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Examining the usefulness of Blockchain-based tokens in their ability to offset carbon emissions

Praca końcowa
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pod kierunkiem
Dr Antona Bubiela

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OŚWIADCZENIE AUTORA PRACY KOŃCOWEJ
pod tytułem **„Examining the usefulness of Blockchain-based tokens in their ability to offset carbon emissions”**

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Świadoma odpowiedzialności prawnej oświadczam, że niniejsza praca końcowa została napisana przeze mnie samodzielnie i nie zawiera treści uzyskanych w sposób niezgodny z obowiązującymi przepisami. Oświadczam również, że przedstawiona praca końcowa nie była wcześniej przedmiotem procedur związanych z uzyskaniem tytułu zawodowego w wyższej uczelni. Oświadczam ponadto, że niniejsza wersja pracy końcowej jest identyczna z załączoną wersją elektroniczną.

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1. Introduction

Climate change has been increasingly moving to the forefront of political, social and economic discourse as one of the most challenging and defining issues of the early Anthropocene period. Its impact has been widespread, impacting both nature and human life. Greenhouse gas (GHG) emissions are considered to be the most threatening factor in climate change, leading to phenomena such as the rising global temperatures, thickening of the heat-trapping layer in the atmosphere, ozone layer depletion, and ocean acidification ('Overview of Greenhouse Gases' 2022).

While GHG emissions have been naturally occurring due to geological and biological processes, such as volcanic eruptions and emissions from wild ruminants, human activities have been identified as the primary cause of changes in the atmospheric composition (Yue and Gao 2018). GHG emissions of human origin are the source of a higher-than-normal concentration of air polluting particles, which have toxic and long-lasting effects. They are known to have a triggering effect on extreme weather conditions, sea-level-rise, and land degradation. This leads to destabilisation of Earth's ecosystems by disrupting food chains and security, destroying habitats and biodiversity, and negatively affecting the health of living organisms (Tan 2014; Sonwani and Saxena 2022). It is necessary to understand the characteristics of human contributions to climate changes before addressing them appropriately.

Human activities are primarily responsible for the emission of the following gases: CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide), as well as groups of gases, such as fluorinated gases (F-gases). The highest emitting contribution is associated with just a few sectors of human economic activity. They include energy production, industry, agriculture, transportation and construction, with fossil fuel combustion permeating all those sectors (World Data Lab n.d.). The share of each sector in air pollution generation varies depending on the geographic location and year. As seen in Figure 1, the overall global emissions level has been on a steady rise ('Overview of Greenhouse Gases' 2022; Shukla, Skea, and Reisinger 2022). CO_2 emissions account for the majority of GHG in the atmosphere, leading to a particularly close focus on this gas by various stakeholders aiming to mitigate its harmful externalities through climate policies and technological solutions.

One example of such efforts is the formation of carbon markets - systems assigning economic and financial value to CO_2 emissions where individuals and organisations trade their emission permits or invest in environmental projects. While the global carbon markets in the current form have existed for almost three decades since the adoption of the Kyoto protocol in 1997, other forms of capping the CO_2 emissions had already been in effect in the 70s (Mazzai 2022). The long journey of creating economic, financial and regulatory instruments to tackle atmospheric pollution has also made room for technological and societal innovations in this field, attracting new solutions to combat climate change. This project seeks to provide more insights into the possibilities offered by the mature market for carbon credits and the rising technological potential of Blockchain-based tokens.

The following chapter will describe the existing types of carbon markets in the traditional economy – mandatory and voluntary markets. Despite their dissimilarities, they both make use of carbon credits as an instrument promoting emission reducing behaviour. The universal features of carbon credits will be presented to understand better what is indispensable in creating this instrument, as well as the challenges associated with it. Furthermore, chapter 3 will describe the carbon tokens as the analogue of carbon credits existing on the Blockchain. Three selected Blockchain-based token standards will be then described and analysed to understand their technical aptitude. With this knowledge, a discussion chapter will follow to relate the findings of the technical analysis to the demands of carbon credits to establish a viable and effective tool to combat CO_2 emissions.

Based on the theoretical research, this work will also provide the answer to the following hypotheses:

- *Existing Blockchain-based token standards can include technical implementations that are similar to traditional carbon credits.*
- *Tokenised carbon credits provide additional incentives for offsetting greenhouse gas emissions, compared to traditional carbon credits.*

The last chapter will conclude the discussion, providing recommendations for the traditional and Blockchain-based carbon markets and acknowledging the limitations of this study.

2. Literature review

2.1. The compliance and voluntary carbon markets in traditional economy

There are two kinds of carbon markets, each incentivising the participants to reduce emissions and switch to non-polluting activities.

Mandatory (compliance) markets have been established under different regional and international regimes, including the Kyoto Protocol and the EU Emission Trading System (EU ETS). Polluting organisations are universally required to measure and report their emissions, as well as adhere to emission limits imposed on them by regulatory bodies (Shukla, Skea, and Reisinger 2022). Should the limits be exceeded, polluters are obligated to purchase allowances in the form of carbon credits. These credits can be generated by companies with excess allowances or through environmental projects in developing countries that are intended to be acquired by entities from developed countries (Kollmuss et al. 2010, 5–10; Lejano, Kan, and Chau 2020). The compliance carbon market relies on the notion of imperfections in the market, limiting the supply of carbon credits available for purchase. As it leads to price inflation, companies are incentivised to reduce their polluting activities and switch to alternatives.

The non-governmental and private sectors have established their position in the carbon finance realm through the voluntary carbon market. It exists to promote investments in low-carbon technology and to propel CO_2 emissions reduction and removal from the atmosphere. Companies and individuals can participate by choosing to purchase carbon credits issued by projects actively reducing CO_2 emissions. Carbon storage or capture, funding reforestation, or investing in energy efficiency initiatives are some examples of the actions (Labatt, White, and Whittaker 2007, 164). Voluntary markets are deregulated, enabling free market trading of carbon credits, driven by active stakeholder participation. The pricing of the non-compliance credits depends on a multitude of factors. Contrary to the compliance market, voluntary carbon credits are priced on more than demand, depending on the type of carbon project producing credits, the length of the credits on the market, trustworthiness of the creditor, brokerage, and others.

Bloomberg estimates that currently the voluntary carbon credits are oversupplied, however a number of global events can tighten the marker and cause short term price fluctuations. These events include the increasingly more frequent closure of unreliable carbon offsetting projects, emission increase due to the war in Ukraine or global recession risks (2022). Simultaneously, in the long run credit prices tend to follow an inflationary trend over the years with the transaction volume rising as well. In 2021 the average price was $3.82/tCO2 (one tonne of carbon dioxide), an increase from $2.49 in 2020. More than 362m credits were transacted in 2021, with the estimated 92% spike comparing to 2020. These trends are attracting investors interested in getting returns from trading credits as investment assets.

The common instrument present in both described markets is the carbon offset credit. Kollmuss et al. define it as “a credit representing the reduction of 1 tonne of CO_2 equivalent that can be used by the buyer of the credits to claim the reduction, even though it has been achieved elsewhere” (2010, 215). Carbon credits typically go through a lifecycle, starting with the verification and credit issuance, through the registration of project and credit details, and finally the retirement of the credits. Retiring credits removes them permanently from the circulation and they can no longer be resold (‘Ownership of Emission Reductions’ n.d.). This is particularly beneficial as it helps prevent double counting of emission reductions as well as certify that the carbon offsets fulfilled their intended role.

The principle of the carbon credit trading solution, both in the regulated setting and on the free voluntary market, is to enable the financing of environmental projects and thus a gradual reduction of emissions in the atmosphere. As pointed out by Allen et al., the type of mitigation activity behind carbon offsets is the key indicator of its effectiveness in combatting the adverse consequences of GHG emissions (2020). The authors distinguished emission reduction projects from carbon removal projects; the latter should eventually replace mere reductions in emissions as they not only prevent the generation of new emissions but also actively remove the CO_2 that had already accumulated in the atmosphere. Regardless of the underlying offsetting projects, several distinctive features of carbon credits must be present to fulfil their environmental role.

