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A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract

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ABSTRACT

Climate change is a major issue that has disastrous implications on the environment, which, if continued, will cause severe consequences. One of the leading causes of climate change is the emissions of harmful gases, particularly CO_2. In 1997, the Kyoto protocol was signed by 192 countries, creating a system that monetizes CO_2 emissions with an aim to control them. Most countries signed a carbon trading scheme, but the scheme fell short of its goals due to manipulation, lack of integrity, and multiple other challenges. This work presents an improved blockchain-based approach to achieve the objective of monitoring the reduction of carbon emissions. Blockchain's distinct features such as security, immutability, transparency, traceability, and trust, make it a robust and reliable solution for the carbon trading market. Previous Blockchain-based proposals were not comprehensive, practical, applicable, or efficient enough to form an effective solution. This research addresses the current gaps and proposes a comprehensive three-stage hierarchical blockchain framework that employs smart contracts in Blockchain of Things (BoT) to ensure integrity in the system and reach fair trade status that favors the environment over companies' cost reductions and profit-making. The result is an optimized carbon emission trading framework, fully transparent with automated trading and control mechanisms.

1. Introduction

Economic growth figures that appear prominently in global discussions are the foremost goal of most countries. Over the 2012-2018 span, global economic growth averaged 3.4% (Olivier et al., 2019). However, to achieve economic growth, the consumption of natural resources arises, and so do human activities such as fuel combustion, transportation, waste generation, and others. As a result, the emissions of Greenhouse Gases (GHG) have increased and thus exacerbated the problems associated with climate change. Climate change is considered one of the most critical global challenges that influence the environment, human well-being, and eventually the economy. Its effects could be irreversible taking the form of extension of species, loss of biodiversity, and melting of glaciers. Most importantly, it increases temperatures and sea-levels, which results in humans migration. Also, climate change impacts the living conditions of developing countries in particular. They are mostly exposed to its effects due to their inadequate investment in resources needed to prevent and mitigate climate change impacts. Therefore, there is a severe need to control human activities to avert climate change. Governments have renewed efforts to solve the issue, and many initiatives came to the fore. Monetizing and trading carbon emissions is one of the proposed solutions.

Carbon emission trading (CET) is a market-based mechanism considered to motivate the emission reduction of GHG, such as carbon dioxide (CO_2) (Abrell, 2010). Carbon emission trading emerged from the Kyoto Protocol in 1997 to control the levels of emissions. It is based on the concept of "cap and trade" in which nations are given a certain amount of CO_2 allowances according to their emission reduction targets. Countries are allowed to emit CO_2 without exceeding their allowances limits, whereas they can trade excess carbon allowances with other nations. Many countries and regions such as Europe, North America, and Asia regions are developing carbon emission trading systems. Over 40 nations and 20 sub-nations have implemented or scheduled to implement a trading system of carbon emissions (Tuerk and Zelljadt, 2000).

The major purpose of emission trading is to achieve the environmental goal and reduce emissions at the lowest cost. The nature of the cap and trade concept encourages environmental protection, whereby it forces participants to remain within the allowable amount not to face

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sanctions. Besides, emission trading encourages businesses to move towards the inclusion of technological tools to identify solutions for obtaining a successful carbon trading scheme along with achieving the environmental outcome. It also has the opportunity of integrating the different carbon emission markets, which enhances the effectiveness of carbon trading mechanism, if a proper integration solution is built. Finally, the concept of cap and trade which is the basis of emission trading has proven to be an effective policy choice. For example, the 2015's status report of the International Carbon Action Partnership has found that 40% of the world's GDP is subject to emission trading (Serre et al., 2015). Thus, indicating the importance of carbon trading and its potentials for controlling human activities and achieving environmental protection. However, the agreement has downfalls such as non-transparency and corruption which allowed manipulation to occur. The agreement also lacks a legislation and tracking system that stores and verifies the information required to monitor and track global transactions. This kind of tracking system is necessary to eliminate corruption and double counting. Another issue with carbon trading is the complex allocation of carbon allowances that results in an unfair distribution of allowances among participants. Also, there is a lack of integration in the carbon markets that would reduces the efficiency of the trading mechanism and creates fewer options for carbon mitigation. Therefore, there is a need to resolve the issues of carbon trading.

Blockchain technology can be adopted to tackle the aforementioned challenges. Blockchain can be viewed as "information storage and transmission technology that is transparent, secure, and operates without a central control body" (Pigeolet and Van Waeyenberge, 2019). With blockchain technology, the verification of transferred data and information is no longer taking place via a central actor, but through a peer-to-peer network. In other words, it is based on a distributed network of peers that preserves highly secured, replicated, and auditable transactions (Patsonakis et al., 2019). Furthermore, it is characterized by the recording, integration, and fair sharing of information that provides transparency and credibility. This technology can monitor, track, and report the carbon emissions and the trading transactions to avoid double counting and demonstrate a strong transparency mechanism in the carbon trading market. According to the Climate Chain Coalition, adopting the technology of blockchain "will build capital market confidence and help reach the targets of reducing climate change at both local and global levels through consensus methods and interoperability" (Pigeolet and Van Waeyenberge, 2019).

Our research is a step towards strengthening existing carbon trading schemes enabling them to better serve their main purpose of achieving sustainability, equitably and effectively by adopting a qualitative method based on document analysis as a primary investigation technique. The methodology adopted in this study was firstly based on conducting an ancestor search to gain an in-depth insight into the Kyoto protocol and carbon trading market. Secondly, inspecting research articles to understand blockchain and its potential for the carbon trading market. Thirdly, reviewing researches discussing the application of blockchain in the carbon trading market and identifying their contributions and limitations. The contribution of this research is achieved through the following:

- Demonstrate the challenges and shortcomings of the currently practiced carbon emission trading methods and platforms.
- Address blockchain as a suitable technology that will adequately implement fair and beneficial carbon trading by explaining the value added by blockchain.
- Propose a comprehensive framework design for carbon emission trading based on blockchain that fills the gaps in existing practices and frameworks and primarily serve the original purpose of carbon emission trading.

The remainder of this paper is arranged as follows: Section 2 provides a brief discussion on greenhouse gases emissions and proposes a background on carbon emission trading (CET). Section 3 demonstrates the challenges and shortcomings of the currently practiced CET methods and platforms. Section 4 introduces blockchain technology and explains its structure, characteristics, classification, main applications, smart contracts and discusses the value added by blockchain technology that makes it a suitable means to serve a proper implementation of fair and beneficial carbon trading. Section 5 presents the literature review and the recent frameworks adopted to implement blockchain in carbon trading, while section 6 demonstrates a comprehensive framework for carbon emission trading based on blockchain that fills the gaps in existing practices and frameworks. Finally, section 7 is the conclusion.

2. Greenhouse and harmful gases emission

The emissions of GHG affect all countries around the globe at all levels. The increase in its emissions is primarily caused by economic growth, and it is expected to continue to increase with elevated industrial activities and energy consumption (Liobikienė and Butkus, 2019). According to (Olivier et al., 2017), GHG emissions are higher than their levels in 1990 by 57% and their levels in 2000 by 43%. The major contributors to the GHG are CO_2, Methane (CH_4), Nitrous Oxide (N_2O), and Fluorinated Gases (F-gases). Additionally, in 2017, the share of major gases in global emissions were 72% CO_2, 19% CH_4, 6% N_2O, and 3% F-gases. Clearly, CO_2 has the highest share of GHG global emissions, and its main source drivers are coal combustion (39%), oil combustion (31%), natural gas combustion (18%), and cement production (4%) (Olivier et al., 2017). We developed the following Figures 1 and 2 based on data from (Olivier et al., 2019). Figure 1 shows the distribution of GHG emissions in major countries where GHG emissions are continuously increasing.

Also, carbon emissions encounter 75% of global emissions (Mondragon et al., 2018), and it is predicted to increase by an average of 0.6% per year between 2018 and 2050 (U.S. Energy Information Administration, 2019). Figure 2 demonstrates the incessant growth of CO_2 across the world in terms of countries' contributions to the global emissions of CO_2.

Six nations are contributing the most to global emissions, namely, China, United States, European Union, India, the Russian Federation, and Japan (Olivier et al., 2019). Table 1 shows the share of the top 6 nations in terms of GHG and CO_2 emissions in 2018.

International efforts strive to reduce global CO_2 emissions to lessen the impact on the environment and control climate change. The efforts of reducing the CO_2 emissions depend on the degree of commitment of major CO_2 producing nations in meeting the targets of global emissions (Tamazian et al., 2009). As a result, many initiatives have been proposed to lower and adjust the emission of CO_2 such as converting it to valuable products, controlling the operational procedures, and capturing CO_2 and storing it. However, there is a lack in the implementation of those initiatives, as they face financial and economic challenges (Ramanathan and Feng, 2009). Therefore, new ways of controlling CO_2 are considered such as Carbon Emission Trading. The next section describes the concept of Carbon Emission Trading and its origin.

2.1. Carbon emissions trading

CET emerged from the Kyoto Protocol, which aimed at controlling the increase in GHG emissions and human activities that were accelerating climate change (Spash, 2010). The protocol which originated in Kyoto- Japan in 1997, established an international market for GHG emission allowances, mainly CO_2 (Calel, 2011). As a result, carbon trading has been formed as trading means to meet the obligations stated by the Protocol. The CET was intended as a key tool for mitigating climate change using market mechanisms to reduce CO_2 global emissions (Liu et al., 2015).

