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Blockchain Application for the Paris Agreement Carbon Market Mechanism—A Decision Framework and Architecture

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Abstract: This paper evaluates the suitability of blockchain technology for the Article 6.2 carbon market mechanism of the Paris Agreement. The bottom-up approach of the Paris Agreement causes challenges to the robust accounting of mitigation outcomes and information asymmetry, both of which result from a high number of heterogeneous emission accounting systems. Blockchain is an innovative technology that can act as an aggregation platform for these fragmented systems while enhancing transparency and automating accounting processes. However, this new technology is not a panacea for all problems, and the trade-offs of applying blockchain technology need to be assessed case by case. We create and apply an eight-step decision framework for testing the applicability of the technology for the Paris Agreement Article 6.2 carbon market mechanism. The analysis shows that, under current mechanism specifications, a blockchain application can enhance transparency and increase automation, thereby eliminating information asymmetry. We outline a system architecture that allows the linking of the heterogeneous systems, the integration of an Article 6.2 exchange mechanism, and the progress tracking of climate targets. This blockchain architecture offers national Parties the opportunity to co-create a decentralised system in line with the bottom-up ethos of the Paris Agreement.

Keywords: Blockchain; decision framework; climate policy; carbon markets; Paris Agreement; Article 6; permissioned; permissionless; Climate Warehouse

1. The Paris Agreement Carbon Market Mechanism

Cost-effective mitigation of greenhouse gas (GHG) emissions is crucial for limiting the global temperature increase to well below 2 °C, the target set by almost 200 national Parties of the Paris Agreement [1]. Carbon pricing is one of the most widely used policy instruments for cost-effective GHG mitigation, with 57 GHG pricing initiatives globally in 2019 and 96 Parties considering to use carbon pricing [2]. Approximately half of these initiatives use market-based mechanisms. The Paris Agreement also outlines a market mechanism in Article 6.2 to promote the cooperation between Parties in achieving their nationally determined contributions (NDCs) through internationally transferred mitigation outcomes (ITMOs).

However, present carbon market mechanisms have limitations to the consistent provision of transparency and robust accounting, compromising the environmental integrity of mitigation actions [3–7]. Transparency in this context refers to the reporting and review of information related

to the tracking of mitigation outcomes, and with enhanced transparency comes trust and confidence in climate action [5]. Zhang et al. [8] (p. 290) divide the issues related to robust accounting into i) validation of information (e.g. compliance with relevant rules or regulations), ii) the linkages among different emission trading systems (e.g. domestic and international), and iii) the building of trusted emission accounting systems. These issues have generally reduced accountability and compromised the levels of trust and cooperation among the Parties [9,10].

In contrast to present carbon market mechanisms, Article 6.2 moves away from centralised accounting, comprehensive rules and standardisation for the issuing and transferring international units by offering decentralised cooperative approaches [5]. This bottom-up approach requires Parties unilaterally to ‘ensure environmental integrity and transparency’ and to ‘apply robust accounting to ensure, inter alia, the avoidance of double counting’ (Articles 6.2 and 6.3) [1,5]. The considerable heterogeneity in emission accounting systems – leading to accounting challenges that result from diverse information formats – magnifies the challenges associated with assessing, tracking, and comparing Parties’ actions [5,11]. The mitigation outcome data in these systems are currently collected in a variety of repositories, including spreadsheets, pipelines and registries, with diverse information formats [12,13].

Blockchain technology, which constitutes an innovative approach to accounting and data harmonisation, has the potential to overcome these challenges. Recently, blockchain technology (also known as Distributed Ledger Technology, or DLT) emerged as a platform providing real-time, verifiable and transparent accounting system. The general carbon markets literature considers blockchain technology valuable in two application areas. First, blockchain could improve data collection procedures and digitise the measuring, reporting, and verification (MRV) processes of mitigation actions [12,14–17]. Second, blockchain could serve as an aggregation platform, a ‘ledger of ledgers’ or meta-registry, linking all heterogeneous emission systems in one platform (e.g. The ‘Climate Warehouse’ proposed by the World Bank for linking national registries) [12,13,18–22].

Nonetheless, despite general agreement about blockchain potential, no study has yet comprehensively evaluated a solution-problem fit. Given the evolving and changing nature of the Article 6 rulebook [23–26], such an evaluation is key to understanding under what conditions a blockchain application is beneficial and which rulebook changes might make a blockchain application impractical. We extend the blockchain and carbon market literature by introducing a blockchain decision framework to evaluate the technology’s applicability in Article 6.2. We base our evaluation on the preliminary design options outlined in the Article 6.2 rulebook at the time of writing (May 2020). We synthesise ongoing environmental integrity and robust accounting discussions, the linking of heterogeneous emission accounting systems, and extend the literature with a particular focus on the bilateral transfer mechanism of ITMOs between Parties. In so doing, we provide a novel approach for climate change policy-makers and practitioners to consider.