2.2. The characteristics of carbon credits

A transparent and verifiable measurement can strengthen the reliability of all the characteristics that define carbon credits. There are four main features that make them a reliable instrument in combatting climate change: additionality, liquidity, vintage, and registry.

Additionality refers to the most basic requirement for a credit that the emissions reduction must be 'additional' to what would have occurred without the offsetting project. In other words, a project, be it an industrial company or a carbon-removal program, should generate credits only for the CO_2 reductions that happen because of the extra effort made, beyond what the business-as-usual activities are. To satisfy this requirement, carbon credits need to be measurable and represent real carbon offsets from projects investing in carbon mitigation (Martins Barata et al. 2016). Additionality is vital to the carbon market as it helps prevent the issuance of 'fake' carbon credits which do not represent real environmental value and could even lead to an increase in emissions.

Liquidity can be defined as "the process of connecting a buyer to a seller in as frictionless a manner as possible" (Ibikunle and Gregoriou 2018, 2). High liquidity is desirable in the carbon credit market as it leads to greater efficiency of carbon offsetting targets. It is important to maintain a balanced level of credit supply and buyers willing to purchase them to create an accessible and transparent market for all actors. Carbon credit liquidity can directly impact the whole market efficiency and pricing of credits since carbon markets focus on fostering the economy of constrained emissions (Ibikunle et al. 2016). Market size can also affect liquidity, and thus offer price signals for carbon credits. A large number of buyers and sellers typically leads to more credits available for trade ('State and Trends of Carbon Pricing 2022' 2022). Regulations also play an important role here, both in the compliance and voluntary markets. A stable and refined standardisation of carbon trade can have a positive impact on the transparency and liquidity of credits as it enables compliance with quality indicators and accuracy of carbon market data.

Vintage refers to the year when the reduction in GHG emissions occurred and affects the value of the credits issued. Older vintages tend to lower the price value due to a larger supply available and the presumed quality of the offset itself. As the offsetting practices have improved over the years, so have the methodologies for verifying them, which in turn can affect the price of older vintages based on the confidence in the reliability of each offset (Bayon, Hawn, and Hamilton 2009). In theory, the longer the credit's issuance period or availability on the market, the more questionable the quality of the offset itself too. While the accuracy of that pricing approach factors in the question of verifiability of carbon offsets, it also makes vintages a feature which purchasers seek out. The pricier vintages might be in demand by actors counting on the reliability of credits or being able to participate in highly restrictive compliance programs, whereas the older ones are simply more affordable.

Lastly, **registries** are essential for the proper functioning of carbon markets itself. Despite their complexities, registries can be used to manage transactional and non-transactional data on carbon credits, the latter including information such as credit ownership, the type of the underlying offsetting project and its co-benefits, baseline emissions, certification regime, and vintage. They can be also responsible for the actual issuance of carbon credits ('Registries & Enforcement' n.d.; Marcos 2012). Some of the largest currently operating carbon registries include the *Verra Registry* under the Verified Carbon Standard (VCS) Program on the voluntary market and the *Union Registry* under the EU ETS on the compliance market ('Verra Registry' n.d.; 'Union Registry' n.d.). An accurate and reliable registry, handling and securing all kinds of relevant data, can become a trustworthy element of the carbon market and a source of verifiable and effective carbon offsets.

The above features are crucial for the implementation of feasible and effective carbon credit system, capable of mitigating the impacts of climate change. In addition to that, they indirectly influence the credits' prices in the offset markets. As affirmed by Azil et al., the financial value has particular importance as it allows carbon markets to play an equivalent role to that of a financial market through a "focus on allocating resources away from emissions-intensive activities and towards emissions removal and reduction" (2021). However, these features can face various challenges and, if not addressed, prevent carbon credits from achieving their intended goal.

2.3. The challenges of carbon credits

The above requirements have multiple points of failure and require constant adjustments from all actors on the market to accommodate changes and provide high quality carbon credits. Most threats that can undermine the ability of carbon offset projects to decrease climate impacts of CO_2 are linked to verification and transparency.

Miscalculation of offsets can diminish the credits' effectiveness in combatting climate change. Projects that use an inappropriate baseline emissions scenario or an inaccurate calculation of emissions reductions could generate unreliable credits. Moreover, an unreliable system for measuring, reporting, and verifying emissions reductions could lead to the issuance of 'fake' carbon credits. That has been the case with the Verra registry, world's leading certifier of voluntary carbon offsets, whose lack of rigorous verification and measurement of offsetting projects it credits is claimed to have led to the valueless issuance of over 90% of all their rainforest credits. Even more than that could potentially be valueless and misleading, however the data that was available on the Verra registry to properly assess this claim has been insufficient (Greenfield 2023). Such lack of information in itself is an indicator of the fundamental necessity for an accurate verification and tracking system, which often require upfront costs from offsetting projects' owners.

Vintage price calculation has been also indicated as somewhat misleading as to the quality of offsets. Walker and Mitchell argue that old vintages are currently priced lower than new ones due to the general assumption that they come from less reliable carbon offsetting projects (2022). That generalisation refers to the regulatory standards becoming more rigorous and the fact that technology naturally advances over time. It also makes believe that credits which have not been purchased for a long time are unwanted for a reason. However, these factors as quality indicators can be refuted when properly assessed. For example, carbon sequestration from preserving a mangrove 10 years ago is more successful in reducing and removing pollution than this year's credit issued by a factory improving energy efficiency. Figure 2 presents the environmental value of different types of carbon offsetting projects which do not follow a universal depreciation in effectiveness over time. Moreover, the quality of carbon offsets and their value should be also reflected in their ability to generate co-benefits for local communities and economies, which is currently overlooked (Azil et al. 2021).

Further challenges could arise because of a trade-off between the economically profitable polluting activities and choosing alternative options. For example, tropical deforestation for palm oil agriculture might be more profitable than preserving a rainforest for carbon credits, if their price is too low (Butler, Koh, and Ghazoul 2009). When it comes to the regulated market, emission intensive companies may be inclined to relocate their operations to some less pollution-restrictive places in order to alleviate the associated cost burden. Such practice, known as leakage, and results in a loss of business operations supporting environmental projects and an increase in emissions elsewhere ('What Is Carbon Leakage?' 2020). Although the regulated leakage-preventive measures might compensate for the cost to decarbonise, their effectiveness is questionable due to dampening the economic pressure on polluters, as well as using up climate funds from taxes for payouts to businesses who profit from their emission-heavy activities ('What Is Wrong with Indirect Cost Compensation?' n.d.; 'State Aid: Commission Approves €1.36 Billion Greek Scheme to Compensate Energy-Intensive Companies for Indirect Emission Costs' 2023).

Therefore, reliance on market forces to set competitive voluntary carbon prices and on the mandatory carbon market to offer a satisfactory economic incentive or strain seems to be an ineffective tool in combatting climate change.

A problem that concerns the voluntary carbon market in particular is its attractiveness for credits trade, as the moral willingness to contribute to a cleaner planet might be insufficient. Low liquidity and accessibility can deter buyers from participating, driving credits' prices down and limiting financing for the carbon projects. Furthermore, an oversupply of credits might in turn force the price of carbon credits to near zero. Currently, a low liquidity scenario is common and may limit the projects' ability to secure appropriate financing, especially in developing countries, even if a project is expected to yield high returns as the risk associated with it remains unaddressed (Blaufelder et al. 2021; Kalirajan and Chen 2018). The lack of transparency and verifiability ties back once again to the cause of these financial shortcomings.

To address the challenges of the carbon markets and respond to their needs, Blockchain technology introduces a new tool – carbon tokens – taking carbon credits to a new level. Carbon tokens aim to deliver the benefits of Blockchain through its decentralised, secure, inclusive, and transparent nature. Carbon tokens have the ability to represent not only real carbon offsets but also to contribute to carbon value creation. Being a financial incentive to support environmental projects, they offer a novel approach to tackling climate change.