It is described as an exchange of carbon credits between nations to lessen the emissions of CO_2 wherein each committed entity is allocated a

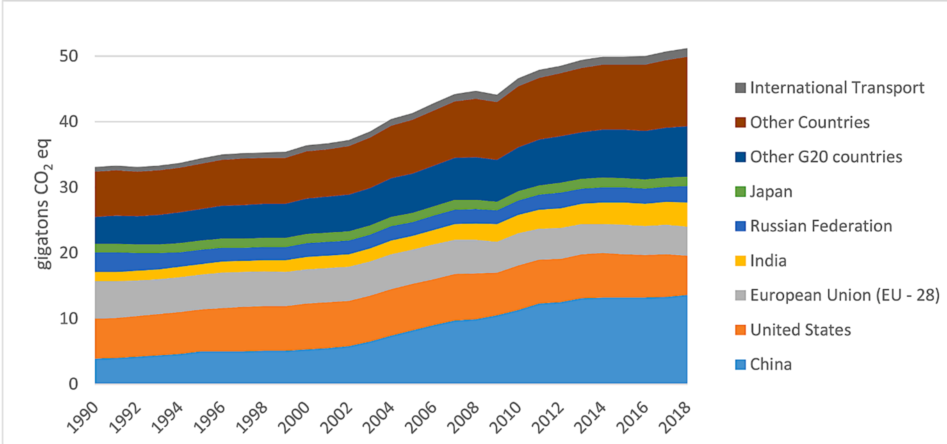

Fig. 1. Global GHG emissions per country

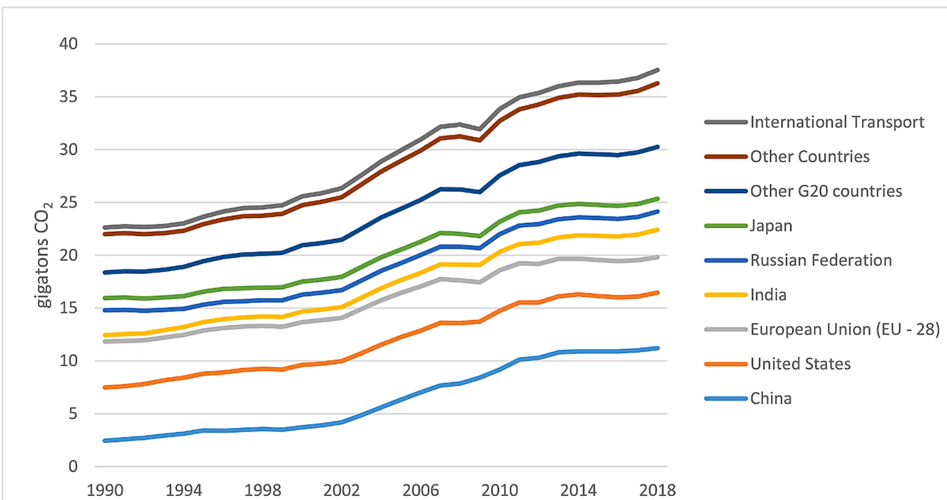

Fig. 2. Top countries in emitting CO_2

Table 1
Share of global GHG and CO_2 emissions in 2018

Nation	Share of global GHG	Share of global CO_2
China	26%	30%
United States	13%	14%
European Union	9%	9%
India	7.2%	6.9%
Russian Federation	4.8%	4.6%
Japan	2.7%	3.2%

certain level of carbon emissions according to its emission reduction targets and within the international emission allowances (Kenton, 2018). A research by (Liu et al., 2015) also described the concept of carbon trading as "one party to the contract pays the other to obtain permits for GHG emissions. The buyer can use purchased emission credits in mitigating GHG emissions, thereby achieving its emission reduction targets" (Liu et al., 2015). CET is based on the concept of "cap and trade" (Gilbertson et al., 2009). The "cap" part includes governments' distribution of a certain number of CO_2 allowances as a credit to companies (Amadeo, 2019). It should be low to reduce the total GHG, which then helps in making the cost of conducting business higher and slowing down economic growth. For instance, the European Union has lowered the carbon cap by 2.2% in 2017, and it aims to decrease carbon emissions by 40% by 2030. The "trade" part addresses the ability of companies who emit CO_2 below their limit, to sell their excess credits to firms who exceeded their CO_2 limits (Amadeo, 2019). Besides, nations that emit more than their limit can purchase additional carbon offset credits (Amadeo, 2019).

In 2011, the global carbon trading volume reached 54.9 billion dollars and in 2014, 40 nations and more than 20 cities have implemented carbon emission trading schemes, which account for more than 13% of the global GHG emissions ('Pricing Carbon').

The world's largest scheme for trading GHG and the first "cap and trade" system is the European Union Emission Trading Scheme (EU-ETS), established in 2005. It provides an absolute limit on GHG emissions, in which the emission rights are carried by tradable permits that are referred to as European Union Allowances (EUAs) (Ellerman, 2010). The EUAs are measured as either one ton of CO_2 or with any equivalent "Assigned Amount Unit" of CO_2 determined in the Kyoto Protocol (Breidenich et al., 1998). ETS-EU operates with a single database for tracking the ownership of EUAs from the date they were issued. The process of ETS is characterized by three main steps: issuance, trading, and surrender.

- **Issuance**: The number of allowances is determined and distributed to businesses and entities that are listed in the Union registry. The distribution is conducted through free allocation and auctioning. Of the total allowances, 5% is set aside for free allocations to new participants (Ellerman, 2010).

- The process of auctioning for the EU-ETS is based on a single round, sealed bid, and uniform price. In the single bidding window, which lasts for at least two hours, bidders can submit, modify, and withdraw their bids. After the closure of the bidding window, the auctioning procedure starts at a clearing price, which is defined as the sum of volume bids that matches or exceeds the volume of the auctioned allowanced. Afterward, bids are filtered depending on whether they are higher or lower than the clearing price, in which only bids with higher prices are successful. In addition, auctions can be canceled if the clearing price is below the auction reserve price, which is a hidden minimum clearing price set before the auction by the platform of the auction and the auction monitor.
- On the other hand, EU-ETS also uses a benchmark approach for the free allocation of allowances. It is based on a reference relative to a product activity rather than a GHG emission limit. If the product activity related to GHG emissions is lower than the benchmark, then it will receive more free allocations than they need. The allocation will be then calculated as the sum product of benchmark, historical activity level, carbon leakage exposure factor, and a correction factor.
- The mechanism for distributing carbon allowances has varied over the years. The EU has set phases for the distribution mechanism. Currently, the distribution mechanism is in the third phase, which states that the annual allowances should be reduced by 1.74% as of 2013's allowances, which is around 38 Mtons of CO_2. Among the total allowances, half are auctioned. Free allowances are distributed via harmonized benchmarks. The fourth phase lies between 2021 and 2030, and it is still under negotiation. In this phase, the annual allowances will be reduced by 2.2% as of 2021, which is equivalent to approximately 48 Mtons of CO_2. In addition, 57% of the total allowances will be auctioned, and the free allowances distribution will have the same manner as in the third phase (Commission, 2015).

- **Trading**: the allocated allowances can be traded through either an exchange or over the counter (OTC). Also, trading should be recorded in the transaction log of the EU and if the cap is exceeded, high polluting firms can purchase additional permits from low polluting firms. They can also trade on Europe's climate exchanges, or purchase credits from carbon reduction projects in developing countries. In case they cannot source enough allowance to maintain compliance, a sanctioned offset, called carbon offset, may be used to counterbalance the excess. A carbon offset is any activity that compensates for the emission of CO_2 or other GHG (measured in CO_2 equivalents) by providing for an emission reduction elsewhere. Purchasing carbon offset is a way of funding green projects that aim to GHG emissions. So, businesses buy offsets to either reduce their carbon footprints or build up their green image. Because GHG is widespread in Earth's atmosphere, the climate benefits from emission reductions regardless of where such cutbacks occur (Kollmuss et al., 2008).
- **Surrender**: businesses are obliged to report their emissions and to surrender an equal number of EUAs yearly (Ellerman, 2010). In other words, At the end of a certain period, all participants are required to surrender the relevant amount of permits along with a report on the amount of emission produced during that period.

Emission Trading provides a clear emission reduction target to achieve the environmental goals, where there is a certain cap for setting the maximum quantity of emissions for a specific period of time. It is also, considered a cost-efficient method, in which the flexible trading scheme provides firms with the same carbon prices. In addition, the scheme offers an opportunity for a concerned party to adhere to the limit by buying and surrendering the allowances. Another point in favor of tradable permits policies relates to the global emission abatement effort, whereby, it is possible to link the individual systems in order to create a larger and more stable market and to motivate developing countries' involvement. Figure 3 provides the steps of ETS.

In sum, carbon trading is a concept that mitigates the effects of global warming and climate change. However, despite its ability to regulate industrial activities and enhance their carbon asset management capabilities, its implementation faces several challenges that are discussed in the next section.

3. Challenges facing carbon trading

This section aims to present the challenges facing CET, and the actions necessary for implementing an integrated transparent carbon trading system. The challenges are:

- **The Carbon Budget's Calculations are Open to Manipulation and Abuse**. The carbon budget is a tolerable quantity of GHG emissions that can be emitted to avoid global warming and climate change. Greater amounts of emissions result in higher temperatures that will eventually be a major cause of climate change (The World Wide Fund For Nature, 2014). Hence, temperatures need to stay within certain limits and carbon emissions should be limited also. To do so, a carbon emissions budget is needed to prevent the serious consequences of climate change. According to (Höhne and Moltmann, 2009), with a likelihood of 66%, a concentration limit of 400 parts-per-million (ppm) of CO_2 should be considered as a global carbon budget for the period between 1990-2100, in order to stay below 2 degree Celsius of global warming. Furthermore, carbon budget calculation is a complex process, and its baseline is considered as a projection and thus, it is subject to gaming and manipulation, which makes it susceptible to artificial incrementation. Therefore, there is a need to develop a fixed carbon budget that cannot be changed or manipulated. Besides, it should be divided fairly between countries by taking into account their historical emissions, state of economic development, economic and technological capabilities of reducing emissions, and others.
- **The Carbon Trading Market is Characterized by Corruption and Non-Transparency (Skene and Murray, 2017).** Companies are not monitored and their systems and decisions are not accessible. For instance, 30% of the Czech Republic's carbon allowances were given to the Czech energy giant CEZ group. However, the company traded with the carbon credits and misused them such that they have sold them when the value of carbon credit was high and bought them back when their price was low. The generated profit was used to increase coal production which enhanced further the country's pollution. It can, therefore, be implied, that companies should be obliged to offer transparency in order to control their carbon trading relation actions (Skene and Murray, 2017). In addition, a committee of experts should be formed in order to check and verify the information provided by the participants to monitor their emissions and publish verified and trusted numbers. In sum, if the participants of the carbon trade market have transparency and can read the carbon process and transacted quantities, then the carbon market will have less uncertainty and higher efficiency.
- **The Process of Allocating Carbon Allowances is Complex**. It includes determining emission limits, reduction goals, and distribution mechanism of allowances. Carbon allowances distribution whether done by auctioning or free allocation is a complex process that depends on many factors such as benchmark value set by the central authority, historical activity level, and carbon leakage factor (Ellerman, 2010). Also, the allocation is done through a central authority, which makes it more susceptible to manipulation.
- **Carbon Allowances are Complex.** For instance, Japan and Russia refused to ratify the Kyoto protocol in 2001, due to the insufficient carbon credit given to them. However, when more carbon credit was

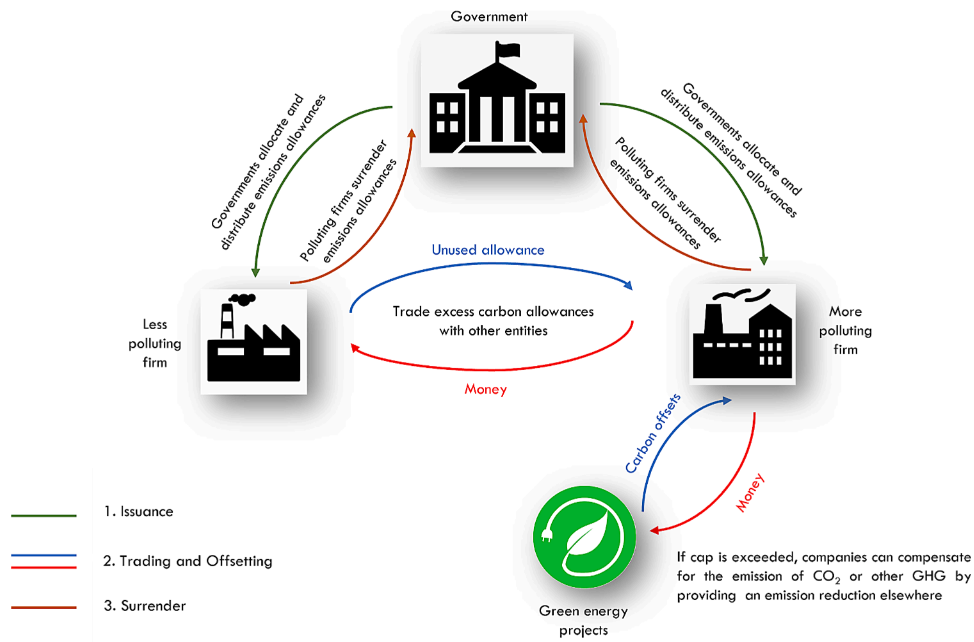

Fig. 3. Steps of ETS

assigned for their industrial forests, they have signed the Kyoto protocol.