We also outline an alternative architecture – derived from our analysis of the Article 6.2 rulebook – that resembles the bottom-up, decentralised ethos of the Paris Agreement and therefore may have an invigorating effect on Article 6 negotiations. We had multiple discussions with subject matter experts from the World Bank Technology and Innovation Lab (ITSTI) and the Carbon Markets and Innovation Practice (CMI) team. These experts provided feedback on and insights into Article 6.2 accounting challenges, the proposed blockchain architecture, and the co-creative development process.

The paper is divided into five parts. Section 1.1 introduces the accounting challenges to safeguarding environmental integrity, and Section 1.2 presents general blockchain concepts and practical approaches aimed at leveraging blockchain systems to carbon market mechanisms. Section 2 gives the blockchain decision framework and applies the eight classifiers to the Article 6.2 case study. Section 3 outlines a blockchain-based architecture for the meta-registry and the Article 6.2 exchange and discusses both the advantages and limitations of applying blockchain technology. Section 4 concludes and discusses implications for future research.

1.1. Safeguarding Environmental Integrity through Robust Accounting

To establish a functioning carbon market mechanism, the safeguarding of environmental integrity is key [27–33]. Article 4.13 of the Paris Agreement explicitly states that ‘Parties shall promote environmental integrity, transparency, accuracy, completeness, comparability and consistency’ ([1], p. 3). Although there are different interpretations between Parties of what environmental integrity encompasses, there is general agreement that transparency and robust accounting are prerequisites to ensure unit quality [5,29]. Article 4 and Article 13 provide general provisions for NDC accounting, and Article 6 provides specific provisions for the accounting of ITMO transfers between Parties. Schneider and La Hoz Theuer [31] further specify the importance of establishing a robust accounting framework for ITMO transfers, which prevents double-counting of GHG reductions, ensures appropriate corresponding adjustments, and warrants correct accounting of the ITMO vintage [34].

Double counting occurs when a single ITMO is counted more than once towards NDCs and non-state actor (NSA) targets. These NSAs comprise private actors such as companies, non-governmental organisations (NGOs) and philanthropists, as well as public sub-national actors like regions and cities [35]. Despite the unprecedented engagement of NSAs in the Paris Agreement [35,36], NSA emission accounting is a significant challenge [37]. While previous versions of Article 6.2 and 6.3 stated that the transfer of ITMO by non-Parties (i.e., NSAs) must be authorised by participating Parties, the reference of NSAs in the Article 6.2 rulebook was removed during the latest Conference of Parties 24 in Katowice [26,38].

Double counting can occur due to double issuance, the issuance of multiple units for the same mitigation outcome; double claiming, i.e., counting the same unit towards multiple targets (e.g., for NDC compliance markets and NSA voluntary markets); or double use, i.e., using a unit multiple times towards a mitigation target [31]. Accounting issues can further arise due to differences in the NDC target year of involved Parties [5,31,34]. These vintage problems occur when Parties with different NDC target years, such as single-year targets and continuous multi-year targets, bilaterally transfer ITMOs [28].

In addition, learnings from the Kyoto market mechanisms suggest that information asymmetry between project proponents, regulators, and auditors caused an adverse impact on the accreditation of project outcomes [4,34]. This asymmetry mainly originated from incomplete or not-existing key project documents, such as monitoring and verification reports [3,4]. The Kyoto mechanisms demonstrated that the transparency and availability of information for other actors, such as domestic institutions, scientists, or civil society organisations, is critical to creating an effective market mechanism that incentivises the transferring Party to adopt ambitious mitigation targets while simultaneously ensuring unit quality [39,40]. These past experiences highlight the need for an accountability mechanism that reduces information asymmetry to incentivise all Parties to contribute sufficiently ambitious mitigation actions.

Given these problems, it is questionable if and how the newly defined Article 6.2 market mechanism can consistently enforce environmental integrity and prevent the reoccurrence of Kyoto mechanism failures with a conventional software and database architecture. Compared to the Kyoto mechanisms, Article 6.2 poses significantly more complicated accounting challenges due to the heterogeneous accounting systems and rules. For example, the accounting of ITMOs outside the scope of the host countries’ NDC [5,41], the uncertain and complex definition of an ITMO metric, and the corresponding adjustment process for the transfer of ITMOs [32,42]. A single and common ITMO metric would be, for example, tCO₂e, which could be issued in a registry and then traded multiple times while ensuring comparability between mitigation outcomes [5]. However, ITMOs could also be defined as non-GHG metrics, or as net flows between two Parties over a certain period [5,26,42]. The accounting of mitigation outcomes outside the NDC scope and the different ITMO definitions lead to complex and diverse corresponding adjustment approaches.