2.4. Carbon tokens

In the context of Blockchain, tokens emerged with the advent of the Ethereum network, which elevated the technology stack to a programmable infrastructure. Blockchain-based tokens represent digital assets or a digital analogue of a tradable commodity, tied to its real-world value. They have the ability to facilitate non-financial transactions by "converting legal rights or valuable information into a simple digital piece of data" (Woo et al. 2021). By assembling unique information related to specific digital or physical assets and facilitating their exchange, tokens can amass users recognising their value and thus effectively be monetised (Braden 2019). This has allowed for the creation of systems in which tokens can be designed to convey a monetary incentive and other functions beyond the financial one.

The transactional nature of carbon markets has been seen as a potential field for applying Blockchain technology and experimenting with its revolutionary principles in the context of carbon finance. Tokens are one of such instruments and can be employed to act as a substitute of carbon credits in the crypto space. This has resonated particularly well within the emerging field of Regenerative Finance (ReFi). ReFi seeks to leverage cryptofinancing in order to shift the focus of the economy away from extraction and exponential wealth generation, and towards rebuilding the natural environment and social capital. ReFi aims to use finance as a tool to foster an inclusive and sustainable economy rather than making finance the end goal leading to a degenerated future (Diaz-Valdivia and Poblet 2022). Tokens, an instrument enabling the functioning of decentralised finance, can be used to bring value to environmental projects, including those that offset carbon emissions.

Scholars and practitioners have proposed numerous Blockchain-based systems for verification and trading of carbon assets where the flow of tokens and information storage improves accessibility, transparency and effectiveness of carbon markets, and therefore the potential of adding real environmental value. Kim and Huh proposed a 5-step model applying an Artificial Intelligence-based blockchain for data validation related to offset creation and carbon emission rights, as illustrated in Figure 4. It applies Hyper Proof of Random algorithm to validate transactions necessary for the reduction of emissions (2020). Another systemic approach was proposed to facilitate both energy trading and carbon allowances for prosumers. Hua et al. consider these two facets inseparable, which is reflected in their framework for optimising pricing and surplus allocation on the smart contract layer (2020). These and other systems are complex and call for further development. For this to happen, real implementations and testing beyond the theoretical assessment is necessary.

In the recent years, carbon tokens have been gaining increasing traction. Used in numerous Blockchain projects, their application ranges from carbon trading schemes, such as Powerledger and its POWR token, through carbon offset programs (for example, Toucan Protocol's TCO2 and BCT tokens, and Flowcarbon's GNT token) to digital ownership certificates (Moss Amazon NFT tokens) (Sipthorpe et al. 2022; 'Powerledger' n.d.; 'Toucan Protocol' n.d.; 'Flowcarbon' n.d.; 'Moss Amazon' n.d.). They can be built on different chains and layers, though Ethereum remains the preferred choice. Other chains, like for example Polygon, Celo, Algorand and Cosmos, have also been explored for carbon offsetting projects in the recent years (Polygon Team 2022; 'Celo' n.d.; ‘Algorand Foundation’ n.d.; Regen Network 2022). Despite the growing number of projects being developed, Blockchain-based carbon solutions are still in their infancy and experimental stage. As shown in Figure 3, most projects are still in the early stages of implementation, with only one (KlimaDAO) having reached market maturation so far. As the Blockchain technology and the area of tokenomics continue to evolve, the ecosystem of carbon offsetting solutions is expected to keep progressing and innovating too, given the interdependency of the projects’ regenerative capabilities and their technical layers.

Token-based projects require careful consideration of their technical details. In the case of carbon offset projects, the creators need to rethink how the technology can be used to implement a successful ecological project, beyond the purely cryptotrading purpose. One of the most fundamental elements is the type of tokens, distinguished by its standard. Token standards have been continuously developed over the years, given the foundation of smart contracts together with an enabling digital environment and a community of participants (Voshmgir 2020). These standards aim to introduce improved protocols and set of guidelines on implementing token-based projects, which helps the Blockchain-based industry progress and evolve into a ‘token economy’.

3. Blockchain-based token standards

3.1. Introduction

Token standards govern the behaviour of the tokens and set out the smart contract deployment guidelines for them. Ethereum is credited with pioneering the development of tokens standards. These standards, besides being compatible with various chains, also set the tone for other chains to develop their own native standards with similar properties. Given that the token standards outside of the Ethereum environment often emulate its implementations, this section will explore Ethereum standards as the reference point for token-based projects.

Ethereum standards are derived from Ethereum Improvement Proposals (EIPs). An EIP can be submitted by the developer community as a set of new features or desired outcomes for Ethereum-compatible tokens. If accepted, they are officially adopted in the form of Ethereum Request for Comments (ERC) standards with their numerical identifiers. Standards also provide specifications regarding the creation (minting) and destruction (burning) of the tokens which are the mechanisms used to manage the token supply, and therefore influence its price (Lee 2019). The relative convenience of the token creation process compared to developing entirely new blockchains makes it easier to build Blockchain-based projects.

ERC tokens are executable through smart contracts – a programmable medium for crypto transacting. In addition to the benefits that tokens bring to the table as a form of cryptocurrency and a digital representation of an asset, smart contracts add another layer increasing token usefulness. As noted by Xu et al. they reduce ‘artificial operations’, that is verification by intermediaries and clearing and settlement process (Xu et al. 2021, 90). Smart contracts make room for automatic trade handling and improve the efficiency of regulatory supervision by using a standardised and transparent coding practices. They are written in the Solidity language, created specifically for Ethereum contracts. Solidity contains a universal set of code (functions) and data (state) for their successful programming and deployment (‘Introduction to Smart Contracts’ n.d.). Each new ERC token standard adds new functionalities to the smart contract logic allowing it to fulfil a new role.

Despite the early onset of the ERC token standards in the Ethereum environment as early as 2015, the smart contract token logic was conceived to have unique features compared to the protocol-level payment balance management of Ether (ETH), Ethereum’s native cryptocurrency (Antonopoulos and Wood 2019). While tokens and ETH share some similarities, for example being a medium of payment, the latter is not limited by any specific programmable token logic, so long as it operates within the restrictions of the Ethereum Virtual Machine. Ether is essential to the blockchain’s trading ecosystem facilitating transactions by covering the associated fees, including those related to token transactions. Smart contract specifications are designed to program the desired behaviour for tokens, and, by default empower the representation of digital assets.

3.2. ERC-20

The ERC-20 token standard has introduced the property of fungibility, making all units of the same token equivalent in value and interchangeable. It remains the most widely used token standard; as of February 2023, there have been 1,100 ERC-20 token contracts implemented (‘Token Tracker (ERC-20)’ n.d.). The provenance of each individual token unit is untrackable, only the transfer history between different contracts or accounts is saved on the blockchain

(Antonopoulos and Wood 2019). This allows the tokens to maintain fungibility because no token can be singled out (whitelisted or blacklisted) to alter its ability to interchange value. Given that they carry no additional rights or properties to give them unequal value, are particularly useful in wallets and decentralised exchanges which rely on liquid and fungible assets (Warburg, Wagner, and Serres 2019).

ERC-20 standard provides a set of 6 core technical functions. The tokens can be easily transferred between accounts and contracts (Ponnan 2023; Vogelsteller and Buterin 2015). This is done through the *transfer* function where the *_value* equals the amount of tokens to be transferred to the *_to* address. The transfer function is programmed to verify that the account balance of the sender has enough tokens to complete the transfer. The function will throw an error if the balance is insufficient.

```
function transfer(address _to, uint256 _value) public returns (bool success)
```

A smart contract can directly return account's current ownership of ERC-20 tokens via the *balanceOf* method. It is important to note that wallets do not store ERC-20 tokens, but instead they store information about an address' token ownership to access and transfer them to another address (McConaghy 2021).

```
function balanceOf(address _owner) public view returns (uint256 balance)
```

Calling the *totalSupply* function returns the amount of tokens in existence in the network. The *totalSupply* check increases security of operations with tokens of a fixed supply as it asserts that the supply remains unmodified through manipulations.

```
function totalSupply() public view returns (uint256)
```

Another functionality of the ERC-20 standard allows an authorised message sender to transfer tokens on behalf of a third-party account. This is indicated with the *_from* argument. Both transfer methods can be prevented from sending tokens to the non-recoverable null address (0x0000000000000000000000000000000000000000) by specifying this with a requirement, as shown in the example below:

```
function transferFrom(address _from, address _to, uint256 _value) public returns
(bool success){
    require(to != address(0), "Cannot transfer to null address");
{
```