- **Carbon Trading Offers the Ability to Buy More Carbon Credits**, which allows for strong and wealthy countries to pollute more (Skene and Murray, 2017). The power of rich countries and wealthy firms allows them to trade their carbon allowances through selling and purchasing carbon credits for their benefits without consideration of the broader negative impacts.
- **Carbon Trading is Characterized by the Lack of Tracking Measurements of Emissions**, in which there is no standard measurement tool that leads to confusion and uncertainty. Carbon trading systems should make use of unified emission management which is capable of regulating carbon trading (Skene and Murray, 2017).
- **There is No Unified Carbon Trading Market.** The market of carbon trading is distributed with different policies and characterized by low coordination and integrity between them, thus leading to an inefficient carbon trading market. Therefore, the construction of legislation is essential. On the ground, the required legislation for controlling the operations of trading markets is still limited. Consequently, there is a need to supervise and monitor the market by collecting emissions data, verifying them, and setting obligations for non-compliances. This would require a legal system that is backed-up with the required data and information (Liu et al., 2015). In addition, the trade of carbon emissions conducted in different carbon markets results in trading carbon emissions allowances at different price levels. For instance, combining carbon markets would allow companies to use allowances from different systems, which helps in achieving compliance, whereby prices of carbon emissions will become identical (Pigeolet and Van Waeyenberge, 2019). Besides, aggregating carbon markets can improve efficiency and provides a large pool of compliance tools and creates more options for carbon mitigation. This implies that the various carbon markets should be aggregated into a single unified carbon market.
- **The Heterogeneity of GHG Emissions is Neglected.** For instance, comparing the GHG emissions in the U.S. and European Union, the U. S. sources of GHGs emissions were estimated in 2017 as 29% transportation, 28% electric power, 22% industry, 9% agriculture, 7% commercial, and 5% residential. On the other hand, the GHG emissions sources in the European Union have been estimated: 28.2% energy industries, 25.8% fuel combustion (excluding transportation), 24.6% transportation, 9.8% agriculture, 8.4% industrial processes, and 3.1% waste (How are emissions of greenhouse gases by the EU evolving?).
- **The Carbon Trading Market Can be Highly Complicated and Require High Transaction Costs**, which results in having fewer participants (King 2018). Transaction costs in carbon trading consist of negotiation costs, approval costs, enforcement costs, monitoring costs, insurance costs, and others. While enforcement and monitoring costs of carbon emissions allowances are set by the governments, other cost types are affected by different factors (Woerdman, 2001). When transaction costs increase, the seller receives a lower price and the buyer has to pay more, which will lead to fewer involvers in the carbon trading market.

The above-mentioned challenges for carbon emission trading must be resolved to permit a proper implementation of the scheme and thus meeting its intended goals of reducing global carbon emissions and promoting a sustainable environment. A proper accounting system is essential to avoid double counting of emissions allowances which is a necessary condition for a successful carbon trading process. Besides, a well-established and maintained end-to-end trading system featured with security, authenticity, and privacy in terms of data storage and transaction transmission is required to prevent manipulation. A binding obligation on the actors of the carbon market is necessary to maintain integrity and transparency. Andrei Marcu in (Pigeolet and Van Waeyenberge, 2019), argued that the participants should be able to transfer their mitigation results between each other, as this would help in the establishment of a proper carbon trading market. Thereby, to establish the linkage and the collaboration between the participants of the carbon market, and to coordinate the carbon market and carbon trading processes, the inclusion of new technologies is needed.

One of the emerging technologies is blockchain which provides extinguished features that represent the perfect and ideal solution for the above issues. Besides, it enhances, upgrades, and expands the impartial implementation of carbon emission trading in a way that strengthens its ability to serve the original purpose it was established for. The way blockchain addresses the above-explained challenges will be demonstrated later on when discussing blockchain solutions and value-added roles in the carbon trading sector.

However, to grasp the value added by blockchain to the carbon trading sector, the technology's structure and characteristics should be fully understood first, therefore, the following section 4 covers those aspects by providing a comprehensive overview of blockchain and its role in improving the performance and integrity of carbon emission trading.

4. Blockchain technology

Blockchain was introduced as the backbone of the cryptocurrency Bitcoin (Nakamoto, 2009) which became accepted as a form of payment by many billion-dollar businesses such as Dell, PayPal, and lately, Microsoft (Bheemaiah, 2018). It is believed that blockchain will challenge established business models as well as open the door for new value creation (Morkunas et al., 2019). The main characteristics of blockchain are its ability to enhance processes' efficiency, transparency, security, immutability, on top of other value-adding features. Also, it moves trust from central authorities such as governments, banks, lawyers, etc.. and places it with stakeholders themselves(Mougayar, 2016).

The following sub-sections will present blockchain characteristics, architecture, classifications, applications, and its value-added role in the carbon trading market.

4.1. Blockchain characteristics and architecture

Blockchain technology is a trusted platform for permanently storing and verifying data records (Murray, 2019). It has the ability to revolutionize business models (Iansiti and Lakhani, 2017) due to three main attributes: decentralization, elimination of intermediaries, and its structure that facilitate irreversible and immutable transactions (Swan, 2015a; Swan, 2015b).

Blockchain is defined as "*a distributed database, which is shared among and agreed upon a peer-to-peer network. It consists of a linked sequence of blocks (a storage unit of a transaction), holding timestamped transactions that are secured by public-key cryptography (i.e., "hash") and verified by the network community. Once an element is appended to the blockchain, it cannot be altered, turning a blockchain into an immutable record of past activity*." (Seebacher and Schüritz, 2017). Blockchain's most powerful feature that serves the CET market is providing a secured data storage and a transparent operating platform that supports interaction between non-trusting parties without a trusted intermediary or a third party (Nakamoto, 2009). Therefore, It is applicable where trust needs to be established between entities-whether humans such as companies, governments, and individuals or machines such as sensors and factories-who do not fully trust each other with the advantage of operating in a decentralized setup (Macrinici et al., 2018). Another key feature of blockchain that serves the carbon trading sector is that nodes can join or leave the network at any time, without disrupting the functioning of other nodes or the ongoing processes in the blockchain (Gideon Greenspan, 2015).

Blockchain's name stemmed from its technical structure as a chain of blocks that are linked together using cryptographic hashing (Zheng et al., 2017). A block is a data structure that stores information created by and shared among blockchain-based carbon trading network participants. Information is not restricted to financial transactions, it could be any type of data such as emissions sensors readings, figures from enterprises' software, thresholds specified by governments. It could even be an executed code called a smart contract (Wüst and Gervais, 2018) which has a central role in ensuring the integrity of trading in the proposed framework described in section 6.

So when information is contained in a block, it gets validated and added to the blockchain by specific nodes in the network called miners (Nakamoto, 2009; Wüst and Gervais, 2018). The validation mechanism requires the consensus of the majority of participants in the network (Crosby et al., 2016). This is called a consensus algorithm (Sultan and Lakhani, 2018). In case any network participant tries to violate the consensus protocol by introducing a new data entry, the rest of the network nodes treats it as an invalid entry (Yu et al., 2018). When a block is verified and added chronically to the blockchain, the contained data become immutable and can never be altered or erased and the identical database copies possessed by each participant get updated accordingly (Nakamoto, 2009). The below Figure 4 demonstrates how blockchain is structured.

The robust structure of blockchain grants it valuable features that serve the carbon trading sector and address its challenges. The following are the main ones (Casino et al., 2019; Galvez et al., 2018; Wang et al., 2019).

1 **Decentralization**: there is no central authority that controls files' access, therefore, blockchain avoids experiencing a single point failure problem.
2 **Distribution**: each participant has a copy of all records that get updated continuously.
3 **Security**: when a block is added to the chain, it can never be altered or erased.
4 **Transparency:** all transactions and information are visible to any node within the blockchain.
5 **Automation:** fulfilled by the smart contract concept in which certain action could be triggered automatically utilizing a certain program whenever prespecified conditions are met.
6 **Traceability:** blockchain holds a historical record of all data from the date it was established.
7 **Privacy:** although blockchain is transparent, information obtained from each node is kept anonymous using cryptography.
8 **Reliability**: blockchains have been implemented successfully by many international market sectors and organizations for years. The reliable performance of blockchain is a result of its characteristics and firm structure.

The above-explained blockchain distinguishing features represent a source of remarkable value-adding roles in carbon trading markets which benefited and may further advance from blockchain in different ways.

4.2. Smart contracts

The emergence of blockchain made smart contracts one of the most popular technologies by adding a high level of customization to traditional transactions (Macrinici et al., 2018) currently performed in the carbon trading market. Basically, smart contracts represent real-world contracts in cyberspace and are binding enforceable agreements by law between two or more entities (Macrinici et al., 2018). Smart contract utility is defined as "*a software program that adds layers of information onto the transactions being executed on a blockchain*" (Sadiku et al., 2018). Reflecting this definition on our research, it is clear that performing carbon trading operations in a digital environment is a very important characteristic that smart contracts facilitate by creating automatically executed programs without human intervention when a pre-defined agreed to term(s) occur (Crosby et al., 2016). As a result, tasks and activities normally managed or executed by a central authority, intermediaries or third parties such as lawyers or carbon brokers are now transferred to the blockchain (Sultan and Lakhani, 2018). Obviously, and since smart contracts reside in the immutable blockchain, they may provide the security needed for carbon trading operations in a superior manner to those operations running under traditional contract law (Tang and Tang, 2019).