Corresponding adjustments are conducted on an emission-based or budget-based approach [5] and require a coherent accounting basis (e.g., the NDC targets of the Parties involved). Parties participating

in cooperative approaches should submit an initial report when receiving authorisation or conducting the first ITMO transfer, possibly in conjunction with the next Biennial Transparency Report (BTR) [26]. Consecutive ITMO transfers are reported in the country's next BTR and included in its NDC accounting [42]. However, the dependence on BTRs for the ITMO transfers introduces significant information asymmetry, as the initial BTRs are first due by the end of 2024 and then every two years [7,43]. These BTRs are used as a key information source for the global stocktake (GST). The GST is conducted in 5-year periods and aims to review and increase ambition over time [44]. The BTRs, including the ITMO transfer information, are reviewed by the Article 6 technical expert review team (TERT). The TERT assesses the reported information and drafts a technical review report providing findings and recommendations for the Paris Agreement's multilateral consideration of progress [7]. However, the cyclical reporting of BTRs and the GSTs, combined with heterogeneous accounting systems and diverse methodologies, places a great burden on the limited TERT review capacity [7]. Consequently, Hanle et al. [7] argue for the 'rethinking and redesigning' of reporting procedures for all Parties under the Paris Agreement. To improve these complex and predominantly manual accounting procedures, a platform that links national registries, NSA accounting systems, the Article 6.2 exchange, and the NDC target progress tracking under the TERT would therefore be highly beneficial.

1.2. Blockchain as an Aggregation Platform

Blockchain is an emerging technology that has reinvented data storage by distributing and synchronising all transactions across the network of participants (i.e., nodes) [45]. Accordingly, the transactions are not stored in a single centralised database but distributed equally across all network nodes so that each participant holds a copy of all the data, i.e., the ledger [46]. The access of all nodes to the entire history of transactions allows the nodes to both verify and publish new transactions on the blockchain [47]. The blockchain consensus mechanism defines how the nodes achieve agreement about a transaction to be added to the ledger [48]. The consensus mechanism evaluates whether the transaction is valid, considering the state of the ledger, and conforms with the rules of the blockchain network [48]. All new valid transactions are collected in a 'block', which is added to the 'chain' of existing transaction blocks and cryptographically linked in chronological order [49]. Due to this interlinked structure, the transaction history becomes immutable and tamper-resilient, as the altering of a block requires the changing of all subsequent blocks [50].

Smart contracts establish verified automation within the blockchain system. Smart contracts are computer protocols that enable automation of predefined rules when a particular condition is met [51]. They are formulated as 'if this is true, then ...' statements, which run on the blockchain and are executed autonomously when the predefined conditions are satisfied [52]. Through this programmability, smart contracts can automatically and consistently enforce regulations and methodologies to ensure transparency and accountability [15]. In the context of carbon markets, smart contracts can support the digitisation of MRV processes by automating the issuance and transfer of ITMOs [12]. During the ITMO issuance, the smart contract can store a wide range of metadata on the ITMO token to enable the traceability and unit quality assessment [19]. Such ITMO token metadata could, for example, include the country of issuance, sectoral scope, project name and identification number, guidance and methodology applied, and date of issuance (i.e. vintage). Furthermore, smart contracts can automate the ITMO transfer mechanisms, which we detail in the subsequent sections.

For the collection and harmonisation of ITMO data, the last version of the Article 6.2 rulebook outlines two centralised accounting and reporting platform, the 'international registry' and the 'Article 6 database' under the United Nations Framework Convention on Climate Change (UNFCCC) secretariat [26]. Previous drafts of the rulebook included references to distributed ledger technology (i.e., blockchain) as a possible technology [23,53], which were removed in subsequent iterations. However, given the limitations and heterogeneity of present market accounting systems, the further magnified accounting challenges under Article 6.2, and the decentralisation and bottom-up ethos of the Paris Agreement, we suggest that a blockchain application should be further investigated.

There exist several suggestions for blockchain-based mechanisms for the accounting and exchange of mitigation outcomes related to Article 6 [18–20]. To the best of our knowledge, the Climate Warehouse [13] proposed by the World Bank appears to be the most advanced solution. It establishes a blockchain-based accounting platform to link heterogeneous accounting systems. This so-called meta-registry connects country, regional, and institutional databases and registries to surface publicly available information on mitigation outcomes. Through this, the Warehouse provides an international platform to enhance transparency and trust among market participants and enable tracking of mitigation outcomes across jurisdictions [12,13]. The Open Climate platform [22] acts as an integrator of climate records to maintain a decentralised ‘ledger of ledgers’. This ledger develops climate communication protocols to harmonise climate actor data—ranging from countries, to companies to individuals—to provide transparency and accountability from the GST to the carbon pricing of mitigation outcomes [22]. Further examples for blockchain applications to enable the exchange of ITMOs are concepts and solutions suggested by the Blockchain for Climate Foundation [54], the Poseidon Foundation [55] and the AirCarbon Exchange [56].