To authorise someone to spend one’s own tokens, the *approve* method can be used. The amount to be spent can be capped via the allowance method.

```
function approve(address _spender, uint256 _amount) external returns (bool)

function allowance(address _owner, address _spender) external view returns (uint256)
```

Besides the 6 functions, the standard specifies 2 events that is signals triggered by specific functions in the smart contract. Events are useful for contract development because they store the input data in the transaction log. While the log is unreadable from within smart contracts, other applications can ‘listen’ to the events being emitted to automate certain functionalities such as updating transactional data on a website (‘Learn Solidity: What Are Events?’ 2023). The events *Transfer* and *Approval* are emitted with the *transferFrom* and *approve* functions respectively. Events make an efficient use of gas, saving it by storing information on the on-chain transaction log and not the gas-heavy storage variable.

```
event Transfer(address indexed _from, address indexed _to, uint256 _value)

event Approval(address indexed _owner, address indexed _spender, uint256 _value)
```

As contracts cannot recognise that a transfer occurred, if they are the receiver, only the *approve* and *transferFrom* functions can be used to make a successful deposit to a contract. This may increase the vulnerability of an ERC-20 smart contract (Dexaran n.d.). Tokens transferred wrongly to a contract via the *transfer* function are lost because they do not hold private keys and the standard does not handle transfer function invocations to revert initiated transactions. The *transfer* function should only be used for token transfers to an externally owned account address as they do have private keys.

Delegating token expenditure via *approve* and *transferFrom*, while being appropriate for contract recipients, is also risky. A bad actors could prevent a change in the approval amount and exploit owner’s funds in a front-running attack by observing pending transactions via events and spending both the original and updated amounts (Antonopoulos and Wood 2019). The ERC-223 standard addressed the issue of fund loss to a contract not supporting tokens by introducing the *tokenFallback* function, causing the transfer to fail if the receiver is a contract. This token standard has not been implemented as a standalone token though, due to the lack of backward compatibility with the well-stablished ERC-20 (Dexaran 2017).

Minting of new tokens can occur at the token contract level and is initiated by the contract owner using the *mint()* function. It involves the creation of a token supply of a predefined amount and saving it onto the blockchain in data validation process (‘Creating ERC20 Supply’ n.d.). The basic method for minting ERC-20 tokens is to hard-code a fixed supply to be issued upon token contract deployment which sends the tokens to the deploying wallet address from where the tokens can be distributed further (Rivabella n.d.). The tokens can be issued all at once or in batches over time. This method is preferred when the issuer aims at having a predictable and stable token supply to ensure high value over time. Although it is not a requirement, this is often the preferred model for tokens that are intended to function as a store of value or a means of exchange. The supply can also be uncapped on the token contract level, though it is not as common as having a fixed cap.

Some third-party libraries also provide custom extensions for managing a flexible minting process. The OpenZeppelin suite developed the *ERC20Mintable* extension which provides a set of addresses with the MinterRole, giving them permission to create new tokens; it can also revoke token minting privileges (‘ERC20Mintable’ n.d.). Thirdweb enabled the *SignatureMintERC20* mechanism for minting ERC20 tokens on the admin’s contract by an authorised third party (‘Signature Minting ERC20’ n.d.). A flexible minting approach takes into account possible market fluctuations (such as increased demand) and is a means for responding to them by setting out the provisions for future minting, possibly delegated too. It requires careful management to avoid high inflation, price depreciation and security risks.

When minting new ERC-20 tokens, the standard also allows for the optional setting of 3 immutable values to be included in the token contract: name, symbol, and decimals. A token’s name and symbol help distinguish it among other tokens through a human-readable string. Decimal points specify the number of decimal points in which the token will be measured, typically 18 to imitate Wei in an Ether (‘ERC 20’ n.d.).

To remove (**burn**) tokens from the circulating supply, holders can transfer them to the null address, so long as the contract had not prevented it. Another method is to use the *ERC20Burnable* extension which allows a holder to destruct their own tokens or those they have the allowance for by executing either the *burn()* or *burnFrom()* function (‘ERC 20’ n.d.). Burning tokens decreases their supply and the token value generally goes up to meet the demand. When this process happens moderately and over time, the price inflation can incentivise buyers to invest in the token and engage in its trading. At the same time, token projects are susceptible to risk associated with burning, which could lead to a failure of the token if large quantities are ‘burnt’ by being sent to an address controlled by bad actors who hold private keys and can withdraw the funds and sell them for their exclusive profit.

3.3. ERC-721

ERC-721 is another standard that has had an impact on the Blockchain tokenomics. It set out the basis for non-fungible tokens, also known as deeds or NFTs. This property essentially entails their lack of interchangeability with one another, even if issued by the same platform. Each NFT has a unique identifier associated with it that enables not only distinguishability, but also provenance checking. This identifier does not change while the token’s smart contract exists (Entriken et al. 2018). An ERC-721 token can also bear individual characteristics and values which make tokens non-divisible into smaller quantities. These unique properties can impact the price for each NFT, often leading to higher valuations for tokens that possess desired features and manifest rarity (Modi 2022). This gives rise to a standard for the digital representation of assets that require traceability, ownership, and individual valuation. Some examples of the usefulness of NFTs include artwork, certificates of ownership, loans, and collectibles, enabling trade in auctions and dedicated marketplaces.

The core specifications for the ERC-721 are more demanding than in the interface of the previous token, mainly due to the features for managing metadata and the ability of the NFT smart contracts to track the tokens’ provenance (Entriken et al. 2018).

The tracking is done through *mapping*, that is value association between data structures (Antonopoulos and Wood 2019). The three mappings below are used to establish and check token ownership. The first one stores the tokens with an address and can be used to search for a token ID based on an owner's address. The second one works in the opposite direction, helping find the address based on the token ID. The last mapping ties an owner’s address to the number of tokens it owns. Three different mapping commands allow for gas optimisation depending on the contract’s needs (Modi 2022).

```
mapping(address => uint256) internal ownedTokens

mapping(uint256 => address) internal tokenOwner

mapping(address => uint256) internal ownedTokensCount
```

Similarly to ERC-20, ERC-721 contract can find the current state of an account by returning the number of all the tokens of an *_owner*. Additionally, it can find the owner associated with the token ID.

```
function balanceOf(address _owner) external view returns (uint256 _balance)

function ownerOf(uint256 _tokenID) external view returns (address _owner)
```

To verify the token balance, the standard allows for the optional inclusion of the *ERC721Enumerable* extension. It contains three functions to publish all the NFTs in a contract and make them discoverable (Entriken et al. 2018). The *totalSupply* returns the number of NFTs tracked by the contract, that is NFTs with an assigned address who can query the tokens' details. If a particular token's order in an array is needed, then the *tokenByIndex* function returns the token ID corresponding to *_index* specified. The last function, *tokenOfOwnerByIndex*, works in a similar manner but is queried among the tokens belonging to a given *_owner*.

The three functions below, *balanceOf* and *ownerOf* are all vital to the proper management of the NFTs in existence since they keep track of the valid tokens available. Valid tokens are those belonging to addresses other than the null address.

```
function totalSupply() external view returns (uint256)

function tokenByIndex(uint256 _index) external view returns (uint256)

function tokenOfOwnerByIndex(address _owner, uint256 _index) external view returns
(uint256)
```

ERC-721 provides a set of functions for direct as well as delegated token transfers. Transferring NFT tokens changes their ownership but it does not alter the token data (i.e. the details of the asset that tokens are linked to). The *(uint256 => address)* mapping for the token owner gets updated with each transfer to reflect the new owner address. It is also possible to retrieve all past owners of the token, for example by mapping the transfer history with details.

