 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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One Earth, Volume *5*

Supplemental information

Blockchain solutions for carbon markets are nearing maturity

Adam Sipthorpe, Sabine Brink, Tyler Van Leeuwen, and Iain Staffell

Supplemental Information

Supplemental Notes

Note S1: Acronyms and Glossary

AI – Artificial Intelligence

CDM – Clean Development Mechanism

CER – Certified Emission Reductions

COP – Conference of the Parties

CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation

DLT – Distributed Ledger Technology

ETH – Ether

EU ETS – European Union Emissions Trading System

GHG – Greenhouse Gas

HFCs – Hydrofluorocarbons

ICAO – International Civil Aviation Organization

ICO – Initial Coin Offering

IoT – Internet of Things

ITMO – Internationally Transferred Mitigation Outcome

NDCs – Nationally Determined Contributions

NETs – Negative Emission Technologies

NGO – Non-governmental organisation

P2P – Peer-to-peer

PoA – Proof-of-Authority

PoC – Proof-of-concept

PoS – Proof-of-Stake

PoW – Proof-of-Work

PV – Photovoltaic

REDD+ - Reduced Emissions from deforestation and forest degradation

ROI – Return On Investment

SHA-256 – Secure Hash Alrogithm-256 bit

tCO_{2e} – Tonnes of carbon dioxide equivalent

TRL – Technology Readiness Level

UN – United Nations

UNFCCC – United Nations Framework Convention on Climate Change

Baseline and credit – An emissions limit placed on a sector, where additional emissions must be offset by purchasing carbon offset credits.

Blockchain – an immutable, tamper-proof, shared ledger of state changes of a digital asset.[1]

Cap and trade – a mechanism used to control greenhouse gas emissions by setting an upper limit (cap) on emissions for a group of companies, with emissions allowances allocated through auctions. Additional emission allowances can be purchased from other companies who have surplus allowances.

Carbon credit – a unit of Carbon dioxide equivalent that can be traded in a market.

Carbon markets – A group of economically efficient methods used to reduce predominantly private sector emissions by allowing the free trade of emission allowances that represent one tonne of CO_2 – equivalent greenhouse gas reductions. The two most common approaches include the cap-and-trade method and baseline-and-credit method.

Cryptography – The science of taking information and transforming it in a manner in which it can be deciphered only by the intended recipient.[2]

Greenwashing – The act of an organisation or individual misleading consumers about their environmental performance of the environmental benefits of a product or service.[3]

Kyoto Protocol – An international treaty that sets greenhouse gas emission limits on industrialised nations.

Node – a device connected to a network.

Paris Agreement – An agreement by almost all countries to accelerate investment into low carbon technologies by limiting climate change to well below 2°C above pre-industrialised levels.[4]

Shared Ledger – A ledger or records that is owned by everyone within that community and cannot be changed without community consensus.

Tamper-proof – A process that makes alterations to the data difficult (hard to perform), costly (expensive to perform) or both.[5]

Technology Readiness Level – a method used to measure the maturity of a technology, from level 1 (basic principles observed) to level 9 (proven system in an operational environment).

Tokenisation – Creating a digital representation of a real-world asset/the concept of tying information about an asset to a blockchain.[2]

Note S2: Blockchain Fundamentals

'Blockchains have one trick that is more magical and revolutionary than anything else they do: they can execute transactions and business logic across a network without requiring a central authority to validate and complete that work. Same symphony, same music, no conductor.'

– Paul Brody, Ernst & Young.[6]

A blockchain (a subset of Distributed Ledger Technology) combines three established technologies: cryptography, algorithmic hash functions and distributed systems. Cryptography is used to link new transactions to previous transactions in the absence of a trusted third-party intermediary.[7,8] Attempts to change an existing block (e.g. to fraudulently change the ownership of an asset) would require all subsequent blocks to be rewritten (as these contain the 'digital fingerprint' of all previous blocks), and for more than half of machines on the network to verify this change. Blockchains are decentralised as no single actor has control over all computers in the network, and the failure of one node does not cause failure of the entire system.[9] This makes a blockchain difficult to attack due as there is no central point to focus efforts.

Some key terms:

Peer to peer – Blockchains are a form of peer-to-peer systems. All nodes in the network make their computational resources directly available to each other as opposed to via a middleman, increasing process efficiency and reducing costs.[10] Blockchains differ from historical peer-to-peer systems as they use the distributed nature to ensure the integrity of the system.[10]

Blocks – Transactions are aggregated into blocks which, amongst other things, reference the previous block through the hash cryptography that links the blocks chronologically to produce a blockchain.[5] When cryptography is combined with algorithms, cryptographic hash functions can be produced. These are mathematical irreversible functions that transform an input into an output of specific, pre-defined length, known as a 'hash output'. It is computationally infeasible to reproduce the original input using the hash function alone and the number of potential hash numbers is so large that it is extremely unlikely that two identical hash outputs will be produced – termed 'collision resistance'.[5,8] Furthermore, any change to the input changes the corresponding hash output, which is integral to ensuring the blockchain is tamper-proof.

Permissions – In a permissionless blockchain such as Bitcoin, any individual has access and can write to the blockchain without authorisation. In contrast, in permissioned blockchain networks the participation is limited to specific participants.[5] Each version has advantages and disadvantages, with the former allowing transactions to occur between parties who do not trust each other and the latter allowing for faster transactions as less security measures must be taken if all participants trust each other.

Consensus mechanisms – Consensus means to achieve agreement among independent individuals.[10] Consensus mechanisms are used in blockchain platforms to agree on one state, which leads to the prevention of double spending. There are many different types of consensus mechanism and the three most commonly used are explained below.

- **Proof-of-Work** was the first used blockchain consensus mechanism. Proof-of-Work is designed to demand large amounts of computational power to achieve consensus. This reduces the chances of criminals achieving 51% of the network (and therefore control of the network), as they will not possess the required computational power. Specialised nodes that add blocks to the blockchain (known as miners) solve mathematical calculations (known as hash puzzles) for financial rewards.[11] It is not possible to solve these hash puzzles using logic as trial and error must be used to guess a 'number only used once' (nonce) value.[10] The correct blockchain is the one that has used the most computational power to create.[12] A block is only verified if over half of the nodes in the network agree with the answer produced by the miner, and therefore 51% of the computing power of the network would need to be dishonest in order for a fraudulent transaction to be added to the blockchain. The scalability of this approach has been criticised as it requires a large amount of power consumption[13] and associated carbon emissions.[14]

- **Proof-of-Stake** has been suggested as a potential replacement for Proof-of-Work. The miners are replaced with validators who stake their money on the block in which they believe is valid.[12] If there is a disagreement, then the miners vote with their stake on which block they believe is valid, with the block with the most votes being added to the blockchain. Those who placed their stake on the losing block will then lose this stake. This model is based on the assumption that those who are more invested in the system (and therefore have more funds to stake) will want the system to be successful more than those with a smaller stake.[5]

- **Proof-of-Authority** is a consensus mechanism that has a greatly reduced energy consumption and offers faster transaction speeds than Proof-of-Work or Proof-of-Stake. Publicly identifiable and trusted computers - commonly owned by large companies - are responsible for the validation of transactions and creation of blocks in the system; known as validator nodes.[15] This method relies on the participants in the network to trust the validator nodes. The incentivisation of this consensus mechanism is that the large companies wish to uphold strong industry reputations and therefore ensure integrity by only validating honest transactions.