These blockchain-based projects provide valuable experience and help to validate the technical feasibility of blockchain for this case study. Through these experiences, they help to overcome the legacy system thinking surrounding the Article 6.2 development, such as removing the DLT reference from previous rulebook versions [23] or only discussing replacing one specific component of the legacy system (e.g., the Kyoto International Transaction Log). This legacy thinking mainly leads to incremental improvements and fails to utilise the full potential of this innovative technology. The challenges and limitation presented in Section 1 clearly show that the legacy infrastructure will not be able to cope with the scale and complexities introduced by the bottom-up approach of the Paris Agreement. In the remainder of this paper, we argue that incremental improvements are insufficient to achieve robust accounting. Instead, we need to ‘rethink and redesign’ the Article 6.2 mechanism architecture. To develop this innovative architecture, we combine the learnings from the existing blockchain-based project to create a holistic vision and overcome legacy limitations.

2. Blockchain Decision Framework for the Article 6.2 Market Mechanism

Compared to conventional centralised database systems, blockchain systems have considerable costs and trade-offs in terms of, e.g., scalability, capacity and latency. Consequently, blockchains are not a panacea for all applications but need to be carefully evaluated based on the specific case study requirements [57]. In particular, blockchain resource disadvantages relative to database systems need to be offset by the benefits of having a distributed and automated system. Hence, viable blockchain technology case studies need to satisfy several characteristics. We integrate these ‘fit-considerations’ into a decision framework enabling a systematic evaluation of the Article 6.2 characteristics. As such, our approach (Figure 1) builds on previously suggested frameworks [57–59] modified to fit the requirements of the climate policy space.

The framework consists of eight classifiers in the form of the following questions: The framework starts with testing the general applicability of a blockchain (classifiers 1 to 3), continues with technical classifiers to determine blockchain performance requirements (4 to 6), and concludes with governance and data-accessibility-related classifiers to identify the most suitable type of blockchain system (classifier 7 and 8).

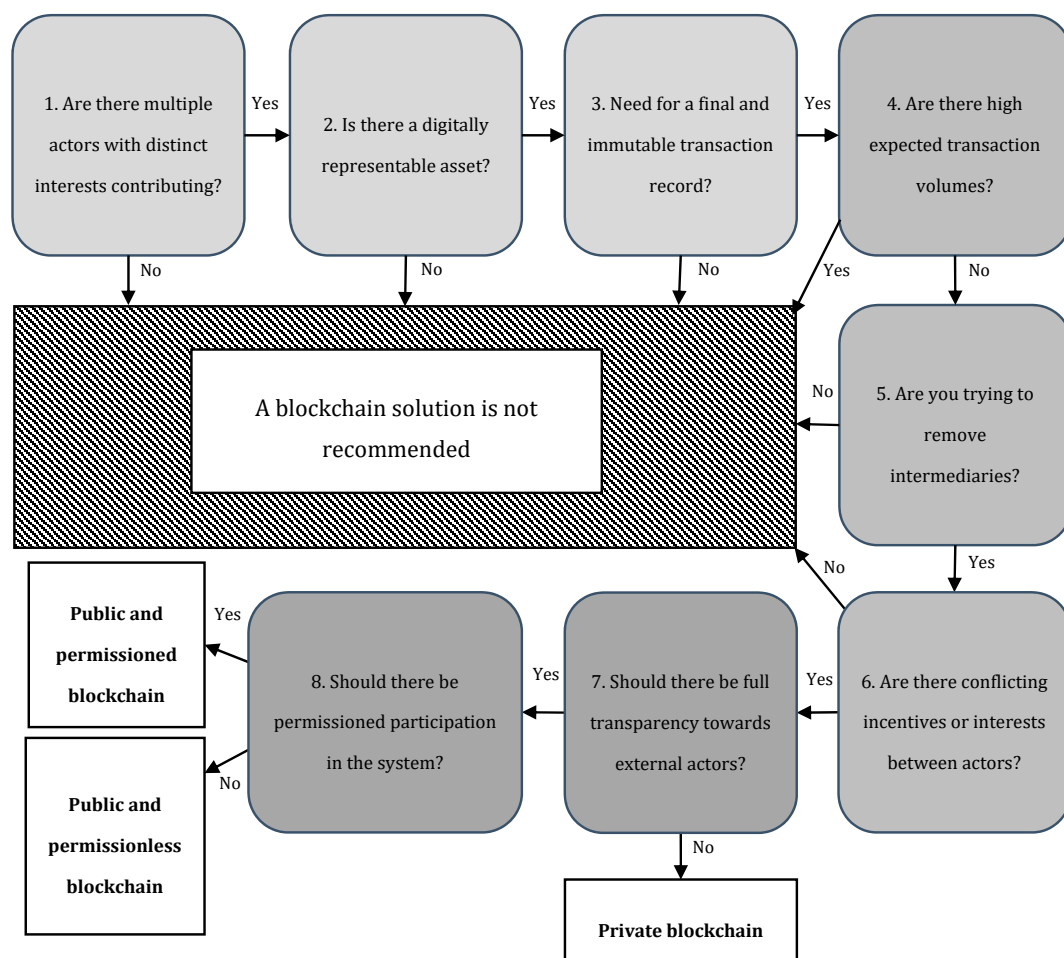


Figure 1. Blockchain decision framework.

In the following, we discuss each classifier based on the case study requirements of the Article 6.2 carbon market mechanism.