Token transfer permission can involve individual and multiple tokens. They can be revoked by the owner's account too. By including the token ID and owner's address in the functions, the transaction history that is stored on the blockchain in a decentralised and tamper-proof manner remains verifiable at all times. This way, the NFT tokens are one of a kind, as no other token contains the same associated data.

```
function safeTransferFrom(address _from, address _to, uint256 _tokenId, bytes
calldata _data) external

function safeTransferFrom(address _from, address _to, uint256 _tokenId) external

function transferFrom(address _from, address _to, uint256 _tokenId) external

function approve(address _to, uint256 _tokenId) external

function setApprovalForAll(address _operator, bool _approved) external

function getApproved(uint256 _tokenId) external view returns (address _operator)

function isApprovedForAll(address _owner, address _operator) external view returns
(bool)
```

For an application to be able to receive NFTs it must implement the *ERC721TokenReceiver* wallet interface, specifying the operator address initiating the transfer, the address where the token is assigned, its ID and, optionally, token data of no specified format, such as token description.

```
function onERC721Received(address _operator, address _from, uint256 _tokenId, bytes
_data) external returns(bytes4)
```

Transaction history is not the only feature distinguishing individual NFT tokens. A token smart contract can, and typically does, include specific metadata that pertains to a token, although this is an optional extension (Entriken et al. 2018). The metadata may comprise of an image, text, name, description, and others. Despite the fact that Solidity can store data in memory, this option is too costly in gas to be a scalable solution. For this reason, the metadata of the underlying asset to be represented by an NFT is linked to the token via an external source. ERC-721 standard makes it possible to link more than one NFT to a single underlying asset. This is done by minting multiple tokens in a smart contract. It does not affect the property of non-fungibility, as each NFT remains unique with its own combination of metadata and provenance.

The ERC-721 standard guidelines recommend IPFS for storage and using its Uniform Resource Identifier to reference the asset. A smart contract can efficiently link a token to an asset by importing a library extension and supplying it with a link to the storage (Croubois, Francisco, and mclovin 2023). IPFS, which is a secure and decentralised data storage system, allows not only for uploading the content to be represented via token (such as an image or a document) but also for a secure and immutable linkage through content addressing. The uploaded data produces a content identifier (CID) which is a hash generated from that content. It can only apply to that one item. The URI that points to the source content in the smart contract is created using its particular CID and including it in the IPFS link format *ipsf://* ('Mint an NFT with IPFS' n.d.).

```
constructor(string memory tokenName, string memory symbol) ERC721(tokenName, symbol){
    _setBaseURI("ipfs://");
}
```

NFT minting is executed via the mint function at a given address. It takes the *tokenID* argument to assign the tokens to an owner and to ensure their uniqueness. Additionally, it can point to the NFT asset's details via *_tokenURI*. TokenURI can be assigned to the *_tokenID* via *setTokenURI* to improve verification. The following is an example of the ERC-721 minting method:

```
function mint(address _to, uint256 _tokenID, string memory _tokenURI) public
onlyOwner{
        mint(recipient, tokenId);
        setTokenURI(tokenID, tokenURI);
```

Various applications and libraries have been created to facilitate NFT minting and streamline the process. Minty was developed by IPFS as a simple Command Line Application in Java Script to mint tokens and automatically save their metadata on its storage ('Mint an NFT with IPFS' n.d.). OpenSea, one of the largest NFT marketplaces, offers the possibility to create an NFT or a collection of them to be uploaded on the platform. It simplifies the creation process by requiring no advanced smart contract coding skills, making it accessible to non-developers. The NFTs created this way represent 'lazy minting' where the items for sale are not immediately written on-chain, but to save gas only the sold ones become tokenised ('What Is Minting?' n.d.). Alchemy offers an Application Programming Interface (API) Provider which uses Ethereum's ethers library and facilitates smart contract creation and NFT minting functions by automatic different stages, such as IPFS storage ('How to Mint an NFT from Code' n.d.).

Moreover, some of the extensions allow the contract to incur fees of a desired value upon minting. The example below provided by Alchemy requires a payment of at least 10 Wei to be paid by the user for a successful transfer of NFT, otherwise the transaction will revert (‘How Do I Set a Price on an NFT?’ n.d.). A no-code way to set NFT prices is to list the tokens on marketplaces for a specific amount.

```
function mintToken(address _to, uint256 _tokenId, string _URI) public virtual payable
{
   require(msg.value >= 10, "Not enough ETH sent; check price!");
   mint(to, tokenId);
   setTokenURI(tokenId, URI);
}
```

Using the above and other NFT minting solutions offer several advantages. These programs have undergone thorough bugs and vulnerability checks. They often require as little as importing a source code into the contract and specifying the desired details. These solutions also help maintain the non-fungibile nature of the tokens by providing bespoke price variability mechanisms. These advantages contributed to widespread adoption of the ERC-721 standard, with many use cases available.

The standard allows to set the values of token name and symbol, however, unlike ERC-20, it does not support decimal setting due to the intended indivisibility of NFT tokens. In order to emulate the ability of real-world non-fungible assets, such as stocks or luxury goods, to provide co-ownership of the same token-like asset, in addition to the previously described issuance of multiple NFTs, later implementations of ERC-721 saw the emergence of fractionalised NFTs. This practice involves an NFT smart contract to generate a finite number of ERC-20 tokens which after distribution to holders give them a percentage of asset ownership. While useful with tokens of high value and demand through potentially providing investment opportunities, they could be viewed as unregulated securities (‘Explained: Fractional NFTs (F-NFTs) and How They Work’ 2022). This raises concerns about the applicability of fractionalised NFTs, even if it also indicates a new market need.

Only a contract-level destruction guarantees permanent deletion of the tokens from circulation. NFT burning can be done through sending them to the null address or using the *burn* function, in a similar way to ERC-20. Although the value or meaning of the NFT could be associated through the metadata linking to an externally held item, altering the data does not destroy the token itself.

Burning is an irreversible option which can be done for various reasons. One of them is to increase the price of other NFTs, if a batch of them was issued in a project, to attract new buyers. Tokens could be deemed obsolete in a project or contain some flaws. Furthermore, some creators might decide to burn unsold tokens to build community trust. Burning can also be used for a gamified experience in a project in exchange for rewards (Hayes 2022; Dapper Team 2022). Given that burning mechanisms could be used by malicious actors, NFT platforms often protect their users from unwanted token destruction. For example, the OpenSea guidelines for NFT creators require specification of how burning is performed and prevents burning by transfer to a private wallet. Creators need to include an element of randomisation to trigger the burn and cannot retain all the control over the process (‘How Does OpenSea Handle NFTs with a Burn Mechanism?’ n.d.).

Similar to how the ERC-20 standard forms the basis for fungible tokens, the ERC-721 standard serves as the foundation for non-fungible tokens. ERC-721 has opened up possibilities for the exploitation of the distinctive representation of assets through the use of metadata linkage and immutable rarity. The inherent property of NFT being permanently linked to an asset holds promise for projects that offer any kind of collectible item and provides the assurance of the underlying blockchain technology being permanently accessible. On the other hand, just as the static character of NFTs can be most beneficial, it poses challenges too. Although upgrades are possible, for example, by changing the token URI pointing to the storage, they defy the purpose of NFTs. If a project decides to make changes to the asset, it risks compromising the security and trustworthiness of the tokens. Furthermore, NFTs do not support intellectual property features and owning the tokens does not legally provide the option to own the underlying asset, only the token as its representation (Garbers-von Boehm, Haag, and Gruber 2022). While the immutability of NFTs can be an advantage, it is important to maintain the authenticity of what they represent not to compromise the value of the tokens.

3.4. ERC-1155

The maturation of the NFT technology exposed the need for upgradable tokens. A novel ERC-1155 standard was introduced to offer interface for programming smart contracts to include a combination of fungible and non-fungible tokens, and their other configurations of them, such as semi-fungible tokens (Radomski et al. 2018). This standard is also referred to as the Multi-

Token Standard, and its tokens – dynamic NFTs (dNFTs). The standard was proposed originally by the Enjin team to accommodate Blockchain-based gaming platforms and their high and diverse volume of tokenised items (‘ERC1155 | API’ n.d.). When employing this standard, it is no longer necessary to utilise separate smart contracts to govern different token types. Transfer of tokens do not require individual approvals, instead it can be executed to send multiple tokens at once. This makes it possible to increase efficiency and trading load, reduce transaction fees and eliminate some of the security risks, for example contract interoperability issues.