4.3. Blockchain classifications

Blockchain is classified according to ownership features and access management to public, private, and consortium (Wang et al., 2019; Zheng et al., 2018). The utilized type of blockchain usually depends on the design requirements and application field. In the suggested

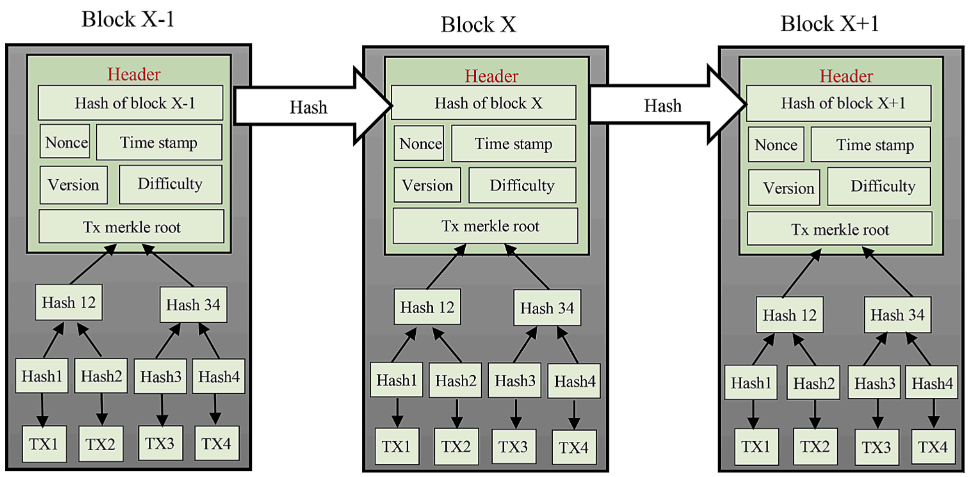

Fig. 4. Blockchain structure

framework, more than one type of blockchain is proposed as per the design purpose and characteristics of blockchain participants' operations structure. Therefore, it is necessary to explain the difference between the three blockchain categories.

1 **Public**, such as the ones used in cryptocurrencies network. It is a permissionless blockchain where transactions are public yet participants are kept anonymous (Wang et al., 2019). It is peer to peer, does not have a single owner, and visible by every entity in the network (Sultan and Lakhani, 2018). A public blockchain is a decentralized open ledger where anyone can use block explorers available online to explore and examine transactions (Murray, 2019).
2 **Private** is a permissioned blockchain that defines a list of permissioned users with particular characteristics to operate within the network (Casino et al., 2019; Wang et al., 2019). This type's ownership belongs to a single entity that controls block creation (Sultan and Lakhani, 2018). A private blockchain is usually used by organizations to record transactions or assets transfer data on a limited user base (Sultan and Lakhani, 2018).
3 **Federated or Consortium or Hybrid** (semi-private) blockchain is a combination of the public and private blockchain (Mougayar, 2016). It is public and permissioned to a pointed privileged node usually including a consortium of organizations (Helliar et al., 2020). In this type of blockchain, authorized gatekeepers verify transactions rather than unspecified random miners (Helliar et al., 2020).

A clear explanation of which type of blockchain to choose and how to utilize it in the carbon trading framework will be detailed in section 6.

4.4. Blockchain applications

Blockchain is successfully and reliably implemented in diversified fields such as entertainment, real estate digital identity, voting, insurance (Murray, 2019), healthcare, distributed cloud storage, Internet of Things (Wüst and Gervais, 2018), Artificial intelligence, finance and banking, digital assets management (Zheng et al., 2017) and more. One of its main implementation areas is supply chain, where blockchain is used to track products' origin and flow, detect counterfeit and fraud items, exchange information, and automate transactions using smart contracts (Kawa and Maryniak, 2019). Research by (Salah et al., 2019a) applied blockchain precisely in the agricultural supply chain due to its complexity and vastness and harvested the above benefits in developing a quality management tool for soybean. Their framework proposed integrating IoT with blockchain to monitor shipments making data trusted and transparent. Also, their approach used smart contracts to efficiently and securely perform business transactions for soybean.

Moreover, blockchain is used to develop proof of delivery solutions for different types of assets such as the system presented by (Hasan and Salah, 2018a). A blockchain-based proof of delivery (PoD) solution of shipped physical items was proposed to ensure accountability and integrity. This system automates the interaction between sellers, buyers, and transporters through smart contracts. Another research by (Hasan and Salah, 2018b) provided a decentralized blockchain-based proof of delivery (PoD) solution for digital media that are subject to payment such as videos and audio files. The suggested system is automated by using Ethereum smart contracts.

Furthermore, Blockchain has wide implementations in the energy sector, which is strongly related to our research since the majority of greenhouse gas (GHG) emissions are linked to energy production and usage (IRENA, 2018). Besides, with the pressures to reach net-zero emissions by the year 2050, there is an in-progress transition of energy decarbonization, digitalization, and decentralization (Ahl et al., 2020). This led to the introduction of the term "blockchain energy" by (Teufel et al., 2019) to describe the applicability of blockchain-based technologies in the energy sector. The researchers stated that blockchain energy covers energy trading, information storage, and energy flows transparent solutions. As per energy trading, prosumers benefit from blockchain to perform trading independently from energy supply companies which prevents manipulation associated with a centralized platform. Also, the traceability of transactions performed through smart contracts enables customers to identify the source of energy and therefore choose to obtain the energy from certain green sources. Additionally, smart contracts reduce costs endorsed by customers due to the elimination of third parties (Ahl et al., 2020; Goranović et al., 2017; Teufel et al., 2019). This enhances the role of small entities such as prosumers in the face of energy giants.

With regards to energy flow, Physical and information flows in energy systems are complicated which makes the existing centralized systems incompetent. Therefore, blockchain is capable of solving this issue by facilitating distributed, peer-to-peer trading platforms with increased security due to the adopted cryptography (Ahl et al., 2020). Also, blockchain supports sharing information and tracking its sources resulting in a transparent energy market (Ahl et al., 2020).

In a related application field, the increasing usage of electric vehicles is an important factor in reducing the released GHG. Blockchain could be effectively utilized in the electric vehicles industry to provide traceability to sources of power batteries (Kim et al., 2019) as well as to batteries' life cycle. This information is vital for long-term battery criteria evaluation (Wang et al., 2021). Also, charging companies can use smart contracts to manage the charging station infrastructure and strengthen their security (Wang et al., 2021).

The next subsection 4.5 demonstrates how blockchain can add value to the carbon trading sector and therefore successfully implement it to elevate the current practices.

4.5. Blockchain solutions and value-added roles in the carbon trading sector

Blockchain technology with its unique characteristics detailed above is capable of solving carbon trading issues as well as advancing current practices and operation schemes. In the following demonstration, the valuable role of blockchain in the carbon trading sector is detailed:

1 **Eliminate Third Parties, Intermediaries, and Central Servers** (Sharma et al., 2018) (Conti et al., 2018) (Salah et al., 2019b) (Kumar and Mallick, 2018): blockchain as a decentralized network eliminates the concept of central servers (Kumar and Mallick, 2018). In a blockchain, data is stored in a decentralized manner where each network participant would have an identical copy of all information that gets updated continuously. Also, data authentication processes will be achieved through blockchain's consensus mechanism without the need for central servers to authenticate data. As per data analysis, it could be performed with the aid of smart contracts residing on a blockchain. Those advantages are extremely important, especially for a large-scale carbon trading platform where new stakeholders continuously join the network, therefore, a decentralized structure is more scalable and does not suffer from single-point failure. Also, the elimination of central authority enhances the integrity and prevents manipulation of carbon trading network. This is because no single entity that could go corruptive intentionally or falsified unintentionally controls the flow, storage, and processing of data such as carbon budget calculations, carbon allowances allocation, carbon shares prices, and other vital information related to the effective performance of the carbon trading platform. Many researchers demonstrated blockchain applications that eliminate central authority such as (Khan and Salah, 2018) who suggested that "With blockchain, a centralized authority and governance, as that of the Internet Assigned Numbers Authority (IANA), is eliminated".

2 **Built-in Trust:** blockchain distributed structure and its adopted consensus mechanism provide trust in carbon emission reading and values since all joining nodes guarantee that the data remain tamper-proof. If all participants have the data and the means to verify that it has not been altered or falsified, then trustworthiness could be achieved (Reyna et al., 2018).

3 **Security:** blockchain cryptographic structure ensures data security and immutability. Due to block hashing, there is no way to alter data in any block unless the hashes of that block, along with all successive blocks, are recalculated again. That is nearly an impossible task. Besides, the distributed blockchain data records do not allow any falsified data authentications because it is mandatory to get the consensus of the majority of nodes prior to updating any of them (Kumar and Mallick, 2018). Therefore, security and immutability are guaranteed.

4 **Data Privacy:** The other part of the cryptographic structure of blockchain is based on private/public pair key, which ensures that only the assigned or targeted network entities would be able to access the data. This shall protect sensitive information related to the business processes carried on by certain manufacturers from getting disclosed while at the same time share the necessary carbon emission reading, allowances, and any generated KPIs necessary to perform a fair and beneficial carbon trading framework.

5 **Historical Action Records:** Information about carbon emission readings, allowances, budgets, prices, and trading are immutably stored in records and capsulated within blocks where they could be traced back to the very first activity or reading. This solves one of the challenges facing the carbon trading sector and assists in tracking the progress of the applied schemes and plans for future enhancements based on historical data.

6 **Transparency:** Entities participating in the CET market will have total visibility of the carbon allowances trading process. All nodes will be able to specify how and where allowances trading occurred (Reyna et al., 2018). Lack of transparency is one of the biggest challenges facing carbon trading frameworks because it opens the door for manipulating actions. Therefore, blockchain transparency is a valuable asset for the carbon trading sector that shall help it to achieve the target it was established for.

7 **Automation:** utilizing smart contracts is a significant feature that would add efficiency to the applied framework due to the high level of provided automation. When a carbon share that is intended to be sold fulfills specific conditions, the smart contract is triggered, and a certain value will be transferred. However, with the right preset conditions, integrity could be established and guaranteed as well. The contracts are coded and stored in the blockchain and would update in real-time and be able to execute carbon trading themselves (Tang and Tang, 2019). It is worth mentioning that these self-executed carbon shares transactions are trackable and irreversible, which, in addition to the elimination of third-party, reduce transaction costs significantly (Tang and Tang, 2019). As a result, high transactions cost is another challenge solved by smart contracts in addition to efficiency, integrity, and flexibility.

8 **Irreversible and Credible Transactions:** the structure of blockchain prevents double-spending which eliminated fraud transactions (Murray, 2019).

9 **Reliability and Robustness:** All the above-demonstrated blockchain features ensure its reliability when adopted in carbon trading frameworks. Also, blockchain reliability, along with the long history of its flawless implementation in many fields, ensures high robustness (Kumar and Mallick, 2018).