2.1. Multiple Actors Contributing?

Arguably the greatest achievement of blockchain technology is the development of a consensus mechanism that creates a consensus between a distributed network of nodes. A consensus must be achieved even in case of conflicting data and untrusted network participants so that there is always one single state of the ledger [60]. This distribution of data can eliminate single centralised points of failure and information asymmetry [18,51,61–64].

In this case study, the blockchain acts as an aggregation platform that combines heterogeneous emission accounting systems and enables ITMO transfers between a diverse group of participants. The Article 6.2 system consists of four main groups of actors: The national Parties, the UNFCCC secretariat, the Subsidiary Body for Scientific and Technological Advice (SBSTA) and the Subsidiary Body for Implementation (SBI), and the TERT. 195 Parties signed the Paris Agreement [65]. Under the Kyoto Protocol, 150 technical experts are selected by the secretariat out of a list of proposed experts from the Parties [66], which provides an indication for the TERT. This variety of network actors creates the necessary foundation of a distributed system. Given the uncertain accounting roles surrounding the integration of NSAs, we assume that NSA mitigation outcomes are monitored and exchanged through the respective national registry.

2.2. Digitally Representable Asset?

Under Article 6.2, an ITMO can be defined as a unit, as an amount, as a net flow, or all three forms interchangeably [42]. In all these forms, ITMOs are represented digitally as already happening in most carbon markets and exchangeable against a monetary unit. In this case study, ITMOs are represented on the blockchain as tokens that are used towards a mitigation target. The conceptual benefits of a token are the automation and disintermediation of the transaction process, a faster and more efficient clearing and settlement time, and the transparency and traceability of the complete transaction history [67]. These tokens could be fungible, i.e., divisible and identical, or non-fungible, i.e., unique and non-interchangeable.

Fungible tokens are favourable in case of a uniform system, e.g., cap-and-trade, where the ITMO token is denominated in a single and common metric (e.g., tCO₂e) and possibly traded multiple times among Parties [5]. Each ITMO token has a similar unit quality, i.e., generated using defined guidelines and methodologies, so that they are equal in terms of value and tradable like currencies. Fungible tokens can store specific metadata on each ITMO token [19,68]. This metadata is automatically inserted on each token by using smart contracts to ensure full information availability to the potential token acquirer.

Non-fungible tokens could be applied in cases where not all ITMOs have an identical metric. Due to the bottom-up nature and the present heterogeneity of accounting systems and markets, different actors will likely apply different scopes, rules and standards for ITMO exchanges [5]. In this case, non-fungible tokens are more suitable as they are not one-to-one exchangeable like a fungible token, but represent each ITMO's property and have varying unit qualities. Non-fungibility is the case when different policy instruments (e.g., taxes, performance or technology standards) or different accounting methodologies, cause the unique characteristics and value of each ITMO token [34]. There is also the possibility of Parties using non-CO₂ metrics [42].

2.3. Final State and Immutable Record?

At any point in time, an ITMO token can only have one owner – preventing conflicting ITMO ownership between Parties – which could otherwise result in double counting. All transactions are placed in sequential order on the blockchain, the history is immutable, and each ITMO can be traced from the origination project to the ultimate usage towards an NDC target. The immutability of the transaction record is an essential feature of blockchain technology and is the foundation for redefining trust, based on the mathematics behind the technology [69,70]. As the blockchain expands at a linear rate, tampering with a block in the chain would also require adjusting the hash of all subsequent blocks. The further the block is away from the end of the chain, i.e., the present state, the more difficult it becomes to change the information in the block. This tamper-resilience of historical transactions is particularly relevant in the auditing context [47,71].

Immutability has the advantage of bringing consistency into the history of an asset, e.g., an ITMO. Criticism against the mechanisms under the Kyoto Protocol included the lack of transparency in the project documentation, implementation, and validation of mitigation activities [3,4]. Hence, a permanent and immutable record is beneficial to enhance transparency and accountability. In an immutable system, it is always possible to go back in time and retrace every single transaction to the origin, which can be useful in case of fraudulent behaviours to trace all actors involved [47].

A final state is a precondition for the utilisation of smart contracts. For the creation of a smart contract, the conditions and possible outcomes are hardcoded into the system. These rule-based computer codes execute the encoded rules precisely as specified, without any possible ambiguity or having a 'spirit of the agreement' [72]. As the mitigation activities in the final rulebook are explicit and direct rules, almost everything specified in Article 6 can be encoded.

2.4. High Transaction Volume?

Compared to a centralised database system, a blockchain system has reduced transaction throughput, limiting the amount and velocity of data stored on-chain [57]. These are often described as the blockchain scalability issue [73–75].