Tokenisation – The process of converting ownership of an asset into digital form. It allows for fractional ownership, so that indivisible assets can be tokenised and owned by many people. The tokenisation of emissions units would produce a transparent tracking system showing the exchange of credits from any individual, company, regulator or government. Wu and Tran[16] note that traceability and immutability can help to avoid information tampering and asymmetry between ledgers in the EU ETS, and Braden[17] suggests that tokenisation could lead to the linkage between other carbon markets.

Trust and integrity – Ensuring trust and integrity in a decentralised system is essential. Users must trust a system in order to be willing to join and contribute to its success. If the system lacks integrity then over time the trust of the individuals in the system will decrease, causing them to leave and the system to fail.[10] Decentralised systems must overcome the 'Byzantine Generals Problem' where not all individuals can be trusted to be honest.[18] Public blockchains include byzantine fault tolerance in their consensus mechanisms (including proof-of-work and proof-of-stake) to overcome this issue.

Smart contracts – Smart contracts are simple lines of code that can be executed to carry out a particular function.[10] They are the equivalent of paper contracts but remove the need of an enforcing body to ensure compliance, as once the contract is executed then it will be completed exactly as programmed, irrespective of any additional human input.[19]

Note S3: Blockchain platforms

The core technological concepts that underpin distributed ledger technologies originate from the 1990s. The Paxos Protocol describes a model in which an agreement can be made in a network. This idea was combined with technology to prove that documents stored in an electronic ledger had not been modified by using a signed digital chain of information[5] and presented in 2008 in the Bitcoin whitepaper.[7]

Since its inception, there have been many different versions of blockchains created. Developers can use some platforms to build their own solutions on top of them, using smart contracts. The two most popular blockchains based on market cap are described below.

Bitcoin – 'A peer-to-peer electronic cash system' was the first proposed use case of blockchain technology, which aimed to create system integrity for financial transactions.[7] An author, under the pseudonym of Satoshi Nakamoto, outlined a system that allowed for the direct transfer of money without the need of a financial institution using a combination of digital signatures and peer-to-peer networks. As it is a public network, everybody can view how much money each member of the system owns and track all transactions since the genesis of the platform. The decentralised aspect of blockchain is what separated Bitcoin from other electronic cash systems, as it meant that no single user controlled the electronic cash; removing a (malicious or otherwise) single point of failure [5]. The main innovation of Bitcoin is that it included a financial incentive to participate in the network via mining rewards. Each transaction requires a transaction fee that (along with a mining reward) is the incentive for validators to use their computational power to be the first one to propose a new block and therefore receive the block reward. The currency used in this system is Bitcoin (BTC) and it uses the Proof-of-Work consensus protocol.[7]

Ethereum – Whereas the main aim of Bitcoin is to create a new digital currency, the Ethereum blockchain is designed to store smart contracts. These smart contracts are written, stored and executed in a decentralised virtual machine known as the 'Ethereum Virtual Machine' that includes a Turing-complete programming language.[20] It is the smart contract functionality that allows organisations to create decentralised applications (dApps), with 2,590 being created on the Ethereum platform as of August 2019.[21] The currency used in this system is Ether (ETH), and this is fractionalised into Gas which must be spent to execute smart contracts.[20] In May 2019, the Ethereum development team announced plans to transition to 'Ethereum 2.0' which uses a Proof-of-Stake consensus mechanism as opposed to the current system which uses Proof-of-Work.[22]

Several blockchain protocols are now implementing the Proof-of-Stake consensus mechanism. Due to the greatly reduced energy requirements these are quickly rising in popularity in the blockchain and climate sector. One example is Algorand, who have partnered with ClimateTrade to become a carbon negative network[23] with superior transaction speed and scalability.[24] Another example is Nori, who in 2022 raised $7 million in venture capital to migrate from Ethereum onto Polygon and launch its new token.[26,28]

Note S4: Carbon market fundamentals

Carbon trading generally refers to the trading of six greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6).[25] The equivalent of 1 tonne of carbon dioxide equivalent removed (1 tCO_2e) is the most commonly used unit.[27]

Carbon trading was introduced as part of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) of 1997. The protocol, enforced in 2005, limits greenhouse gas emissions for 42 industrialised 'Annex I' countries [29] by setting binding targets.[30] This led to the establishment of three carbon markets; the Clean Development Mechanism, International Emissions Trading and Joint Implementation; which allowed for additional carbon reductions from one Party to be traded and count towards another Party's reduction targets.[31]

The main market used was the Clean Development Mechanism (CDM) which allowed Annex I countries to purchase carbon reduction credits from developing countries called Certified Emission Reductions (CERs), providing a source of revenue to help fund carbon offsetting projects. The additionality of carbon offsetting projects in the CDM has been highly criticised, with Cames *et al.* concluding that 85% of carbon offsetting projects would have occurred without the additional income achieved from selling CERs and the offsets themselves being over-estimated.[32]

As climate change mitigation gained momentum, local, national and regional emissions trading programmes began to form. This market value grew by 56% in 2018 due to the introduction of the Chinese national ETS and additional schemes in North, Central and South America.[33] Recent international climate mitigation agreements such as the Paris Agreement and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) create the potential for growing participants in carbon markets worldwide, particularly with the completion of the Paris Agreement Rulebook, making Article 6.4 transactions possible.

Voluntary carbon markets are much smaller than compliance markets, but these are rising in popularity. The UN Emissions Gap Report highlights the importance of voluntary markets as additional, unregulated approaches to reducing global emissions are required to limit warming to less than 2°C.[34] That said, although the demand for carbon offsets has increased 100-fold over the last decade to 43 $MtCO_2e$ in 2018,[35] this is paltry compared to the 11,000 $MtCO_{2e}$ covered in ETSs and carbon taxes,[33] but a 140x voluntary market increase from 2008 to 2018 suggests that they will play a significant role in the future.[35] Further detail on current carbon market dynamics is given in Notes S5 to S8, and also in Refs [36–38].