It is clear from the above explanation of blockchain added values that integrating this technology with CET market shall resolve many challenges facing it. The combined blockchain-CET system will utilize smart contracts in calculating the carbon budget and determine carbon allowance automatically and without human intervention. This in addition to providing a transparent and tamper-proof record of all logs which shall address the challenge of carbon budget calculation and prevent manipulation and abuse. As per the existing distributed CET markets, the integrated blockchain-CET system will establish a unified carbon trading market which shall eliminate the diversity of policies, unify the carbon allowances prices, and resolve the implications of the distributed markets. Also, in order to tackle the corruption and non-transparency in CET market, blockchain transparency and traceability characteristics enable holding corrupted entities accountable for their action. To address the complexity of allocating allowances, the combined system shall include the appropriate terms and conditions in the utilized smart contracts. This way, the allocation process shall be performed automatically and seamlessly without intervention from a central authority. The automated smart contracts can provide a transparent trading platform that shall facilitate fairness and equality between participants. Additionally, smart contracts can set specific terms and conditions to limit wealthy countries' power over the CET market by setting boundaries for acceptable traded allowances per participant. Moreover, since smart contracts get executed without intermediaries, the performance costs are reduced tremendously (Tang and Tang, 2019). Lastly, utilizing the concept of blockchain of things where sensors communicate using blockchain shall provide vital monitoring, tracking, and measurement tool for the released CO_2 as well as provide the CET market with trusted and secured information that is transparent to all parties. Regarding the issue of neglecting the heterogeneity of GHG emissions that faces the CET market, blockchain may provide trusted and transparent data records that shall assist governments in deciding on the best way to address this problem.

Blockchain benefits were recognized by researchers who proposed integrated blockchain-CET frameworks. Moreover, a collaboration between IBM and the Energy Blockchain Lab in China is established for the development of an emission allowances trading platform. This implies that the capability and strength of blockchain are not solely hypothetical but have an actual potential towards improving carbon trading mechanisms. Also, Massamba Thioye, the Co-Chair at United Nations Framework Convention on Climate Change, believes that blockchain can "strengthen monitoring, reporting, and verification of the impacts of climate action; improve transparency, traceability, and cost-effectiveness of climate action; build trust among climate actors; make incentive mechanisms for climate action accessible to the poorest and support mobilization of green finance" (Pigeolet and Van Waeyenberge, 2019).

Although blockchain proved to be a reliable and effective technology, its adoption is still slow, obstructed by many factors(Choi et al., 2020), and associated with risks (Crosby et al., 2016). While decision-makers sometimes prefer to play it safe, others have limited resources or perceive the supposed blockchain benefits to be insufficient (Choi et al., 2020). Also, it is known that blockchain started as the backbone of bitcoin in 2009, however, it is way after that when other blockchain applications were revealed. This late implementation of blockchain in other fields is affected by the inaccurate accusations that blockchain is mostly a means of illegal activities which aggravated the slow adoption of the technology (Woodside et al., 2017). Another reason behind the slow adoption of blockchain is bootstrapping which is transferring frameworks and associated documentation from current business practices to the new blockchain platform which is a huge task that consumes time and money (Crosby et al., 2016). Also, introducing a new technology could be a complicated and lengthy process for companies (Choi et al., 2020). Furthermore, blockchain standardization is considered to be an important issue since it provides guidance for developers and customers (Zhao et al., 2019). Till now, there is no global legal compliance code that governs blockchain implementation which represents an issue mostly for service providers (Atlam et al., 2018).

The slow adoption of blockchain resulted in a limited number of blockchain-based frameworks for the CET market. In order to design our framework, we reviewed previous researches proposing frameworks that implement blockchain in the carbon emission trading market and evaluated their contribution as detailed in the following section 5.

5. Literature review of existing carbon trading frameworks

Blockchain's rise has a remarkable influence on the evolution and progress of sustainable practices, especially carbon emission trading. However, current blockchain applications in sustainability are considered to be in the primary stage (Fu et al., 2018). The intend of this section is to review the existing frameworks that propose blockchain as a solution for carbon trading. The section highlights the contributions and limitations of these suggested frameworks in order to propose a comprehensive conceptual framework.

Blockchain is promoted as a distributed digital ledger that enables the transformation of the CET market. However, the literature only reports on creating new market schemes, and little has been addressed to implement blockchain in advancing the existing market to achieve the intended goal of carbon trading of environmental protection and sustainability.

One of the frameworks found in the literature is (Ashley and Johnson, 2018), the CEO and founder of Clean Energy Blockchain Network (CEBN) in the U.S.A., which joined silicon valley power in supporting participation in low carbon fuel standards (LCFS) program. The study explained the shortcomings of conventional renewable energy systems. CEBN company implemented a blockchain-based system to generate renewable energy credits (RECs), which represent one megawatt-hour (MWh) of clean energy fed into a grid, and carbon credits, which represent one metric ton of avoided CO_2-equivalent. Authors utilized data collected from smart energy meters and input it into a cloud database that generates meter identification and energy production data. However, Tokenizing credits, awarding, trading, and retiring them are done through blockchain. The established blockchain-based trading system is transparent, secured, fast, and automated due to using smart contracts in generating credits. Also, their system reduces the time and cost associated with trading, tracking, redeeming, and auditing carbon credits and RECs. Consequently, credit purchasers are paying less while energy producers make more profit. Researchers did not provide any details regarding their framework. They only facilitated credit trading using blockchain without changing trading rules or impose additional integrity trading conditions that support sustainability. Also, smart contract codes were not revealed. However, they argue that supporting trading will encourage more customers to join.

A carbon asset management (CAM) system framework based on distributed carbon ledger (DCL) was proposed by another research by (Tang and Tang, 2019). The presented Blockchain-enabled DCL suggests integrating organizations' carbon asset management with European Union (EU) emission trading schemes (ETS). The system network nodes may share CAM data. Also, as part of the framework, government creates digital carbon allowances and distributes them using DCL. firms trade their allowances using smart contracts and surrender their digital allowances and carbon report to the government via DCL. The framework facilitates management activities through smart contracts by linking the organization's carbon accounting system with ETS. The suggested framework enhances reliability, traceability efficiency, auditability, and reduces transaction costs. The framework tackles double-counting and emission leaking issues. However, carbon measurement is not included in the framework. Also, the researchers did not detail the smart contract utilization and did not discuss carbon assurance, and carbon financing.

Also, (Hartmann and Thomas, 2019) presented a framework for the Australian carbon market using process design which improves efficiency, equity and effectiveness. The suggested framework depended on discrete design decisions at four decision stages: decentralization, computation and storage, blockchain configuration and other design decisions. The first stage starts with decentralizing trust, however, the decentralization decision is taken by a trusted authority which sets the role of permitter and verifier in the blockchain. The second stage decides on data storage (i.e. whether it will be on-chain or off-chain) and computation method (i.e. whether to use a direct transaction or a complicated smart contract). The third stage is the blockchain configuration protocol which enables the system to be updated when an agreement is made. The last stage could be upgraded to improve security and scalability as well as to make a decision on establishing a new blockchain, connect to the available one or adopt multiple blockchains. Lastly, the fourth stage tackles other design decisions, such as anonymity degree, system's supporting incentives, and blockchain deployment method. The framework, as implemented in the Australian carbon market, supports decentralization and enhances transparency, security, efficiency, and reduces transaction costs. However, the framework's major limitation is its dependency on document analysis without validation support.

Furthermore, (Hua and Sun, 2019) demonstrated a blockchain-based trading framework combining energy and carbon markets. The suggested framework's main objective is to tackle the problem of imbalances and leakage during energy transformation, in a centralized market. The framework consists of three stages, and it enables the prosumers to buy and sell energy and carbon allowances by peer t peer connection. The first stage supports ownership of token while the second stage includes blockchain model selection which enables secure transactions and address generation. The final stage supports a carbon emission trading mechanism which involves tracking prosumers and carbon footprints using a virtual concept. Also, the final stage tackles the incentive mechanism that provides monetary compensation to reward participants for reducing their carbon emissions based on the revenue generated from trading carbon credits. Prosumers will be able to receive compensation only if they consume less carbon allowance. The framework facilitates cost and carbon emission reduction. However, the peer-to-peer trading system increases the complexity of carbon tracing and degrades the carbon emissions accounting process.

Moreover, (Khaqqi et al., 2018) presented a reputation-based emission trading framework utilizing blockchain technology. The framework aimed at resolving the problem of fraud and enhance emission trading management. This emission trading system is referred to as BCRB since it combined blockchain and a reputation-based mechanism of trading carbon emissions. The Blockchain part of the scheme supports carbon emission trading by monitoring, reporting, verifying carbon permits as well as providing transparent, immutable records of data required for the scheme. Also, the proposed framework implements strict trading rules associated with the reputation system and inputs them to an algorithm that regulates transactions. In this case, blockchain only guarantees the immutability of the data but fails to ensure its credibility. Therefore, to achieve information credibility, smart devices or meters should be utilized as an input source. The BCRB plays four main independent roles in the carbon emission trading system: authority, firm, sanctioned projects to generate and sell certified emission reduction units, and auditor to determine the reputation of the firm by evaluating its emission rates and strategies. The drawbacks of the framework are those of blockchain itself, which are for example a shift in paradigm, resources required to keep multiple records copies, and the response of participants to any shift. The Reputation-based trading system which is part of the framework consists of a mechanism for market segmentation and priority-value-order using the Reputation points. The Reputation points(RP) decides on participants' access. Whereas market segmentation manages the distribution of access based on which participants can collect offers or be deprived of better offers if they have lower reputation points. Besides, priority-value-order acts as a sorting mechanism that reflects on reputation-price. The reputation-based framework supports a long-term solution to emission reduction, but it also leverages the participants to force the market price. Thus, the BCRB complements the existing CET market with transparency, the ability of implementation in any environment (whether it is existing or new), or motivation using financial incentives and e elevated public perception. However, certain uncertainties appear which impede the merit of BCRB. Also, the framework does not explain the reputation source, and the priority value does not reflect the transaction.

Moreover, (Liang et al., 2019) presented a reputation-based double blockchain framework for ETS. The framework aimed at enhancing the efficiency, security, and privacy of the ETS by encouraging companies to improve their reputation by reducing emissions. The framework used the double-blockchain architecture to handle transactions independently from the confirmation and financial chain which results in reducing redundancy and improving security. In the framework, organizations can improve their reputation by increasing their investment in emission reduction through a reputation-based fee mechanism. The framework enables companies to become either a seller node, buyer node, or a node that addresses other needs. The transaction objects are open to all sellers and buyers. The confirmation chain determines the intent of the transactions and helps buyers and sellers agree on the terms while the financial Chain handles funds circulation. The chains in place complete a transaction in three stages, firstly, the company accesses the confirmation chain to target its trading requirement. A transaction is considered complete after block verification, which then becomes accessible in the confirmation chain. Secondly, the financial chain will be fed with the transaction information that includes the public key, reputation value, quantity, and amount of the transaction, using the communication channel. Finally, the flow of funds can be completed using a financial chain involving a transaction fee. Once generated and verified the legal financial block is inserted in the financial chain. The proposed framework allows a speedy transaction, improves security, and difficult to tamper with data because of double blockchain. However, certain drawbacks that challenge the merit of the framework are initial data acquisition, the process for determining the transaction fees, allocation, and collection of the transaction fees.