The most notable distinction of ERC-1155 is the configuration of the token ID to represent a flexible and upgradeable token type, which is particularly useful for non-fungible tokens. Contrary to the previously described standards, a contract does not hold a single token type for distribution but instead it can hold various tokens, here referred to as categories, which in turn have their own number of iterations. For example, a contract can have four different NFT token categories with their unique names and symbols, two of them holding 100 tokens each and the others – 200 individual tokens.

ERC-1155 allows to conduct multiple operation in a single transaction. This standard comprises 4 core concepts for transfer handling. The first two are functions which are called to transfer a single (*safeTransferFrom*) or multiple tokens (*safeBatchTransferFrom*) from owner (*_from*) to receiver (*_to*). Upon transfer execution, two events are emitted to notify external applications.

```
function safeTransferFrom(address _from, address _to, uint256 _id, uint256 _value,
bytes calldata _data) external

function safeBatchTransferFrom(address _from, address _to, uint256[] calldata _ids,
uint256[] calldata _values, bytes calldata _data) external

event TransferSingle(address indexed _operator, address indexed _from, address
indexed _to, uint256 _id, uint256 _value)

event TransferBatch(address indexed _operator, address indexed _from, address indexed
_to, uint256[] _ids, uint256[] _values)
```

This standard allows for approving a third-party management of all of the owner’s tokens on their behalf via the *setApprovalForAll* function. While this basic function is included in the core specifications for the Multi Token Standard, it is also recommended to use the ERC-1761 Scoped Approval Interface for a more granular approval specification (Radomski et al. 2019). Smart contract can also retrieve information on whether or not approval has been set for a given owner with the *isApprovedForAll* function. It is imperative to hold approval in order to make transfers of dNFT tokens, although the owner is allowed to transfer their tokens by default.

```
function setApprovalForAll(address _operator, bool _approved) external

function isApprovedForAll(address _owner, address _operator) external view returns
(bool)
```

To ensure interoperability between different ERC-1155 smart contracts, the standard requires the implementation all *ERC1155TokenReceiver* interface functions to accept transfers. Two functions are specified to transfer either a single or multiple tokens at once. The *_id(s)* and *_value(s)* array parameters contain the IDs and amounts of the transferred tokens. The Receiver functions are called at the end of the *safe(Batch)TransferFrom* functions. If the receiving contract had not implemented the interface to accept transfers from the ERC-1155 standard, the transaction will be reverted. This way the tokens will not be lost if sent to unsupported address ('ERC1155' n.d.).

```
function onERC1155Received(address _operator, address _from, uint256 _id, uint256
_value, bytes calldata _data) external returns(bytes4)

function onERC1155BatchReceived(address _operator, address _from, uint256[] calldata
_ids, uint256[] calldata _values, bytes calldata _data) external returns(bytes4)
```

Smart contracts can retrieve the balance of one or more addresses at once. Given that this standard requires the *_id(s)* parameter to be specified, the contract can also return distinct balances for each token that an address owns ('ERC1155 | API' n.d.).

```
function balanceOf(address _owner, uint256 _id) external view returns (uint256)

function balanceOfBatch(address[] calldata _owners, uint256[] calldata _ids) external
view returns (uint256[] memory)
```

The dynamic character of the ERC-1155 standard is another novel feature among token standards. It has to do with the non-fungibility property but unlike in the ERC-721 standard, the underlying item can be updated without compromising the token's reliability. While in ERC-721, the metadata pointing to the location of an item is included in the token contract, ERC—1155 separates its metadata from the contract's state and provides options for token upgradeability.

The tokens in each category have their own unique token IDs, split into two 128-bit parts. The first part represents the base token ID, referring to the category, and the second – the index that distinguishes an individual token from all others (Radomski et al. 2018). By not making the tokens contract-specific, such fragmentation of a token structure helps to efficiently manage, store and configure a great number of tokens within the same contract. Simultaneously, the metadata or functionality changes concern individual tokens or only the base token ID, and not all the tokens at once.

Tokens are linked to an externally held storage via URIs which can make use of ID substitution. ERC-1155 that allows for an efficient management of token metadata in a smart contract is the ability to reuse a single URI for many tokens. The creators of the standard specify that an URI can contain the *{id}* string which can then be replaced with the token IDs in their hexadecimal form, thus assigning the URI to tokens dynamically, like in the metadata format example below. It removes the need to provide separate URIs for each NFT token. This method allows to reuse the same URI string reducing the amount of data stored on-chain, making the contract less gas-intensive.

```
"properties": {
        "image": {
                "type": "string",
                "description": "https://token-cdn-domain/{id}.json",
        }
}
```

Furthermore, a multi-token project can make use of the *setURI* function provided in the OpenZeppelin ERC1155 contract. This way, a contract without previously specified URIs can assign them to all token categories, while already existing URIs can be overwritten with new ones (Croubois, @takahser, and @frangio 2022). URI update will trigger the URI event which can be used to notify the users or applications of the token metadata change.

Given the flexibility to update the information pertaining to the tokens, it is no longer necessary to employ entirely new contracts to make changes if needed. Even though updates are possible to some extent in ERC-20 and ERC-721 smart contracts, due to the associated high gas costs it might be preferrable to use new contracts entirely. With ERC-1155 these costs are largely reduced.

```
function setURI(uint256 _tokenId, string memory _tokenURI) internal virtual{
        _tokenURIs[tokenId] = _tokenURI;
        emit URI(URI(tokenId), tokenId);
}
```

To mint dNFTs, there are two options available: the *mint* and *mintBatch* functions for creating one or more token categories (@frangio et al. 2022). These functions specify the account the tokens will be assigned to, the token category ID(s), the amount of individual tokens to be minted, and optional data to be included. Token *name* and *symbol* use is not supported by ERC-1155 as this standard focuses on efficiency and gas optimisation.

```
function mint(address _to, uint256 _id, uint256 _amount, bytes memory _data) internal
virtual

function mintBatch(address _to, uint256[] memory _ids, uint256[] memory _amounts,
bytes memory _data) internal virtual
```

Burning mechanism is also possible in for single tokens or in batch. The contract uses the *burn* and *burnBatch* functions. The safe transfer method for sending ERC-1155 tokens prevents contracts from burning tokens through a transfer to the null address. This way programs based on dynamic NFTs can be transparent about their token destruction mechanisms.

```
function burn(address _from, uint256 _id, uint256 _amount) internal virtual

function burnBatch(address _from, uint256[] memory _ids, uint256[] memory _amounts)
internal virtual
```

ERC-1155 offers all the benefits of fungible and non-fungible tokens as well as several more. It is a highly gas efficient standard, especially fit for handling large amount of tokens and transfers. It implements some resource saving options, such as reduced on-chain data storage, batch transfers and single-contract management of an infinite number of tokens. It allows for upgradability of the items represented by the tokens, making which token projects can adjust to their own needs. They could issue tokens which are conditioned to respond to external events, provide new attributes to the existing tokens, and many others.

Despite aiming at creating a simplified token standard, ERC-1155 has faced some challenges related to building a new ecosystem around a new token standard. Dynamic NFTs were introduced when many other projects using standard fungible and non-fungible token had already created a robust ecosystem of applications. This can create limitations in terms of the number and type of applications that can be built on top of the ERC-1155 standard, particularly in cases where developers need to integrate with existing smart contracts or other blockchain infrastructure that only supports one type of token. Being known mostly for its usability within the gaming community, ERC-1155 requires continuous development and more diversified use cases to evaluate its true potential.

4. Discussion

Considering the theoretical research of this study, carbon credits and carbon tokens can be compared according to their ability for offsetting carbon emissions.

Carbon credits represent CO_2 emission reductions or removal from the atmosphere and function as a ‘token’, regardless of the form they are issued in – digital, paper, written or numerical. Blockchain-based tokens are suitable for this role since they can represent an infinite number of underlying assets in a fungible or non-fungible way. Technical properties, enabled by Blockchain-based token standards, facilitate this task. As shown on the example of ERC standards, token functionalities are clearly defined and deterministic, setting a canvas for carbon token projects. Creators can focus on refining incentive mechanisms and ensuring real-world value rather than creating a new framework for crediting offsets.