Some key terms:

Price floors and price ceilings – Price floors are used in carbon markets to guarantee a minimum price on carbon. This can lead to additional investment in low-carbon technologies as it increases investor confidence by providing price certainty. In contrast, price ceilings are used to avoid economic downturn if reducing emissions proves more costly than expected.[39]

Carbon Leakage – Carbon leakage refers to the act of production facilities relocating from areas with more stringent to less stringent emissions reductions targets.[40] Free allocation of emission allowances is used to avoid this outcome in many systems, including the EU ETS.[41] Over time, the amount of free allowances allocated should decrease, providing an incentive for the hard to reduce sectors to implement low-carbon technologies.

Additionality – To ensure the integrity of a scheme, carbon credits should only be awarded to emissions reductions that would not have occurred in the absence of an emissions reduction scheme.[42] This is done to make sure that any emissions reductions that take place would not have occurred in a scenario where the financial policy or mechanism had not been enforced.

Cap-and-trade schemes place an emissions limit on a group of companies. This 'cap' on emissions is reduced over time, making the total emissions of the group decrease. Emissions permits are distributed via free allocation or purchased through auctions. If a company emits more than the amount of emissions permits that they own, then they must purchase additional permits by trading with another company. At the end of the trading period these permits must be surrendered to the regulator.[43] If a firm emits more than the value represented by its permits, then is liable to pay a penalty. This creates a market dictated by supply and demand, whereby an incentive is created to reduce emissions in the most cost-effective way.[44] In a cap-and-trade scheme such as the EU ETS, governments have full control over the amount of CO_{2e} that can be emitted.[43]

Baseline-and-credit mechanisms place an emissions limit on a sector, where any additional emissions must be counterbalanced by purchasing carbon offset credits. This differs significantly from cap-and-trade schemes as there is no hard cap to these systems as long as carbon offsets are purchased.[43]

Note S5: Blockchain case study: The EU Emissions Trading System

The European Union Emissions Trading System (EU ETS) is a market-based method for gradually reducing greenhouse gas emissions and promoting investment in low-carbon technologies.[45] It operates as a cap-and-trade system, covering the 12,000 largest emitters from within the EU, Iceland, Liechtenstein and Norway (45% of total EU emissions).[46,47] Power stations and manufacturing industry are allocated allowances that represent one tonne of carbon dioxide or the equivalent of N_2O or perfluorocarbons (1 tCO_{2e}) through auctioning to determine the market value of carbon. Firms can then freely trade the allocations, and at the end of each financial year they must report their emissions and surrender enough allowances to cover the emissions from the previous year or pay a fine for over emitting.[47]

In its third trading period (2013-2020), the total 'cap' on emissions is reduced by 1.74% per year, giving 21% lower emissions in 2020 than in 2005.[47] Phase 4 (2021-2030) aims to reduce emissions to 55% below 2005 levels and to link the EU ETS with other ETS that are operating in other regions.

While centralised solutions such as the EU ETS have successfully reduced emissions, several issues must still be addressed. Many relate to the complexity of trading; for example, Carousel Fraud is a known issue, with high trading volumes being reported in spot markets in 2009 being evidence for this.[48] Carousel Fraud is the act of buying credits from a member state where they aren't subject to VAT and then reselling within a country with VAT added, without declaring this tax to the government.

In 2011, 2 million carbon credits were stolen from Austrian, Czech, Estonian, Greek and Polish registries via a 'phishing' attack. Criminals sent emails to registries with links to fake websites which captured log-in details that were then used to illegally sell the carbon credits from these countries' registries. Spot trading on the ETS was frozen for several days.[49] Two-thirds of credits were recovered, but still around €10m was stolen, highlighting the risk posed by the security of the EU ETS computer systems. To mitigate this, the EU moved to a single-registry system, although this produces its own problems such as reduced transparency during auctioning.[17] A centralised, single registry system is a barrier to implementing Phase 4 as it makes the administrative task of avoiding double counting of allowances and offset units much more difficult, due to a reduction in monitoring capacity.[17]

Blockchain technology has the potential to mitigate some of these issues. Pan *et al.,*[50] state that blockchain technology can be used for assessing, storing, trading and managing carbon emissions. Carbon has many of the same characteristics as a currency, and hence the characteristics that make blockchain successful as a currency are shared with carbon markets. Two parties can trade in the absence of trust without a third-party intermediary, giving reduced administration costs across the system.[51]

Although the concern of carousel fraud has technically been alleviated by the European Commission making carbon credits exempt from VAT,[49] this sidesteps rather than fixes the problem. The transparency of blockchain allows carbon credit transactions to be tracked by any individual, company, regulator or government. EU member states could benefit from reintroducing VAT if they were to switch to a blockchain based ETS. Wu and Tran[16] state that traceability and immutability avoids information tampering and asymmetry between ledgers. Furthermore, the tokenisation of emissions units enables the linkage to other trading schemes, and to other markets such as CORSIA.[17] The combination of the factors above presents a possible methodology to implement Phase 4 of the EU ETS.

Blockchain technology is not a panacea for emissions trading schemes. As with all systems, the blockchain is only as accurate as the data inputted. Therefore Khaqqi *et al.,*[45] suggest that to reach its full potential, Internet of Things (IoT) connected smart metering technology should be issued and used to automatically update the blockchain ledger. This has the potential to replace the current 29-page document of legislative articles, clauses and annexes that are used for the verification of GHG emission reports and accreditation of verifiers in the EU ETS.[40] Connecting the smart devices to the blockchain allows for costs savings where third-party verifiers are no longer required. This approach could be applied for many standard industry processes. Furthermore, direct machine to machine communication in this way eliminates the possibility of human error in this process. However, it is unlikely that it will be economically viable to incorporate smart devices for niche industry processes and therefore a reduced verifier workforce would still be required.