Additionally, (Pan et al., 2019) presented blockchain for the carbon emission trading market by demonstrating the similarities between them that synchronize their processes. The article clarified that blockchain as a decentralized database fulfills the need of the carbon trading market which includes assessing, storing, and managing carbon emissions data. The framework consists of three parts: registration system (responsible for generating, storing and managing carbon emission quotas), carbon emissions trading system (responsible for carbon emission quota transaction), and corporate carbon emissions management system (handles corporate carbon emissions calculation) using blockchain accounts which enhance system efficiency and saves on maintenance cost. Additionally, the framework supports point-to-point transactions between participants. The framework provides useful features such as considering firms' emissions regardless of their size and reduce the entry threshold for CET markets.

Lastly, the advantages of blockchain were demonstrated in (Niya et al., 2018) which proposed a pollution monitoring system based on automatic measuring, storing, and monitoring of environmental qualities for water and air. The research is based on a low power consumption protocol combined with blockchain. In the framework, data is transmitted between the IoT sensors, Blockchain, and the LoRa network. This shall ensure the security and immutability of data stored on a local database once retrieved using blockchain for processing. The literature findings for blockchain-based carbon trading systems are summarised in Table 2.

From the above table, it is clear that most limitations of the existing blockchain-based carbon trading systems found in the literature revolve around the lack of trading boundaries, measurement authenticity, unified global platform, and initial data acquisition and transfer method. Those drawbacks are addressed by our proposed framework, which shall adopt a comprehensive architecture that used the concept of BoT to assure measurements and data authenticity and integrity as well as smart contracts to set up a fair trading mechanism. Also, governments are included in the framework to play an important role in implementing the CET scheme which other frameworks do not account for.

6. The proposed framework: a comprehensive and hierarchical blockchain for emission trading system (CHBETS)

This section aims to propose a comprehensive carbon emission trading framework based on multiple level blockchains with distinct types and roles in a hierarchical blockchain network, referred to in this research as (CHBETS). The blockchain entries in the framework represent transactions, contracts, assets, identities, or practically anything else that can be digitally expressed using smart devices. However, any required input information that can not be captured by smart devices could be obtained by integrating the organization's ERP system with the blockchain.

The intent of using a multi-level blockchain network that comprises of a public blockchain (Government, factories, stakeholders, warehouses, individuals of the community) and private or consortium blockchain (standalone carbon-emitting entity) is:

- Initially to ensure the privacy of participating individual organizations and the safety of their trading and manufacturing secrets as they often feel reluctant to share their confidential manufacturing processes with others especially competitors and stakeholders. It is known that blockchain users can be identified by transaction behavior (John, 2015; Tasca et al., 2018). Therefore, performing emission measurement in a separate blockchain from the allowance trading blockchain will provide more privacy for participating companies. As per trading carbon allowances, it is preferable to transact them openly in a public blockchain opposite to transferring cryptocurrencies such as bitcoin since identifying sellers, buyers,

Table 2
Blockchain-Based Carbon Trading System Frameworks

SN	Research	Contribution	Limitation
1	(Ashley & Johnson, 2018)	Transparency, security, automated, reduced time & cost	Local platform, lack of trading boundaries, revenue centered, no data authentication scheme, smart contract not explained, no governmental role
2	(Tang & Tang, 2019)	Trust, reliability, traceability efficiency, auditability and reduces transaction costs, addresses double-counting and emission leaking issues, government role exists	Lack of integrity rules and trading boundaries, accounting centered, no input data authentication scheme, smart contract clauses not explained, no validation for framework
3	(Hartmann & Thomas, 2019)	Transparency, security, reduced costs, scalability, efficiency, and disintermediation of the market	The framework depended only on document analysis with no validation support.
4	(Hua & Sun, 2019)	Addressing the imbalances and leakages during the transformation such as energy and carbon reduction imbalances and leakage of residential privacy in a centralized market.	The trading system increases the complexity of carbon tracing and degrades the accounting process of carbon emissions.
5	(Khaqqi et al., 2018)	Addressing fraud and emission trading management, Transparent, easier to be implemented in any environment, or by motivating through direct financial incentives and improved public perception.	Uncertainties exist that impede the merit of BCRB, additionally, the framework lacks any explanation over the reputation source and the priority value does not reflect the transaction.
6	(Liang et al., 2019)	Improving efficiency, security, privacy of the ETS, allowing speedy transactions, difficult to tamper with data because of double blockchain.	Certain drawbacks that challenge the merit of the framework are initial data acquisition, the process for determining the transaction fees, allocation, and collection of transaction fees.
7	(Pan et al., 2019)	Supporting seamless system, reliable, save cost, consider company's emission regardless of size.	The framework was based on theoretical advantages and disadvantages.
8	(Niya et al., 2018)	Secured, untampered, and fast data processing.	Data is stored on a local database and transferred through LoRa to blockchain which makes data vulnerable

price, and amount of traded allowances are desirable to increase system integrity. In our case, privacy is vital for companies' internal processes and manufacturing secrets which might be exposed when implementing BoT on a public blockchain. The major issue other researchers' frameworks fail to address is that a public blockchain allows data transparency to all included parties while we introduce a permissioned blockchain (lower measurement level) based on BoT that shares only the relevant CO_2 emission data to public blockchain under full understanding, acceptance, and agreement between the government, company, and relevant stakeholders. Therefore, our hierarchical structure provides the balance between organizations' internal privacy and allowance trading transparency.

- Secondly, to save GAS which is an incentive that should be paid for every running node during the implantation of smart contracts. The multi-level blockchain reduced the unnecessary nodes running smarts contracts.
- Thirdly, the multi-level design addresses the time issue as blockchain tends to grow bigger, blocks require more time to propagate which causes delays.
- Finally, the consensus algorithm in a large blockchain is more difficult to process. Therefore, multi-level blockchain allows each level to implement its own algorithm such as upper application level public blockchain will adopt POW or POS, and the lower measurement level blockchain adopts a lighter algorithm that saves time and power such as PBFT (Practical Byzantine Fault Tolerance).

In a related context, the carbon emission trading market adopts two different approaches for price levying which are: carbon taxes and tradeable permits. The approaches differ in terms of their mechanisms of determining the price. The carbon taxes approach adopts a fixed price mechanism determined by policymakers whereas the tradeable permits approach takes into account the supply and demand to determine the price. Literature reports on the benefits of both the approaches as equally effective, while some prefer the one over the other (Breidenich et al., 1998; Protocol, 2010). However, the tradeable emits often referred to as ETS or cap-and-trade scheme is the largest scheme for trading that is adopted by over 25 nations. Therefore, this framework will adopt the tradeable permit approach or emission trading system based on several essentials elements defined under the Kyoto protocol (Protocol, 2010) such as:

- **Scope** (decision about economic and industrial sectors and the type of harmful gases to be addressed).
- **Cap Allocation** (determine emissions limit, reduction goals, permits/allowance amount, time period, and flexibility ratio (unused permits/allowances to be used for future cap).
- **Permits/Allowances Distribution** (Distribution through either free allocation, auction, or their combination).
- **Offset Policy** (specifies what type of offset in terms of source or amount can be used in the scheme),
- **Trading Mechanism** (guidelines of emission trading).
- **Monitoring/Reporting and Verification (MRV) Procedure**.
- **Expansion Potentials** (allows the flexibility to link ETS with other ETS or use them in additional sectors).

Furthermore, the framework considers the government's role as essential and vital. Governments need to monitor and implement sustainable approaches in free business and industrial sectors in order to force them to choose the environment over profit and sustainability over economic growth

In our framework government enforce setting up a carbon sensing and calculating system (CSCS) which is a private or a consortium blockchain connected to CO_2 measuring devices. Thus, it requires sensors and smart meters to be set at the right places within factories, manufacturing production lines, warehouses and their entrances or exits, and other private and public premises to measure the released CO_2 in premises. The setup spot for CO_2 sensors is critical and should be tailor-made by a specialized company and follow rules and guidelines specified by authorities' experts to achieve the purpose of the whole system of providing accurate and correct values of the released CO_2 gas. The CSCS is similar to fire alarm systems or CCTV systems that the governmental authorities oblige firms and organizations to set up and run. For most governments, trade licenses are not renewed, and fines are imposed on any businesses that violate these laws. We, therefore, propose issuing similar laws to set up Blockchain CSCS with the same mechanism of fire alarm systems where authorities overview implementing those systems and arrange periodical supervision on them. Similar to the fire alarm system, any premises which miss on establishing, maintaining, and utilizing them the proper way or vandalize them shall be fined and legal actions shall be taken against them. Also, as there are special companies responsible for designing, wiring, and applying the hardware and software systems for CCTV, alarm systems, and fire detection systems, there will be specialized blockchain developers for designing and implementing CSCSs for factories, offices, warehouses, and facilities. In addition, Governments in association with experts should layout CSCS guidelines for each type of plant, premises in line with the carried-out manufacturing or services process and nature of the corresponding sector. This represents the lower measurement level in our hierarchical blockchain system. At this level, CO_2 emissions are measured and detected using sensors and smart meters connected to the consortium or private permissioned blockchain in what is called BoT. The lower measurement level blockchain is responsible for storing the emission data immutably and securely in the permissioned blockchain. Additionally, the CSCS permissioned blockchain assists in determining the carbon allowance based on the released CO_2. The Blockchain of Things adopted at the lower measurement level permissioned blockchain which is often referred to as BIoT, BoT, or BCoT is “the fusion of Blockchain and IoT technologies where both can benefit from each other in a reciprocal manner” (Miraz, 2020). It was found that BoT offers tamper-proof recording, distributed architecture (no single point of failure or single point of attack), trusted consensus, transparency yet privacy for smart contracts’ input data. Therefore, BoT was adopted as one of the technologies to address carbon emission trading.

Our proposed framework is novel because it is the first among all other suggested solutions for carbon emission trading that incorporate the BoT paradigm where sensors are directly connected to a blockchain. Blockchain of Thing (BoT) has gained popularity recently with a paradigm shift in the research towards integrating the standalone technologies of Blockchain and the Internet of things. The internet of things (IoT) is defined as a system that connects physical devices and computing platforms over a network. The devices include sensors, actuators, computers, mobiles, and users that are connected together over the internet. However, using the wireless sensor network technology as a platform to operate, make IoT vulnerable to security and privacy threats. Therefore, integrating Blockchain with IoT addresses the limitation of these standalone technologies as blockchain is based on consensus and cryptographic techniques that ensure untampered, immutable, and verifiable data. Thus, making them complement each other which can revolutionize the future as argued by (Miraz, 2020). The BoT being the promising future technology has been adopted by many academia and scholars in their research areas such as Transportation (Cebe et al., 2018; Leiding et al., 2016), Transactive energy(Laszka et al., 2017), Smart cities and homes (Dorri et al., 2017), Drones and Robots (Liang et al., 2017) and Manufacturing (Bahga and Madisetti, 2016; Liang et al., 2017; Rabah, 2017).