The storage of larger files and pictures poses a challenge to most blockchains as it increases data synchronisation volumes. Based on the draft of the CMA [76] and experiences with past market mechanisms like Kyoto and the EU-ETS, the information in reports are mainly text or tabular documents. Franke et al. [77] estimate the peak volume to triple compared to the Kyoto mechanism, reaching approximately 1.2 billion transactions annually. This annual volume translates to an average of 36 transactions per second, which can be supported by most blockchains. To further reduce the requirements and avoid scalability issues, it is possible to store larger files in an off-chain database repository [57,73]. The metadata stored on each ITMO token can include the specific link to this off-chain repository. The InterPlanetary File System (IPFS) could be used as such a repository [77].

2.5. Removing Intermediaries?

In a centralised database system, one or few network authorities govern the system and have the authority to make decisions for the system. Under the Clean Development Mechanism (CDM), the UNFCCC hosted the CDM registry [78]. Despite the trust of the Parties in the UNFCCC, a central authority can become a single point of failure or a bottleneck [18,51,61–64].

In current emission accounting systems, there are various manual steps and bottlenecks related to the MRV and distribution of data that could be automated through blockchain and smart contracts, to reduce transaction and administrative costs [79–81]. The interconnection of blockchain and other emerging technologies might create innovative data collection approaches to support the Third Party Verifiers (i.e., the Article 6 technical review team). Emerging technologies, like the internet of things (IoT), artificial intelligence (AI), mobile and web applications can enhance MRV by automating data capture from source (e.g., IoT sensors like smart meters [18]) or remotely (e.g., remote sensing technologies, LIDAR, RADAR or even drone capture), and enhance datasets (through AI or machine learning for data verification to identify data errors or fraudulent behaviours [82]) [12].

2.6. Conflicting Incentives of Actors?

Blockchain is a ‘distributed trust technology’ [83–85]. This trust is achieved through decentralised data storage and governance, which is enabled through the participating nodes of the system [52,57]. The nodes in this case study are distributed across the actor groups of Article 6.2, i.e., national Parties, the UNFCCC secretariat, SBSTA and SBI, and the TERT.

The setup of Article 6.2 requires a high level of trust among the Parties, as each Party is required to submit their own ITMO data. There is an inherent economic incentive for Parties to overstate ITMO supply, to either use them to achieve the NDC targets or sell them for a profit [86]. Based on experience with the Joint Implementation (JI) Track 1 mechanism of the Kyoto mechanism, which had a similar design to Article 6.2, several problems and grievances were leading to an overall poor environmental integrity rating [3].

Accordingly, there is a strong case for implementing a blockchain-based system that offers enhanced tamper-resilience and more robust transparency and auditability features to ensure unit quality against the diverging incentives. Past problems under Kyoto, like double-counting or unit quality problems, could be prevented by unambiguous guidelines and transparency that are programmed as smart contracts into the system and automatically enforced. The formulation of these guidelines at the political level is very challenging due to the diverse and often contradictory interests. Once guidelines can be unambiguously formulated, smart contracts can be applied and automate enforcement.

2.7. Public or Private Transactions?

After confirming all previous classifiers in favour of a blockchain application, the next two classifiers examine the desired system governance design in terms of system transparency and openness for participation. Blockchains can be distinguished in terms of public or private data access and permissioned or permissionless rights to validate data or change the protocol [57]. On a public blockchain like Bitcoin or Ethereum, all transactions can be viewed in public, whereas private blockchains like Hyperledger Fabric or Corda require authorised reading access [51,57].

In this case study, there is a trade-off between the data confidentiality requirements of Parties and the transparency importance underlying robust accounting and environmental integrity. To maximise transparency and accountability, a public system, where all data are available, would hence be the best solution. However, it is uncertain at this point if all national Parties' and potentially NSAs are willing to disclose all mitigation action data. While all mitigation project-related data under the Kyoto mechanisms are publicly disclosed and available in the project design documents of the UNFCCC homepage. A recent report from the CLI [14] states privacy issues and the access to commercially sensitive data as a challenge for the implementation of blockchain in carbon markets. The World Bank [13] expresses similar uncertainty regarding protecting the privacy of buyers and sellers, specifically in hindsight of regulation like the General Data Protection Regulation (GDPR) of the European Union. The GDPR requires all digital systems to obtain permissions for data utilisation and sharing. However, it is questionable to what degree personal data will be recorded, and hence if the GDPR is even applicable.

In the case in which the Parties prefer to restrict the visibility, a private transaction would be possible. Technical encryptions methods as zero-knowledge proof and Zero-Knowledge Succinct Non-Interactive Argument of Knowledge (zkSNARK) might be of interest [87].

2.8. System Permissioning?

Similar to the transparency considerations described in the previous classifier, there are also trade-offs regarding the degree of system permissioning. Contrary to public or private, however, system permissioning is not a bivalent characteristic but a gradual property ranging from permissionless and permissioned. Permissionless blockchain systems are fully decentralised, and anyone can become a ledger node to validate data or even change the decision-making process of the protocol (if securing sufficient support from other nodes) [19,48,57]. Conversely, a small number of entities control permissioned systems, and only authorised entities may become a ledger node or participate in transactions [19,50,57].