Case study: Swytch is a blockchain solution built on the Ethereum platform that aims to incentivise carbon-neutral energy production.[52] Their application allows for the tracking and verification of CO_2 emissions, with 'Swytch Tokens' awarded based on the impact of a given unit of energy in carbon abatement. The algorithm for allocating Swytch tokens is open-source, allowing all participants to fully understand the system and contribute to its continued development. These tokens can be monetised through trade, and the blockchain solution can be used in parallel to the EU ETS to create trading and arbitrage opportunities for the companies involved. Swytch claim that the solution allows for compliance and verification to be ensured as well as enabling the accounting of cross-border trades.[53]

Note S6: Blockchain case study: Voluntary Carbon Markets

Voluntary carbon markets harness the willingness to pay of governments, corporations and individuals to offset their greenhouse gas emissions above what is required through regulation.[54] They can work in parallel to compliance markets and provide revenue for projects that are not eligible in these markets.[35] As they are voluntary, the offset for each participant are not determined by cap-and-trade or other methods, and so voluntary offset verifiers such as The Gold Standard and Voluntary Carbon Standard produce standardised rules. Gaining certification under these schemes allows the market to assess the credibility of the carbon offsets purchased.

Voluntary markets have reduced administrative burden, allowing smaller project owners to enter the market who cannot afford the high UN certification costs.[55] This lack of official regulation also enables additional flexibility in how offsets are produced, fostering to experimentation and innovation. This has allowed small communities in developing countries to participate in carbon markets where the quantity of offsets produced is too small for compliance markets to be profitable. New technologies that can be tested in these small projects can then be scaled up and implemented into regulated markets if they are successful.[55]

The major issue with current voluntary carbon markets is the lack of participation. This has led to an oversupply of carbon credits, resulting in low offset prices and no guaranteed return on investment from offsetting projects as many credits are left unsold. However, participants are willing to pay more than the current market clearing price for an offset.[56] Private investors are willing to reduce their financial return on investment to contribute to climate change mitigation, but current markets cannot facilitate this[57] and so understanding the causes of low market participation is crucial.

Edwards[57] states that investors are not confident that their donations are managed by credible institutions. The centralised approach of these markets gives little transparency as to the specific source of the offset credits that are purchased. The data provided to customers is often no more granular than the offset type, such as ‘energy efficiency’ and ‘afforestation and reforestation’.

The current amount of CO_{2e} that is offset is not accurately known due to poor industry accounting. Current estimates are based on offsets issued, transacted or retired, rather than offsets generated (which is likely to be higher). This is because many offsets generated will not be listed unless a buyer is found, and thus the current oversupply means many are left unlisted. Offset generation data is publicly available in project design documents, validation and verification reports, but there is currently no database that aggregates this information.[35]

Selling carbon offsets in minimum quantities of 1 tCO_{2e} makes the offsetting of every-day purchases (e.g. refilling your car, buying coffee) impossible without additional complicated accounting. Therefore, there is a potential new market of microtransaction offsets that is currently untested.

Finally, there is concern regarding voluntary carbon offsets being counted towards host countries’ NDCs.[54] A decision must be made regarding whether these will be accepted; the result of which may increase accounting costs. In current systems, ensuring that this is avoided increases the complexity of monitoring NDCs by host countries.

The tokenisation of carbon offsets on a blockchain has the potential to solve all the issues raised above. The transparency of a public blockchain allows for the potential tracking of carbon offset credits across the entire supply chain, from the project verification through to retirement of the credits.[58] Coupled with the tamper-proof nature of DLT, this significantly increases the integrity of voluntary carbon markets.

Tokenisation allows carbon offsets to be 'fractionalised', enabling microtransactions that could serve the growing environmental consumer movement.[59] Blockchain solutions operating in carbon markets have seen the formulation of new business-to-consumer marketplaces whereby any retail business can give the customer the opportunity to offset the carbon emissions in their purchased products.[60]

Blockchain allows for carbon offset projects to link into several different regulatory systems, such as the EU ETS and future international markets as well as into voluntary offset registries.[61] This ensures that double counting of offsets in two or more markets is not possible, as once the offset credit is sold, then the ownership is then transferred away from the project owner.

A blockchain based voluntary carbon market has the potential to dramatically change the roles and power structure of the current set-up. Currently, carbon asset development intermediaries and standards bodies are well respected and well used in the market to provide assurances on quality. For example, Verra's Voluntary Carbon Standard hosting 85% of all voluntary carbon offset volume in January to August 2021.[38] Blockchain solutions such as Toucan Protocol appear to provide a threat to these actors, as seen by Verra prohibiting tokens based on retired credits from their registry.[65] In the future, the entities creating the token and programmers of the public blockchain network may play more important roles in the market and reduce the need for intermediaries by setting clear market rules and enabling trusted devices to automatically record data to the ledger.

Case study: Poseidon Foundation is a non-profit company who have developed a carbon offsetting platform for business-to-customer transactions called 'reduce'. The Stellar blockchain platform was chosen as it is less energy intensive than developing an application using Ethereum. Their solution allows retailers to give the opportunity to customers to pay an additional charge to offset the embodied carbon in their purchase through land-based carbon credits. Blockchain technology was used to store transaction information publicly and allow for near real-time processing of micro-transactions. This gives customers confidence in their offsets through adding transparency and traceability to the system.[60]

Poseidon Foundation had a pilot project at a London Ben & Jerry's store, where customers were given the opportunity to offset the carbon emissions in their purchases, which enabled the conservation of 5500 trees during the 7-month trial.[62] The success of this pilot project has resulted in Liverpool City Council partnering with Poseidon foundation to offset the city's carbon emissions by 110% by 2020 (i.e. becoming carbon-negative).[63]

Note S7: Blockchain case study: Article 6 of the Paris Agreement

The previously mentioned use cases work on regional scales. However, there are international agreements that have been proposed to create global carbon markets. Article 6 of the Paris Agreement aims to allow international cooperation between countries in order for all parties to reach their respective Nationally Determined Contributions (NDCs), and is governed by the UN.[64] Compliance to this scheme is voluntary, and parties can choose to not participate in this scheme to achieve their emissions reductions targets.

Article 6(2) states 'cooperation approaches' which allow direct trade between complying countries, and although not explicitly mentioned in the legal wording, negotiations to date suggest that this is likely to be carbon trading. It presents the fundamental process of balancing parties' NDCs while trading to ensure that there is no double counting.[66] Article 6(4) proposes a 'mechanism to promote mitigation and sustainable development'.[64] This aims to create a functional unit for simplified accounting of international cooperation by creating a standardised unit of measurement (yet to be agreed).

This article is a direct way of incentivising private sector action by providing the opportunity to help reach the Paris Agreement targets when the parties disseminate their NDCs. It allows countries with high marginal abatement costs to use carbon markets to help achieve their NDCs by investing in emissions reduction schemes in other countries.[67] For example, the cement production industry in the United Kingdom could fund a reforestation programme in Indonesia to support reaching their own emissions targets, as this may be less expensive than changing their own industrial processes. Indonesia could not use the carbon offsets from this programme towards their own reduction targets, but benefits financially from the agreement.