Previous research work and practical implementations of blockchain in carbon emission reduction depended on providing the required data to facilitate a carbon trading system through other systems or where human intervention is present or possible. Although this ensures the security and immutability of the input information and the following transactions, it does not ensure the credibility of this data which is the base for related calculations, decisions, and actions. Our framework fills this gap and addresses the limitations of existing frameworks by utilizing BoT which ensures the credibility of input data as well as its immutability and security. Consequently, provide credibility to the calculations and decisions based on those data.

As per the upper application level of the framework, it consists of a public blockchain that uses another set of smart contracts to perform carbon emission allowances trading between buyers and sellers. The concept of emission trading was initiated under the Kyoto protocol where nations can obtain offsets using mechanisms such as Joint Implementation (trading between developed nations) or Clean development nations (CDM) (trading between developed and developing nations). The Clean development mechanism allows the developed countries to help evolve the less-developed countries by investing in green technology and infrastructure (McKibbin et al., 1999). In return, the developed country can claim emission reduction in terms of credit. It is worth mentioning that extra carbon units are called carbon credits. Also, the lower a country cap is the more expensive its allowances are. In the proposed framework, smart contracts are used to monitor and cover excessive CO_2 emissions by performing carbon offset transactions to renewable energy projects such as wind farms, tree-planting activities, energy efficiency retrofitting (to reduce heat loss), efficient transportation, and reduction of potent industrial greenhouse gases (Kim and Deka, 2019).

Having defined the significance and purpose of the lower measurement level (private or consortium blockchain) and upper application level (public blockchain) it is important to adopt a protocol that allows seamless data sharing and transfer between them. At the transfer stage, the CSCS will transfer the required data through the appropriate protocol (such as Polkadot, Interledger, or Hyperledger Grid) from the low-level consortium blockchain to the upper-level public blockchain where CO_2 emission and surrender reports will be generated that will be shared among all the nodes.

Furthermore, another significant concept adopted in the framework is carbon asset management that allows recording, measuring, controlling, and reporting the allocated carbon allowances, investments made, capital expenditures, carbon mitigation capacity, and usage of renewable energy. Besides, the use of blockchain aids in improving management at firms and national levels by developing the carbon credit or reputation-based trading system. The asset management system can be used to address any flagged activity which has been embedded by the parties in the smart contract such as changes in production conditions, energy over-consumption, different raw materials, or change in the carbon performance. However, the limitation of carbon asset management is the accounting issues for carbon performance monitoring, measurement, authentication, and reporting (Tang and Tang, 2019).

This multi-level framework utilizes blockchain’s decentralized architecture and features of transparency, immutability, and security in addition to a specially designed smart contract code to overcome the limitations of existing carbon asset management practices. The framework addresses the following carbon asset management elements:

- **Carbon Control** manages green technology initiatives by allowing planning, monitoring, and evaluating green programs, investments, and project management.
- **Carbon Performance** measures carbon reduction and allows stakeholders, employees, managers, supply chain partners to increase the carbon performance capacity by contributing towards the performance assessment.
- **Carbon Asset Verification and Assurance** verifies and audits carbon footprint constantly and in real-time.
- **Carbon Asset Reporting** allows for transparent and real-time based asset reporting to make decisions.
- **Supply Chain Carbon Management** allows the strengthening of links between supply chain partners to control and minimize the carbon emission footprint. (Tang and Tang, 2019).

It can be summarized that the European Union has developed a single database for tracking the emission trading system. However, as discussed in section 3 regarding the challenges facing the carbon trading system, the question often arises on its transparency and integrity as the system is prone to data fraud. We, therefore, in this framework provide an upgraded comprehensive global alternative trading platform that addresses the same goal but with higher efficiency and additional features thus adding value to the existing trading system. Also, since the existing system has been deviated from its primary purpose and becomes part of the materialistic market and a tool for organizations to twist to serve their interest, we propose adopting governmental legislation to facilitate the implementation of the proposed framework. The framework with its comprehensive design ensures integrity in carbon allowance trading by utilizing smart contracts as well as facilitate enhanced end product carbon emission minimization by carefully adding clauses.

The hierarchical blockchain network enables more stakeholders integration and engagement and makes the unified carbon emission trading market easier to join and expand, therefore, enhance the scalability of the system. Also, our framework does not offer any trade-off between the environment and any other prospective or goal such as reducing operational cost or optimize supply chain operations as some other frameworks did. The proposed framework is specially designed for carbon emission trading, but the foundation should be set for future expansion to include other GHG because the end goal of the framework is to take into consideration the concentration of gases, not to disturb that in a certain geographical area.

6.1. Framework discussion and design

The intend of this section is to discuss the functioning and significance of the proposed framework for carbon emission trading system. The proposed framework consists of three levels: Upper application-level Public blockchain, Lower measurement-level consortium blockchain, and a cross transfer level.

6.1.1. Upper application -level public blockchain

The upper-level public blockchain is where governments around the world distribute carbon allowances among and within them. Also, the same blockchain supports organizations' allowances trading and offsetting operations. The distribution, trading, and offsetting of carbon shares are secured, transparent, immutable, and traceable because they are all recorded on a public blockchain. The public blockchain from its name is open to all governments, companies participating in the ETS, public people, non-profitable concerned organizations, clean energy projects, and tree planting activity projects. In the upper-level public blockchain, the following procedures take place:

- **Allocation Processes:** governments distribute allowances among them and then each government distributes its allowances as per their cap to its companies and entities as per the latest percentages and ways agreed on internationally in terms of how many allowances are allocated free and how many are auctioned. The fact that these processes are performed on a public blockchain (upper-level blockchain) ensures the transparency of each government's performance in front of the whole world, thus addressing the corruption issues within governments.
- **Smart Contracts Automation:** the allocation process of allowances is performed automatically by smart contracts and this is an addition to preventing corruption within the system governance. Smart contract terms and conditions are written in a way that follows the agreed-on allowances distribution percentages and it will be fed by the input which is the allowance specified for each country. Thus, allowing the smart contract to run automatically and transparently to distribute them to the nodes (companies) that fulfill the terms of the contract. Besides, a smart contract reduces the fees of transactions, running overhead of the system, errors, and time. Though smart contract requires incentives or an execution fee for nodes to run them which is called GAS, however, that is much less cost compared to traditional transactions costs. The smart contracts thus perform the following roles:
  - **Auctioning**: which ensures integrity, reduces cost, time, and increases trust. All data related to allowances distribution and auctioning is kept forever immutably and could be traced back at any time. Also, companies will be transparent about the amount they receive.
  - **Trading***:* occurs in upper-level public blockchain between firms who emit more CO_2 than their allowance where they buy allowance from other companies emitting lower than their cap. Thus, smart contracts ensure the integrity and ability to achieve the sustainable goal that the scheme was initiated to fulfill in the first place such as prevent price manipulation by selling allowances at a high price and re-buying them at a low price, prefer trading among the same supply chain partners to enhance end product sustainability and reduce its total carbon emission during the whole supply chain, and other terms.
- **Carbon Offsetting:** where extra allowances are offset by buying shares from renewable energy companies. This process is entirely carried on by smart contracts. Carbon offset management performed in the public upper-level blockchain is called carbon control activities.
- **Carbon Asset Management (CAM)***:* blockchain and smart contracts overcome the limitations of carbon asset management and its elements which are: carbon control, carbon performance, carbon asset verification and assurances, carbon asset reporting, and supply chain carbon management. The way blockchain performs CAM is by sharing input data from sensors (BoT concept) as well as other needed information in a decentralized manner between nodes and code all calculations and decisions using smart contracts algorithms.
- **Surrender Process**: takes place using another set of smart contracts where at the end of a specified period, all participants are required to surrender the relevant amount of permits along with reports on the amount of emission produced during that period.

Once the companies got their allowances, they are allowed to produce only the permitted amount of CO_2 as per their allowances whether they were obtained freely or by auction for the subsequent year. This is where the lower measurement level comes into place.

Design aspect: the upper-level blockchain could be implemented using a multichain blockchain which is an off-the-shelf platform derived from Bitcoin Core software blockchain and have the same concepts of mining and financial transactions. Also, it supports smart contracts, which are called chain codes. Similar to Bitcoin Core software, MultiChain supports Linux, Windows, and Mac servers and provides a simple API and commandline interface (Gideon Greenspan, 2015).

Another design method is to build a new Ethereum project. Ethereum blockchain is known for being the first to support smart contracts. Also, its currency, Ether, is well trusted and the blockchain is highly secure (Ethereum, 2020). The above two blockchains can be public for interested parties to join as nodes.

A third design and implementation way is to build a new blockchain dedicated to the carbon trading market and establish a currency for the purpose of trading allowances, which, for instance, could be called C-Coin.

Whatever the implemented design for the upper-level public blockchain, a registry service could be used to register companies, governments, green projects, and global organizations and provide them with access to the related smart contracts. Therefore, the unregistered public individual may access the framework for monitoring only. This scenario depends on the design of the algorithm of the smart contract.

Users' interaction with blockchain can be done by building a user-friendly frontend application working on top of this blockchain. The front-end application will be written in one of the famous front-end technologies such as HTML and javascript, so we build a Webpage or a special application for users. Connecting the front-end to the blockchain is done using specially designed libraries provided by the blockchain platform and compatible with it. For Example, there are libraries available for Ethereum such as web3.js (the heaviest and bigger size) (Ethereum, 2016) and ethers.js (simpler and smaller so frontend will not lag) (Moore, 2016). Both libraries are built using javascript and support HTTP, so those libraries should be included in the javascript of the frontend application and the javascript will start interacting with it. At the same time, these libraries will make sure that users are interacting with the smart contract and the blockchain network.

6.1.2. Lower measurement-level permissioned blockchain

In the low-level permissioned blockchain, the following procedure occurs:

- The emission measurement data is directly received from sensors and meters, which are then stored on the low-level blockchain; it will be securely saved and immutable to alteration, so no corruption can occur at this level.

- The data will then be matched with the allowances using a special set of smart contracts that will calculate whether the allowances are consumed, or the company needs to buy or offset these allowances. This blockchain is called CSCS. The sensors will also be used to monitor the emission and give inputs for the surrender process and reporting.