Different standards can be chosen depending on the project needs and goals. For simplicity and tradability, ERC-20 tokens can be useful; fungible tokens can be traded beyond its carbon niche of the token market. ERC-721 can provide uniqueness and trackability and derive value from rarity. ERC-1155 are capable of handling large volumes of transactions cost-effectively and make use of different token properties in one contract. In addition to guaranteeing immutable digital representation of offsets, carbon tokens can be also explicitly distinguishable by name, symbol, transactional provenance, custom metadata, and other properties. This could be used to mark the vintage of a tokenised offset, timestamp the issuance and tie it to a specific environmental project, ensuring that carbon tokens represent the non-financial nature of carbon credits permanently. They could even contribute to an improved valuation for vintages since their underlying environmental value is more transparent.

Regardless of whether the credits exist on the compliance or voluntary market, an overseeing institution issues them according to their certification framework and makes them available for trade. Tokenised projects can handle carbon token issuance using programmable and automated mechanisms from various token standards. Smart contracts provide a clear and transparent infrastructure for it through the mint function and the optional fixed, controlled supply. A carbon project could, for example, leverage the potential of ERC-721 could be used to mint NFT tokens representing real-world CO_2 offsetting actions with bespoke certificate-like images to trade them and treat as collectible certificates confirming the offsets they funded.

To prevent traditional offsets from being used more than once for the same emissions reduction, they must be retired. Token standards representing an avoided CO_2 increase allow carbon tokens to be burned and taken off the market permanently. This is done on the contract level and written on the blockchain. Supply management is an important consideration too as it could affect pricing so burning abilities can be restricted on the contract level, using the safe transfer option and hardcoding the null address exclusion. Certifying that a carbon offset took place and was realised through token destruction allows token holders to finance environmental initiatives. Furthermore, project creators should develop a strategy for burning tokens and communicate it clearly with the community. To maintain trust, private addresses should not substitute the null address for permanent token destruction. Regular token burns can remove unpurchased or fraudulent carbon tokens, ensuring responsible token destruction and maintaining healthy prices. This enhances additionality of the carbon tokens by preventing double counting of offsets.

Carbon credits must be traded to fulfil their role of funding carbon removal or emission reduction projects. Blockchain tokens, which are designed to be tradeable, leverage the transferability and ownership management functionalities of token standards. Smart contracts automate the token transfer process certifying carbon token purchase securely. Transactions leave a trace on the blockchain, providing a permanent digital track of financial history of tokens or transactions, in addition to the non-financial data. Token ownership is transparent, be it the amount of fungible tokens belonging to an address, or historical provenance of a non-fungible token. These features support the maintenance of carbon offsetting projects registries, verifying transfers between stakeholders and burned carbon offsets.

Given that contracts can retrieve current state information and verify token ownership, real-time oversight is possible for carbon projects. Token delegation features improve the management of them, allowing others to dispose of one’s tokens, which is particularly convenient for escrow arrangements or to prove the token holder identity to regulated auditors. Carbon projects can quickly respond to supply and demand changes and notify other applications of any changes. This feature can be used, for example, by platforms for trading carbon NFTs or decentralised exchanges to make immediate updates and notify users. Furthermore, Blockchain technology's global reach and its supporting ecosystem of platforms and applications makes carbon tokens highly accessible. Buyers and sellers can be connected instantly and trade carbon tokens, creating a large-scale and highly liquid market for carbon offsets. A standardised, trusted process for issuance of tokens and their digital representation could increase the liquidity of tokenised carbon markets, with a lower risk for value depreciation.

In short, Blockchain-based tokens, having the ability to represent underlying assets, allows carbon tokens to reflect both the financial and non-financial aspects of carbon credits, including those pertaining to vintages and trade history. The immutable and verifiable character of on-chain transactions and data storage create a secure registry, while token issuance and burn certify the realised carbon offsets. The supply management mechanisms of tokens, along with the global online accessibility and trusted data source, enhance liquidity, making them equivalent to carbon credits. Therefore, the first hypothesis is accepted.

To add to the previously discussed similarities, analysing token features across various standards has uncovered some other benefits of employing them in carbon offsetting projects. These properties are less tangible but closely aligned with the core values of Blockchain technology and Regenerative Finance: decentralisation, community involvement and innovativeness.

Tokens offer a more inclusive approach to carbon markets for stakeholders. This is important because traditional carbon markets often have unaddressed inequalities which could limit the positive environmental and social impact of carbon credits. With internet access and a crypto wallet, anyone can participate in a tokenised carbon market, regardless of location. This creates financial incentives for entities to dedicate their resources to emission-reducing activities instead of switching to a polluting business option. Carbon tokens can help companies reduce the risk of leakage by not only providing the opportunity to purchase tokens that may increase in value over time and surpass the cost savings from relocation, but also by enabling them to demonstrate their commitment to meeting ESG targets in a transparent and tamper-proof manner.

Tokens also strengthen the entire crypto ecosystem, unlike traditional carbon markets which, besides offering some investment opportunities, operate separately from other financial markets. Carbon tokens provide liquidity necessary for trading and can be exchanged for other tokens and currencies, even cross-chain. Creating new projects supplies use cases allowing for a continuous improvement of tokenomics and addressing vulnerabilities through standardisation. At the same time, a better standardisation should not lead to the stagnation, as Blockchain technology undergoes constant upgrades and helps projects adapt to changes, which in the case of offsets could involve new regulations and environmental challenges. Carbon tokens incentivise community contributions to use the infinite potential of Blockchain for good and spur the development of new ideas, just as other crypto tokens do.

Carbon tokens offer additional benefits compared to traditional credits, including those mentioned above. Thus, the second hypothesis can be accepted, as carbon tokens can incentivise more effective carbon offsetting.

Regardless of the findings of this work, further studies are needed to address the limitations of this work, including the need for case studies to verify the claims and financial competitiveness of carbon tokens with traditional carbon credit markets. The tokenised carbon market is still young and needs to mature before providing reference information for other carbon projects. Additionally, exploring other blockchains and token standards beyond ERC could provide valuable insights into the properties of Blockchain-based tokens. Further research could also examine the applicability of carbon tokens in various tokenomic scenarios, including staking, yield farming, DAO governance, and oracle inclusion.

5. Conclusions

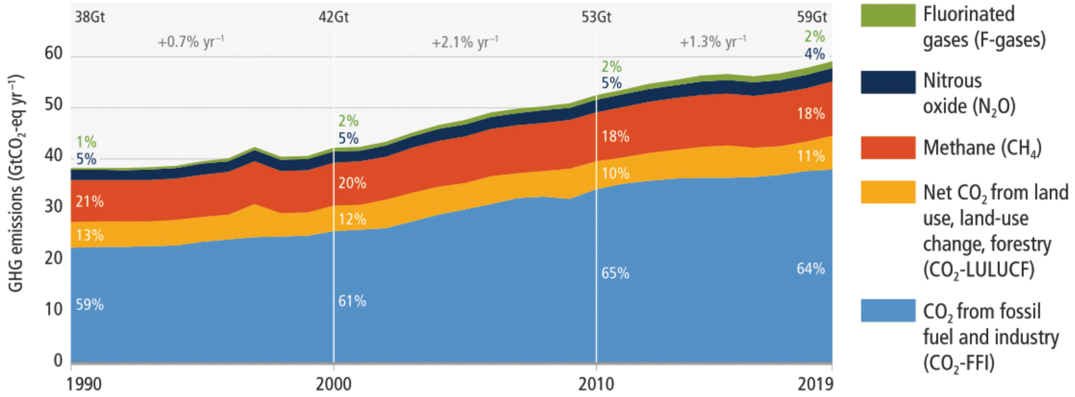
This work focused on investigating the potential of tokens based on Blockchain technology in offsetting carbon emissions. Specifically, the study attempted to demonstrate the overlap between the traditional carbon credits and Blockchain-based tokens as instruments on the carbon market. The theoretical analysis included an assessment of the existing carbon markets, carbon credits with their characteristics and shortcomings, and an introduction to the concept of carbon tokens. The technicalities of token standards were described in detail, using the three most well-known ERC standards as examples. Additionally, this study sought to identify new benefits that could that the tokenisation of carbon credits could enable.