Generally, for a governmental system or a system with highly regulated actors, an open, permissionless system is often too risky as the system is not controlled by the initiating actors [51]. However, a permissioned system might conflict with the bottom-up ethos of the Paris Agreement [13,15,18,78]. On the other hand, Article 6.3 of the Paris Agreement [1] (p. 5) states that activities under Article 6.2 fall under the full responsibility of the Parties involved in the transfer. This responsibility indicates the need for a certain permissioning of the system that is primarily aligned towards the national Parties and potentially other actors like the UNFCCC secretariat, the SBSTA and SBI, and the TERT.

3. Discussions—Carbon Market Platform Architecture

In the decision framework evaluation, we show that a blockchain application for an Article 6.2 market mechanism is promising: classifiers 1 to 3 confirm the applicability of a blockchain, as the carbon market network consists of a heterogeneous group of actors that will use the network to transfer digital ITMO assets and benefit from a permanent and immutable transaction record. Classifiers 4 and 5 confirm that a blockchain can satisfy the case study performance requirements and lead to efficiency gains and reduced administrative costs by removing intermediary steps through smart contracts. In the future, the interlinkage with other emerging technologies can enhance transparency

and efficiency through innovative digital MRV data procedures. Classifier 6 confirms the role of blockchain technology as holding actors with diverging incentives accountable. The remaining two classifiers, 7 and 8, concern the system design in terms of the degree of system transparency and openness for participation. Adequate system design is not a technical question alone, but requires fit to the preferences and requirements of the participating Parties individually and from the perspective of the overall system ambition, as partly determined by the ongoing Article 6 rulebook negotiations.

As initially described, the new the blockchain-based Article 6.2 architecture assumes three important functions (Figure 2): The first role is as a meta-registry for linking national Party registries and NSA emission accounting systems. Second, the blockchain acts as an integrated exchange platform for ITMO tokens to address the complex accounting challenges associated with corresponding adjustments (as outlined in Section 1.1). Third, it serves as a tool for NDC compliance targets and NSA voluntary mitigation targets, to provide real-time progress tracking towards the Paris Agreement long-term goal.

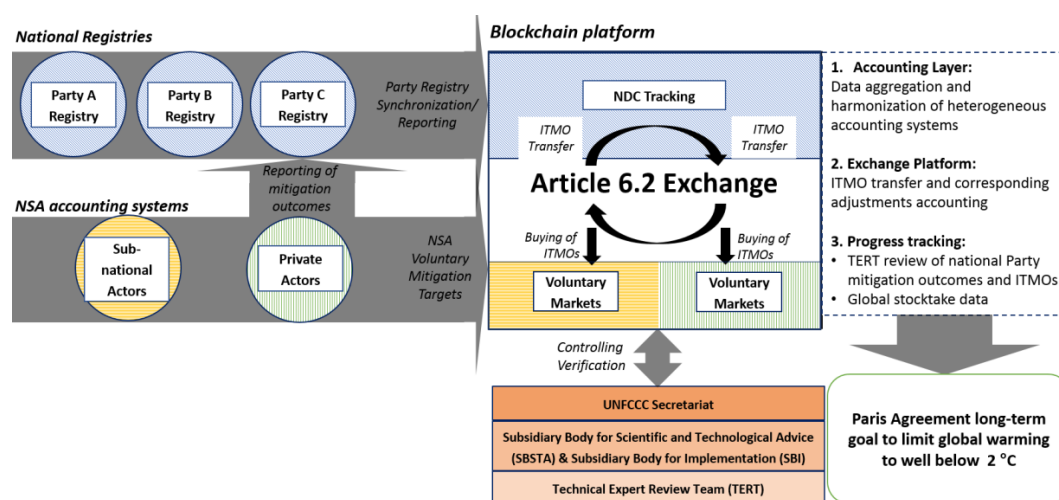


Figure 2. Blockchain architecture design for the Article 6.2 market mechanism. Inspired by [13,37,42].

A blockchain application provides the most benefits if all three functions partake within the same platform to ensure data harmonisation, robust accounting and eliminate information asymmetry. Otherwise, there is a risk of creating additional data siloes and fragmentation in the already fragmented legacy system. Based on the blockchain meta-registry, the Article 6.2 exchange allows for the bilateral trading and settlement of ITMO tokens between Parties and NSAs to comply with their compliance or voluntary mitigation targets. This architecture enables the collective accounting of all transactions by distributing and validating the meta-registry across the network of verified participants [88,89]. The blockchain automates double-entry bookkeeping of ITMO transfers between Parties, ensuring that there is only one Party holding the ITMO at any time, eliminating the risk of double claiming and double use. If two Parties conduct an ITMO transaction, the entire system of nodes (i.e., all Parties) determines the authenticity of the transaction and conducts the appropriate corresponding adjustments (e.g., of the NDC targets). If the transaction complies with the platform rules, the transaction is validated, and the ledger of all nodes is collectively synchronised [88]. As activities under Article 6.2 fall under the full responsibility of the Parties involved in the transfer, the acquiring Party is obligated to assess and safeguard the unit quality and environmental integrity of the purchased ITMOs [5]. For this assessment, the metadata stored on each ITMO token (e.g., country and sector of origin, sector and methodology) are crucial. This information is timestamped and immutable and can be retraced retrospectively in case of disagreement between actors.