To date, almost 100 countries are involved in discussions to use Article 6 to attain their NDCs,[68] but there are still major issues to resolve before implementation. Many essential factors are yet to be agreed upon: the scope of greenhouse gas mitigation activities, the methodology to prevent double counting of emissions reductions between parties,[64] and the settlement period for all parties to ensure that the central balance sheet is updated and correct at pre-determined intervals.[68]

In essence, Article 6 must operate as a cap-and-trade system to be effective. The collective ambition of all parties must be quantified and presented publicly to allow for a cumulative carbon budget to be produced. This can then be disaggregated back to each party's NDC and used to impose fines for emitting above this limit. This creates a market system where members can compete to produce the cheapest emissions reductions / removals possible and to trade to members who must purchase ITMOs to reach their reduction targets, incentivising innovation. However, Parties are cautious to declare a quantifiable carbon budget as ultimately this induces accountability. The ambiguity of NDCs that use wording such as 'a reduction from a business as usual scenario' can be viewed as a failure of the Paris Agreement when comparing it to the Kyoto Protocol as it does not allow for the 'unitisation' of reductions (i.e. for definitive values to be used as required in a 'cap and trade' type market), whereas the latter did.[69]

It has been suggested that blockchain technology can be harnessed to solve some of the barriers to implementing Article 6.[70] Each Party would become a node and would be responsible for validating each transaction using a Proof-of-Authority consensus mechanism.[68]

The immutability and cryptography of blockchain ensures that no asset can be owned by two parties at once, rendering double counting impossible. A public blockchain can be fully transparent and therefore allow anyone to check the records and ensure all targets are met, providing accountability. The added transparency and accountability of blockchain could enable faster and cheaper administration and real-time settlement. Blockchain and collaborative governance systems could increase the efficiency of monitoring, reporting and verification.[67]

Schneider does however identify several limitations of using blockchain technology.[68] If the number of nodes is limited to the number of Parties who wish to participate in Art. 6, the risk of collusion is increased. If over 50% of the nodes act maliciously, they have the potential to falsify records. Furthermore, the added complication of implementing blockchain technology is likely to make the negotiation process of introducing Art. 6 as a mechanism for reaching climate targets more difficult. The entire system would have to be set up with blockchain in mind from the offset as once the algorithm is programmed it is increasingly difficult to modify and therefore all negotiations must be completed at the start. Given the progress in negotiations since COP21, this seems improbable.

The issues surrounding Article 6 of the Paris Agreement are much larger than can be solved by blockchain alone. Applying blockchain architecture leads to a system that requires a binary yes or no solution to every outcome, which is rarely the result of negotiations. Furthermore, there is no evidence to suggest that the issues surrounding the general reluctance towards Party accountability will be resolved expeditiously. On the basis of these arguments, it is unlikely that blockchain technology will be used to implement Article 6 in the near future, despite the clear benefits it could bring.

Case study: The Decentralized Autonomous Organization Integral Platform for Climate Initiatives (DAO IPCI) is a non-profit organisation that produces decentralized carbon markets using smart contracts. The platform allows any individual or organisation to create specific use-cases known as modules. They have proposed a module to implement Article 6 of the Paris agreement on a blockchain. In this system, each UN Party is issued Internationally Transferred Mitigation Outcome (ITMO) tokens that represent a quantity of carbon credits which are deducted from the Party's NDC. Carbon offsetting projects can then apply to have their offsets verified by an independent entity and if successful are issued ITMO tokens. A Party can then purchase these tokens, and once they are retired, they will be counted towards the Party's NDC. Private users can also purchase these ITMO tokens for offsetting which does not count towards the NDC commitments of Parties. DAO IPCI believe that this system removes the issue of double counting.[71]

Note S8: Blockchain case study: CORSIA

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a UN environmental protection programme aiming for 'carbon neutral growth' of the aviation industry post 2020.[72] A baseline will be calculated based on the average emission levels in 2019 and 2020 and emissions above this level in all subsequent years must counterbalanced via airlines purchasing carbon offset credits that represent the equivalent amount of CO_2.[43] The UN's International Civil Aviation Organization (ICAO) was tasked in Article 2 of the Kyoto Protocol to provide policy measures to reduce or limit the emissions from the aviation industry[31] and CORSIA is the culmination of its efforts over the past 20 years.

The scheme will begin with a pilot phase in 2021-2023, where flights between 71 countries will be regulated, and participation will remain voluntary until 2026. As the scheme is still in its infancy, it still has many issues to resolve. The ICAO state that double counting must be avoided;[73] however, they have not provided a mechanism to ensure this.

Concern has been raised over the eligibility criteria of carbon credits that will be accepted in the scheme. If credits issued under the Kyoto Protocol are used, CORSIA will have no positive impact on the environment.[43] There is a surplus of 4 billion credits from the Clean Development Mechanism (CDM) due to demand for carbon credits being much lower than supply. CORSIA is expected to demand 2 billion credits, and so would yield no additional carbon sequestration if CDM credits are accepted.

Blockchain technology has the potential to increase the credibility and success of CORSIA. It can provide full supply chain history of the carbon offset, from the generation of the offset credit at the source, to the surrendering of the credit by airline companies. Each eligible offset credit could be identified as not generated via the CDM and therefore 'additional' via encoding a unique serial number. A smart contract could then be executed to only accept offsets from certain eligible verified sources or schemes, such as The Gold Standard. Blockchain technology also allows for the immutable record of all surrendered carbon credits to be stored in an append-only ledger, which ensures the compliance of all airlines covered in the scheme and that no carbon credit is counted twice. This approach also benefits airline companies in the face of increased pressure around corporate sustainability, as this provides a tamper-proof way to transparently show the reductions made by each company – thus avoiding 'greenwashing'.[61]

The ICAO are in an optimum position to design and implement this blockchain application as they already have blockchain expertise and recognise its potential, stating '*blockchain has the potential to virtually exclude loss, distortion or forgery of vital log data in all aviation sectors where certificates are issued and controlled*'.[74] As carbon credits have similar requirements to certificates (identifying ownership, traceability, no tampering etc.) then the use cases discussed during the ICAO-UAE Blockchain Summit and Exhibition can be adapted to CORSIA.[74] However, as of August 2019 there are no current blockchain solutions which outline a clear use-case to use blockchain technology for CORSIA.

Supplemental Tables

Table S1: Sources used to assess blockchain solutions in this study. Anonymous sources refer to the interviews conducted as part of this study.