In conclusion, the technical specifications of Blockchain-based tokens, as outlined in the token standard specifications, indeed demonstrate the ability to function as carbon credits. The continuous development of tokenomics and the ecosystem of applications, platforms, programming improvements, and community feedback further strengthens their potential. Moreover, tokenisation could address the challenges of the current carbon markets and credits, which include flawed verifiability, inaccurate registering of relevant data, market illiquidity, and leakage. Token-based offsetting projects bring some new benefits too. They can contribute to the development of Blockchain-based economy and Regenerative Finance, strengthening alternative approaches to wealth redistribution. Not only that but they can also lead to measurable environmental and social benefits, such as direct financing of carbon offset projects, rewarding participants for ecological behaviour, and building foundations for an improved standardisation.

Carbon token projects can drive innovation in the carbon markets, using Blockchain technology and community involvement to adapt to emerging challenges and devise strategies to overcome them. These projects can incentivise participation in carbon offset trading by attracting users willing not only to offset emissions, but also to engage in cryptotrading for the potential rewards. Carbon token projects also foster inclusivity by allowing anyone with internet access to get involved, trade and perhaps even build new solutions. They can indirectly raise environmental awareness by providing accessible tools for making real and impactful contributions, thus onboarding more people and organisations onto the carbon market.

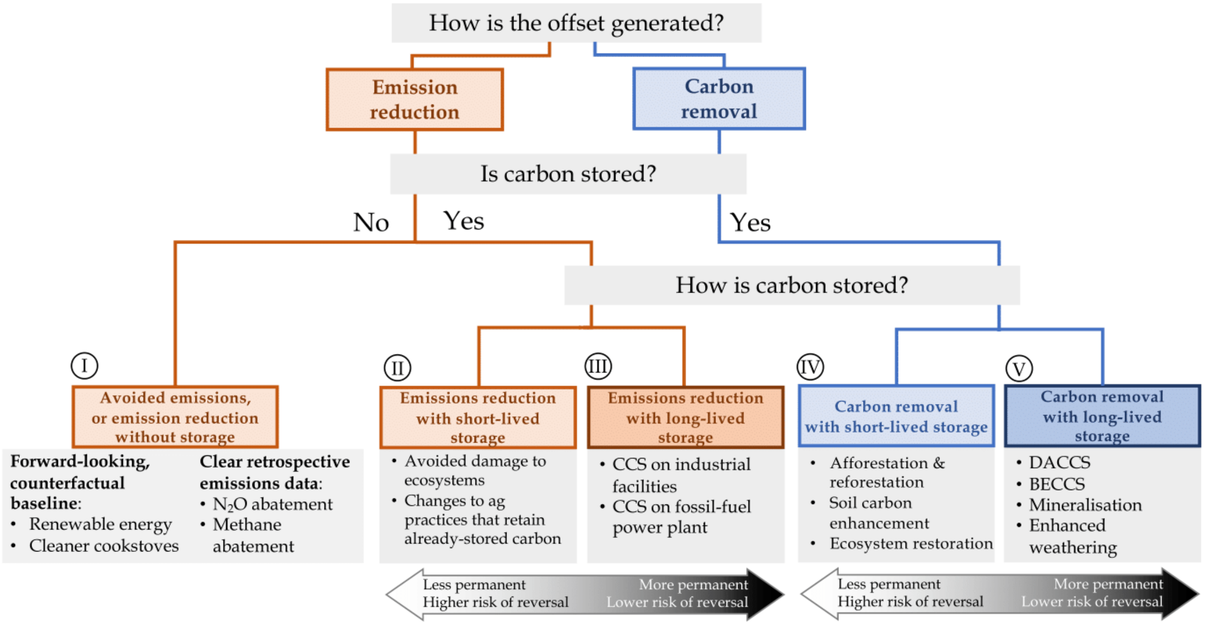
Figures

Figure 1. *Global net anthropogenic GHG emissions 1990–2019*



Source: Climate Change 2022. Mitigation of Climate Change. Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Shukla, Skea, and Reisinger 2022, 7)

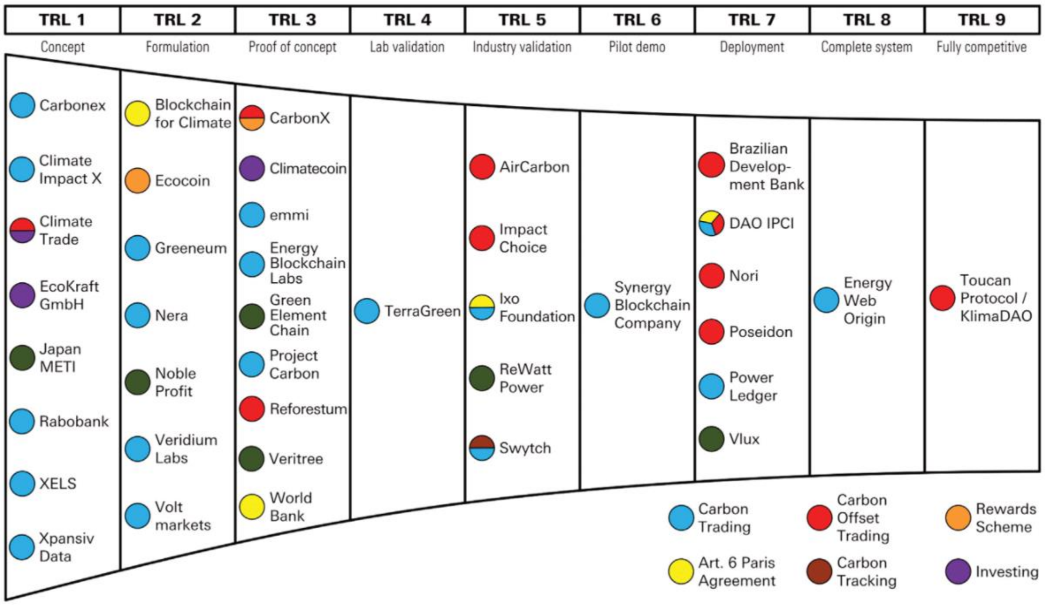
Figure 2. *Taxonomy of carbon offsets*



Abbreviations explained: CSS: carbon capture and storage; DACCS: direct air capture with geological storage; BECCS: bioenergy with carbon capture and storage.

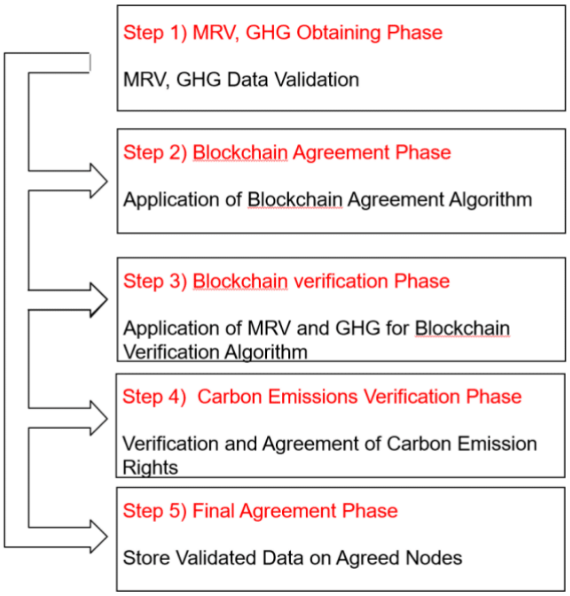
Source: The Oxford Principles for Net Zero Aligned Carbon Offsetting (2020, 8)

Figure 3. *The technology readiness level of blockchain solutions in carbon markets*



Source: Blockchain solutions for carbon markets are nearing maturity (Sipthorpe et al. 2022, 783)

Figure 4. *Verification blockchain for measurement, reporting, and verification (MRV) and greenhouse gas (GHG) data*



Source: Blockchain of Carbon Trading for UN Sustainable Development Goals (Kim and Huh 2020, 12)

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