Lessons learned from Kyoto show that sole oversight of the market mechanism by the host Parties alone is insufficient [4]. The involvement of other non-state reviewers, like domestic

institutions, scientists or civil society organisations, is critical to creating an effective market mechanism that incentivises the transferring Party to adopt ambitious emission targets to ensure unit quality. This platform would also facilitate the work of the TERT and other auditors by providing complete audit-related information in close to real-time [47], in comparison to the present every two- to five-year reporting cycles of the BTRs and GSTs [7,43,44].

The blockchain platform eliminates information asymmetry once information has entered the blockchain system. However, the blockchain suffers from the ‘garbage in/garbage out’ problem or ‘last-mile issue’ [12,14,51], meaning that the data input quality determines the data quality on the blockchain. In legacy accounting systems, MRV is mostly carried out in manual processes, based on disconnected data trails, spreadsheets and static reports [12,15,18,90,91]. Ideally, this process is automated through emerging technologies and innovative digital MRV procedures. Particularly, the replacement of manual data collection in the field would significantly increase system efficiency, enhance the data quality, and reduce costs. Smart contracts play an essential role in improving the system by automating the enforcement of MRV procedures and reducing data collection costs and execution delays [47,49].

We acknowledge that the formulation of Article 6 accounting rules is a controversial issue, with the disagreement between Parties causing stalling rulebook negotiations. At the current stage, Article 6 does not contain any reference to the engagement of stakeholders or the implementation of stakeholder consultations [92]. Through this innovative and inclusive development approach, we outline an alternative system that national Parties could shape and adopt in a bottom-up and co-creative approach. This alternative is needed to overcome present technical and political barriers inhibiting the Article 6 market implementation. The blockchain-based architecture is flexible in the design and can be adjusted based on changing Article 6.2 rulebook specification once the rulebook negotiations are concluded.

4. Conclusions and Future Research

This paper outlines an alternative blockchain-based architecture to address carbon market challenges and limitations. For this, we present a decision framework to test the applicability of blockchain technology to the emission meta-registry and specifically the Article 6.2 exchange. We found that, for the bottom-up and decentralised governance system envisioned in the Paris Agreement, a blockchain application is promising and can yield benefits in enhanced transparency and increased automation. The technology enables a novel democratic governance system, providing each Party with ownership of the system data to eliminate information asymmetry.

Although blockchain can address challenges, it is a nascent technology and not the panacea to resolve all carbon market issues. The legacy market infrastructure comes with the advantage of being tested and refined over a long time, e.g., the Kyoto mechanisms were implemented in 2005. However, these mechanisms have clear limitations, being based on many manual steps and a centralised and fragmented databank structure. The dependence on national BTRs (every two years) and the GSTs (every five years) for the assessment of ITMO transfers and progress tracking by the TERT maintains or even aggravates the significant information asymmetry between the fragmented legacy accounting systems. We therefore argue for the consideration of blockchain technology, despite it being a nascent and largely untested technology, to overcome legacy system limitations. By aggregating all information in the blockchain platform, the TERT and other relevant actors can have close to real-time data on the status of national registries, NSA accounting systems and the transfer of ITMO between Parties.

When designing the Article 6.2 market mechanism, we suggest considering blockchain as an innovative technology option. Otherwise, when only considering legacy database architectures, there is the risk of designing a ‘new’ post-2020 market mechanism that is already outdated at the date of inception. Integrating a blockchain platform offers clear benefits in terms of interoperability with other emerging technologies, automating the process through smart contracts, enhancing transparency, traceability and auditability, and enhancing system security and trust between Parties.

The Article 6 rulebook negotiations show the complicated political dynamics, which make up the background fabric on which our suggested approach is positioned. The success of this architecture or any alternative approach is dependent on developing a clear and nuanced understanding of the needs and interests of each Party. A sound understanding of Parties' interests is needed for achieving an innovative and valid system and governance design following a solution-problem fit. For future research, we recommend a proactive and iterative development approach, where the Parties are actively involved in a co-creating and inclusive system development. This approach allows for the testing of different governance designs and can create a sense of ownership among the participating Parties. From a policy perspective, we recommend stakeholder consultations to understand the design and governance preferences within the implementation of cooperative approaches under Article 6.2 of individual Parties. We further propose to consult the Parties to co-create the governance and system design for full ownership in a bottom-up approach and to develop pilot projects, test technology alternatives and refine them for this specific case study. The Paris Agreement has a decentralised and bottom-up ethos, based on transparency, which is similar to the ethos of blockchain technology. Parties of the Paris Agreement will ultimately decide if the blockchain will be adopted for their carbon market system or not. Hence, it will be crucial to design the system not *for* the Parties but *with* them.

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