Company	Source
AirCarbon	AirCarbon [75]
Blockchain for Climate	Blockchain for Climate Foundation [76,77] Pallant [78]
Brazilian Development Bank	Braden [17] ABES [79] Marl [80] The Brazilian Development Bank [81]
Carbonex	Carbonex [82,83]
CarbonX	*Anonymous E* CarbonX [84]
Climatecoin	Climatecoin [85] Etherscan [86]
Climate Impact X	Climate Impact X [87–89]
Climate Trade	Climate Trade [90] Climate Blockchain Initiatives [91]
Dajie	Montemayor and Boersma [92] Dajie [93] *Anonymous F*
DAO IPCI	DAO IPCI [71,94–98]
Ecocoin	Nextnature Network [99] Ecocoin [100,101]
EcoKraft GmbH	EcoKraft GmbH [102–104]
Emmi	Emmi [105,106] *Anonymous A*
Energy Blockchain Labs	IBM [107] Energy Blockchain Labs [108]
Energy Web Foundation	Energy Web Foundation [15,109–111] *Anonymous B*
Green Element Chain	Green Element Chain [112,113]
Greeneum	Greeneum [114–117]
Impact Choice	Impact Choice [118,119] Saunders [120,121] Harley [122]

Company	Source
Ixo Foundation	Ixo Foundation [123–125] London Letter [126] Foster [127]
Japanese Ministry of the Environment	Japanese Ministry of the Environment [128]
Nera	New Era Energy [58,129–132]
Noble Profit	Noble Profit [133,134]
Nori	Nori [59,135–137] Kenyon [138] Jospe [139] Dell [140] Picchi [141]
Poseidon Foundation	Poseidon Foundation [60,62,142–145] Green [63]
Power Ledger	Power Ledger [146–150] Etherscan [151]
Project Carbon	Ledger Insights [152] Carbon Place [153] *Anonymous H*
Rabobank	Rabobank [154,155]
Reforestum	Reforestum [156,157] *Anonymous C*
ReWatt Power	Bentein [158] ReWatt Power [159–161]
Swytch	Swytch [52,53,162,163]
Synergy Inc.	Vertrade [164] Synergy Inc. [165,166] Lin [167] *Anonymous D*
TerraGreen	TerraGreen [168,169]
Toucan Protocol / KlimaDAO	KlimaDAO [170,171] Polygon [172] Toucan [173]
Veritree	*Anonymous G* Veritree [174]
Veridium Foundation	Veridium Foundation [175] Veridium Labs [176] Veridium Labs and Veridium Foundation [177]
Vlux	Green Running Ltd [178–180] Jackson [181]

Company	Source
Volt Markets	Volt Markets [182,183]
World Bank	World Bank [184,185] Michaelowa [37] Mok *et al.* [186]
XELS	XELS Project [187,188] Akihabara News [189]
Xpansiv Data	Investable Universe [190] Xpansiv [191,192]

Table S2: Descriptions of the technology solutions studied.

Organisation	Use case	Short description
AirCarbon	Carbon offset trading	Aircarbon are creating a digital exchange that reduces inefficiencies in carbon markets. They are a member of IETA.
Blockchain for Climate	Article 6	Aim to put the Paris Agreement on the blockchain, using Proof-of-Authority consensus with all states and the UNFCCC as nodes.
Brazilian Development Bank (BNDES)	Carbon offset trading	Uses a blockchain based workflow management tool called 'Trubudget' to increase trust when sharing data on REDD+ projects.
Carbonex	Carbon trading	A carbon trading platform that will be compatible with existing markets.
CarbonX	Carbon offset trading	A private blockchain that uses REDD+ linked tokens to create a peer-to-peer trading system that rewards carbon reducing behaviour.
Climate blockchain Initiatives (Climatecoin)	Investing	An investment programme that allows individuals to invest in carbon-reducing projects.
Carbon Blockchian Initiatives (ClimateTrade)	Carbon offset trading, investing	Gives corporations and individuals the opportunity to offset their emissions or invest in green finance.
Climate Impact X	Carbon trading	Climate Impact X (CIX) is a collaborative effort of DBS Bank, Singapore Exchange, Standard Chartered and Temasek to use satellite imagery, machine learning and blockchain to improve transparency and integrity of carbon credits.
Dajie *(no longer operating)*	Carbon trading	Allowed household renewable owners to trade energy with their neighbours using an IoT device that functions as a node of a blockchain. State that carbon credits could be claimed from this trade. Company transformed into 'Prosume' and no longer operating in carbon markets.
DAO IPCI	Carbon trading, carbon offset trading, Article 6	Aims to create a common marketplace to link current markets, using different blockchain solutions that they will create and a 'MITO' token as the payment method.
Ecocoin	Rewards scheme	Rewards carbon reducing behaviour, such as changing the method of commuting to work from a car to bicycle.
EcoKraft GmbH	Investing	An investment platform for community energy projects in developing countries. Uses smart metering devices to collect consumption data, including how much CO_{2e} was reduced.
emmi	Carbon trading	Aim to create a carbon market that doesn't require government cooperation.

Organisation	Use case	Short description
Energy Blockchain Labs	Carbon trading	Creating a carbon asset development programme for the Chinese carbon markets to aid companies to comply with government mandated carbon reductions.
Energy Web Foundation's Origin platform	Carbon trading	A public, Proof-of-Authority blockchain platform for renewable energy certificate and carbon accounting markets. Allows for developers to build dApps using their platform.
Green Element Chain	Carbon tracking	A subsidiary of Energy Blockchain Labs who have a carbon tracking dApp called 'M-Green'.
Greeneum	Carbon trading	Allow peer-to-peer trading of energy in their marketplace, using 'GREEN' tokens. These tokens can be used to purchase sustainable products or be exchanged for fiat currency.
Impact Choice (Earth Token)	Carbon offset trading	A proxy carbon market as tokens represent the value of natural assets and can be used for carbon sequestration.
Ixo Foundation	Carbon trading, Article 6	Impact tokens are produced for activities related to the Sustainable Development Goals, including tokens which represent carbon credits.
Japanese Ministry of the Environment	Carbon tracking	Track CO_{2e} emissions reductions using blockchain technology.
New Era Energy (Nera)	Carbon trading	Have a blockchain solution called Carbon Grid Protocol that aims to put current carbon markets onto a blockchain.
Noble Profit (BFlow)	Carbon tracking	Aim to make the reporting of sustainability metrics easier.
Nori	Carbon offset trading	Creating a carbon removal marketplace that will launch in 2020, with the first use place being carbon offsetting through soil carbon sequestration.
Poseidon	Carbon offset trading	Aims to simplify the carbon market and enable microtransactions to increase the number of participants.
Power Ledger	Carbon trading	Created an application with the primary aim of peer-to-peer energy trading. Has an additional use case of facilitating carbon trading.
Project Carbon	Carbon trading	Project Carbon is an alliance between CIBC, Itaú Unibanco, National Australia Bank and NatWest Group aiming to use blockchain to provide reliable issuance and tracking of carbon credits.
Rabobank	Carbon trading	The Rabo Carbon Bank aims to reduce and remove 1Gt of CO_2 from the atmosphere by 2030, partially through developing voluntary carbon credit projects with farmers. They will also launched a Rabo Carbon Bank Marketplace.
Reforestum	Carbon offset trading	Validates carbon offset projects using smart contracts, satellite imagery and biomass calculations. Aims to link carbon offset tokens to physical pieces of land.

Organisation	Use case	Short description
ReWatt Power	Carbon tracking	Aims to monetise microgeneration by using blockchain technology to more easily track carbon reductions.
Swytch	Carbon trading, Carbon tracking	Using a Proof-of-Production protocol to create evidence of energy production, creating additional revenue for carbon-neutral energy production. Aims to use the carbon credits produced in EU carbon markets.
Synergy Blockchain Technology Co. Ltd.	Carbon trading	Aims to create a single carbon trading platform for all carbon markets worldwide. The platform works like an auction, where individuals or corporations can bid for specific carbon credits.
TerraGreen	Carbon trading	Producing a blockchain platform that dApps can be deployed on. Energy tokens can be produced and added to a tradable exchange. If the energy produced was from a renewable source then carbon credits can be claimed, which can then be bought on the exchange by consumers who wish to offset their emissions.
Toucan Protocol / KlimaDAO	Carbon offset trading	Toucan Protocol links off-chain registries to the blockchain, creating tokenized carbon credits (tCO_2) on the Polygon Blockchain. KlimaDAO uses these to create KLIMA Tokens (each representing 1 carbon credit) with the goal to raise the price floor of carbon assets.
Veridium Labs	Carbon offset trading	Tokenises REDD+ projects that are backed by Infinite Earth
Veritree	Carbon tracking	Veritree are utilising technology to collect and manage ground-level data on-site of reforestation projects and detailing this on a blockchain ledger.
Vlux	Carbon tracking	A home energy assistant that uses AI to reduce carbon footprints and lower electricity costs. The Verv Trading Platform (VTP) aims to track all electricity trades to make the data public and aid carbon traders.
Volt Markets	Carbon trading	Creating a peer-to-peer energy trading platform to remove intermediaries from the sector. Uses smart contracts to automatically generate and issue certificates.
World Bank	Article 6	Aims to enhance global ambition through carbon markets. Creating a 'Climate Warehouse' infrastructure to implement Art. 6 of the Paris Agreement on the blockchain
XELS	Carbon trading	A blockchain based trading platform in development where tokenized carbon credits will be available for purchase.
Xpansiv Data	Carbon Trading	Publicly supported the development of Distributed Ledger Technology since 2018, and in 2021 announced a partnership with Daml, a leading builder of blockchain applications, to publish ESG data.

Table S3: The number of market solutions being developed for each use cases currently being designed in the sector.

Use Case	Number of market solutions
Carbon trading	19
Carbon offset trading	10
Carbon tracking	7
Art. 6 Paris Agreement	4
Investing	3
Rewards scheme	2

Supplemental Figures

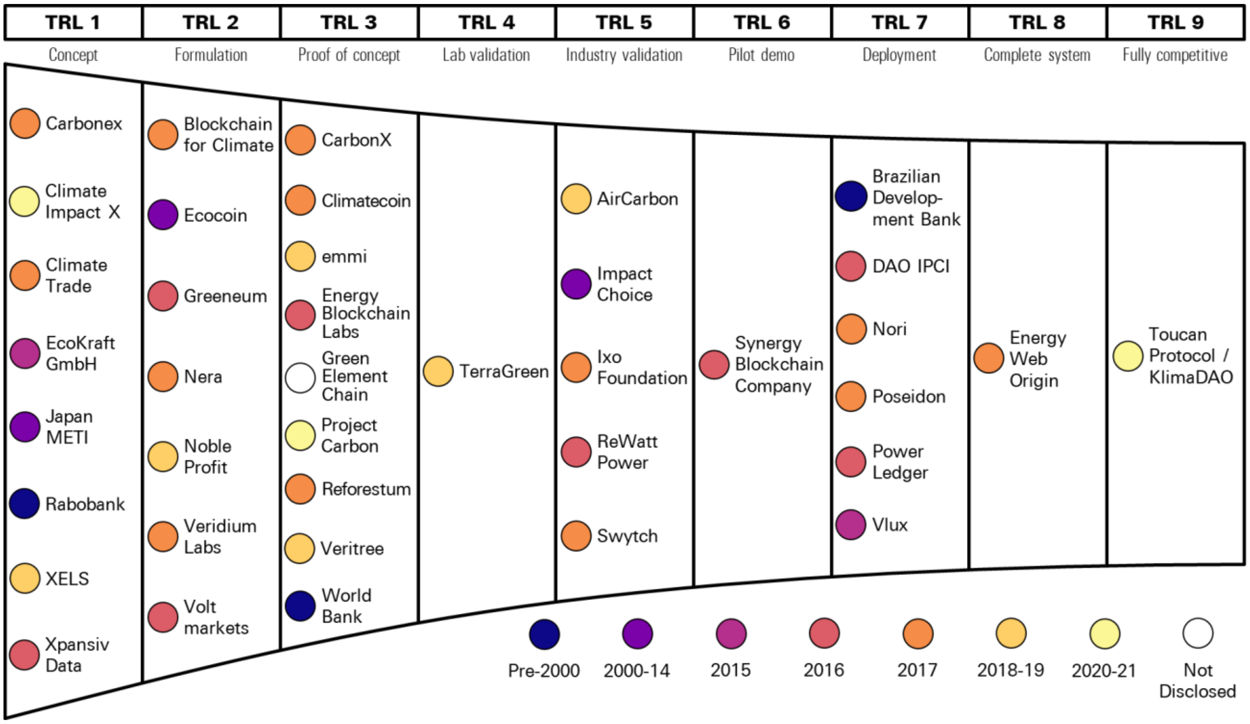

Figure S1: The Technology Readiness Level of blockchain solutions in carbon markets, showing the age of each project. A full list of sources is given in Table S1.

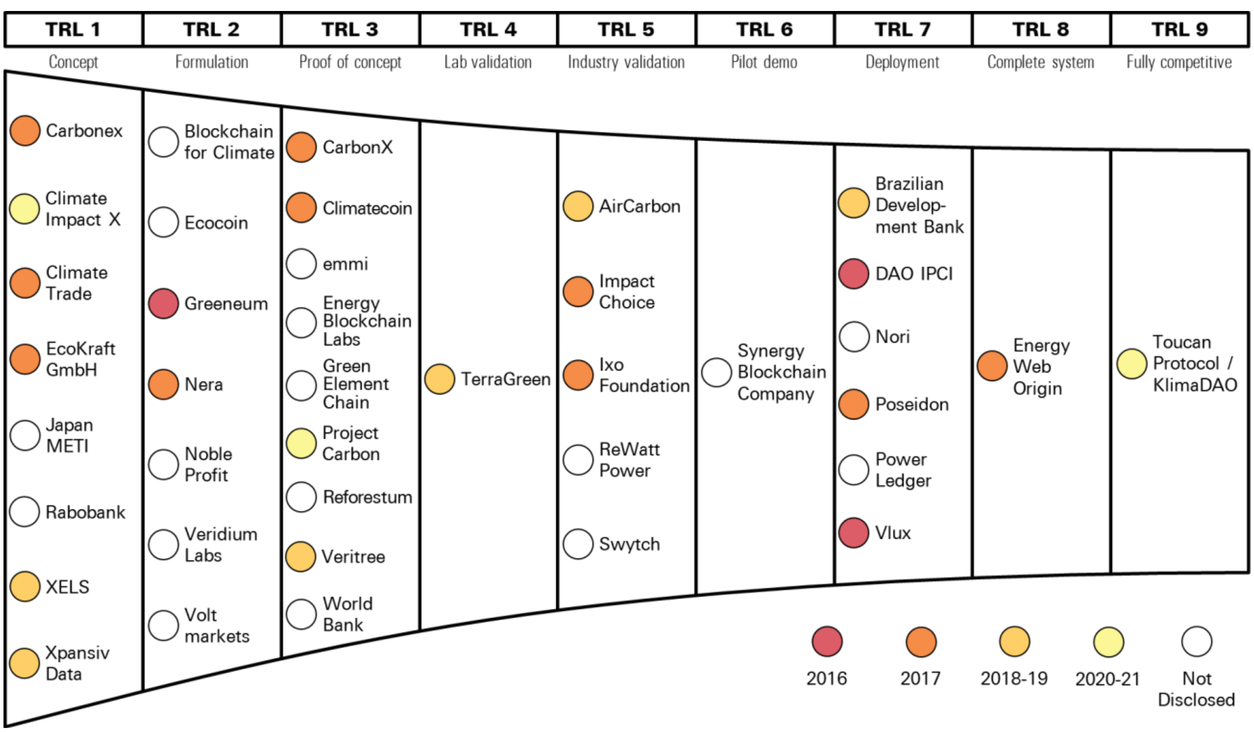

Figure S2: The Technology Readiness Level of blockchain solutions in carbon markets, showing the year blockchain development began for each project. A full list of sources is given in Table S1.

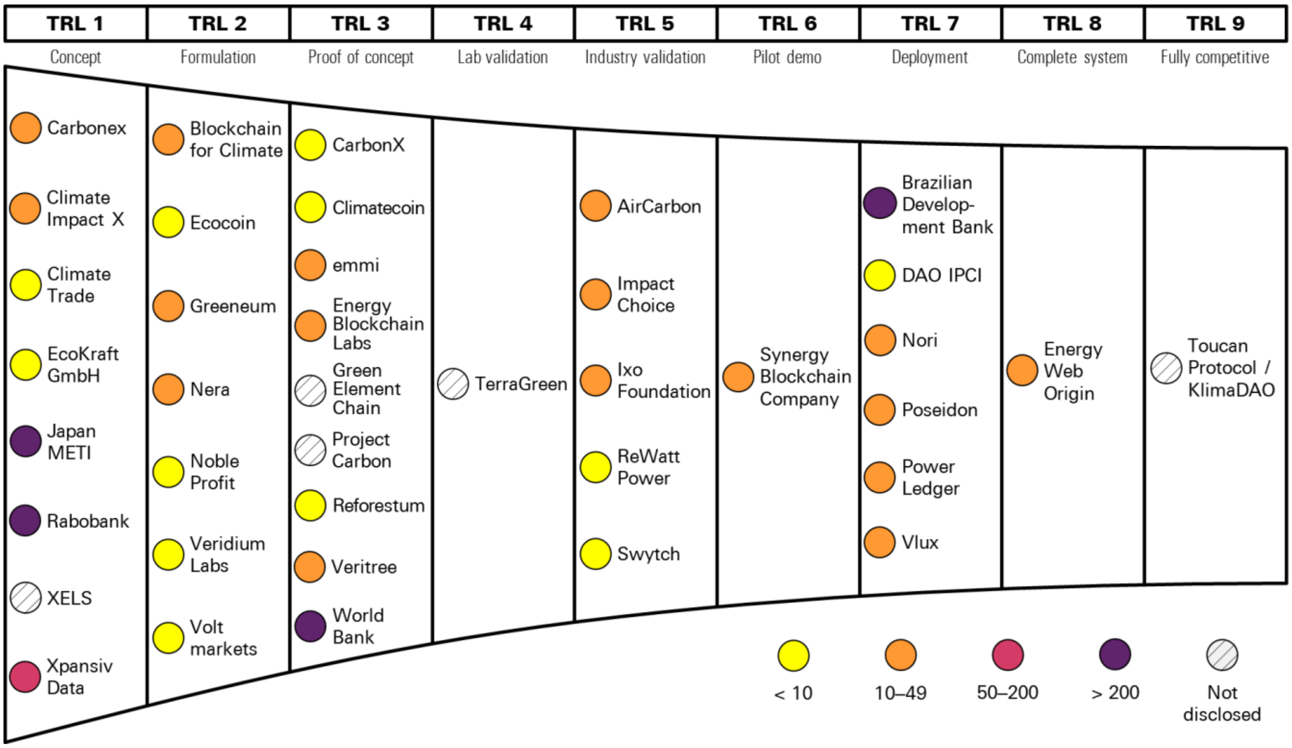

Figure S3: The Technology Readiness Level of blockchain solutions in carbon markets compared to the number of employees of each organisation. A full list of sources is given in Table S1.

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