Design aspect: One of the proper projects for this low-level blockchain is Hyperledger project which is an umbrella of open-source blockchains and related tools. It is specially designed for enterprises and has received contributions from IBM, Intel, and SAP Ariba (Linux, 2020). We recommend Hyperledger fabric and Hyperledger composers as they support smart contracts.

Our Framework design is based on connecting the low-level blockchain to CO_2 sensors and meters using the BoT concept. To enter data generated from IoT devices to Hyperledger Fabric blockchain, a lightweight remote procedure call (RPC) protocol called JSON-RPC should be used. Requested shall be initiated through this protocol and sensors' data would be running through this protocol as JASON messages (JSON-RPCWorkingGroup, 2013).

Sensors wiring and connection could be done using node-red which is an IoT network for programming IoT devices so it is incorporated with Hyperledger Fabric to get data from IoT devices and feed and process information into a blockchain (Node-RED, 2020).

Users' interaction with the hyperledger blockchain can be done by building a user-friendly frontend application running a software development kit (SDK) with it. The hyperledger provides different SDKs for interaction with frontends such as java SKD, python SDK,node.js SDK, etc. depending on the language used in build the frontend interface application (Linux, 2020).

Another suggested design is a BoT based framework proposed by IBM known as IBM Bluemix-based Hyperledger services. The framework is based on two parts: the Bluemix blockchain and the Watson IoT platform. The blockchain handles the transactions, consensus process whereas the IoT platform gathers the data through the sensors, which is then sent in terms of chain codes that enable smart transactions to be completed in the Bluemix blockchain (Kim and Deka, 2019).

6.1.3. *Cross transfer level*

At the transfer stage, the CSCS will transfer the required data through either polkadot, interledger or Hyperledger Grid protocols from the low-level consortium blockchain to the upper-level public blockchain where

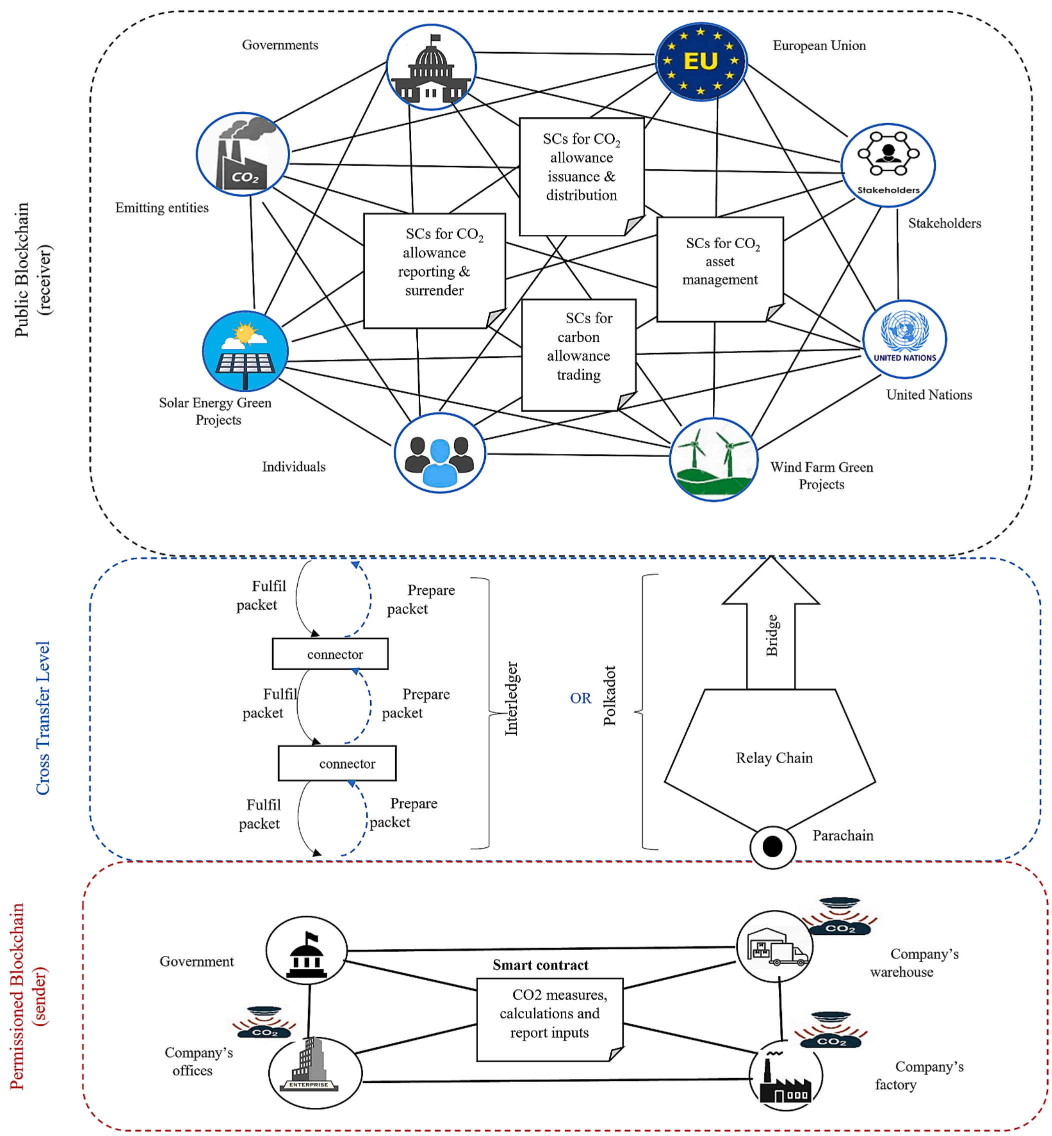

Fig. 5. A Comprehensive and hierarchical blockchain for Emission Trading system (CHBETS)

reports will be generated and shared among all nodes.

The widely used protocols are:

- **Polkadot Protocol** that allows cross transfer between multiple blockchains to connect and operate seamlessly, the protocol allows interoperation between multiple blockchains in the Polkadot network where any type of data, asset, and tokens can be transferred. The network allows the chains to remain independent in terms of their governance and united in terms of security (Polkadot, 2020).
- **Interledger Protocol** refers to the interoperability between different distributed ledgers (Blockchains), the protocol allows the flexibility of transferring cryptographically linked information between multiple chains (Siris et al., 2019).
- **Hyperledger Grid** is a major project under the umbrella of Hyperledger for interoperable blockchain. It could be used for the implementation of a centric model that combines multiple blockchains (Linux, 2020).

Two of the above-explained protocols namely, polkadot and interledger are shown as illustrative examples in the framework drawing Figure 5.

As noticed from the above, different technologies could be used to implement the design aspect of each level in the framework. This is due to the individuality and diversified specialty of organizations and entities participating in this framework. Having multiple design options facilitates covering companies with all types of business activities in order to join the CHBETS framework. The Comprehensive and Hierarchical Blockchain for Emission Trading System CHBETS framework is shown in Figure 5.

As seen from the figure, the proposed framework is a cycle, therefore, the procedure of allocation, auction, trading, surrender, carbon asset management (Control, monitor and reporting) is a continuous process. Governments monitoring activities and fining illegal ones are performed in the public blockchain-based on reports input data collected from the lower measurement level. So, report forming, and the actions based on these reports are carried on in the public blockchain. It can be summarized that the proposed framework, offers an upgraded comprehensive global trading platform that addresses the challenges and limitations of the existing system as shown in Table 3.

The table therein, explains the significance of the proposed framework for the existing carbon emission trading system and markets.

Table 3
Challenges addressed by the proposed carbon trading system

Challenges of carbon trading	Framework elements
Carbon budget calculations are open to manipulation.	• Auctioning is performed by **smart contracts** to ensure integrity. • **CSCS** permissioned blockchain assists in determining the carbon allowance based on the released CO_2. • **BoT** ensures tamper-proof recording, distributed architecture, trust, and privacy.
Corruption, non-transparency, and lack of integrity.	• **Multiple blockchains** ensure the safety of trade and manufacturing processes secrets. • **BoT** shares CO_2 emission-related data only with public blockchain under a full agreement between the government and the firm. • **Smart contracts** perform carbon allowances transactions between buyers and sellers, facilitate enhanced end-product emission minimization by adding specific clauses. • **Polkadot/Interledger/Hyperledger Grid protocol** allows the flexibility of transferring cryptographically linked information between multiple chains.
The allocation process of carbon allowances is complex.	• **CSCS consortium blockchain** assists in determining the carbon allowance based on the released CO_2. • **Carbon asset management** allows recording, measuring, controlling, and reporting carbon allowances that ease up the allocation process. • **Smart contracts** perform allocation processes among and within governments utilizing CSCS and CAM performed on the blockchain. • Distribution of allowances is done on the **public blockchain**.
Lack of tracking measurements of emission.	• **Sensors and smart meters** measure and detect CO_2 emission. • **Permissioned blockchain** stores data immutably and securely. • **BoT** ensures tamper-proof recording, transparency, trust, and privacy. • **Carbon asset management** allows recording, measuring, controlling, and reporting the allocated carbon allowances.
No unified carbon trading market.	• **BoT** ensures a unified way of capturing input information • **The hierarchical blockchain** network facilitates stakeholder's integration and makes the unified CET market easier to join and expand and enhances the system scalability. • **Public upper-level blockchain** provides a unified platform for the CET market.
High transaction costs resulting in less participants.	• **Smart contract** runs automatically and transparently in allocating, trading and offsetting allowances once contract terms are met, which reduces transaction costs.
Firms can buy credits without considering the negative impacts of unfair trading.	• Governments enforce using **CSCS** which includes smart sensors in businesses and industries to monitor their practices and impose fines on whoever misses the rules. • **Smart contracts** handle carbon offset transactions to cover and monitor excessive CO_2 emissions to renewable energy projects. • **Smart contracts** ensure the integrity and achieve sustainable goals and prevent price manipulation.

7. Conclusion

The greenhouse harmful gases emissions have been a major concern for environmentalists around the world for a long time due to their significant impact on the earth's temperature, causing what is known as global warming. This phenomenon is highly dangerous and could affect humans' development nevertheless existence. Therefore, countries around the world agreed on reducing CO_2 emissions that represent the greatest portion of harmful gases by signing a protocol that regulates monetizing CO_2 emissions. In this Kyoto protocol, each country is given a certain cap that determines the maximum CO_2 emission allowances allowed by its entities. Also, a trading mechanism was established to offset extra emission allowances. However, the trading scheme was not able to achieve the goal it was established for due to several challenges it faces. Researchers presented many solutions using different methods and technologies, but none was effective enough to solve the issues undermining the carbon market. Many studies proposed blockchain technology as a vital solution for corruption, ineffectiveness, and lack of trust that carbon emission scheme suffers from among other issues. Blockchain characteristics of immutability, security, and transparency while maintaining privacy presented it as a strong candidate to fix the current carbon trading market, however, previously suggested frameworks were never comprehensive nor effective enough. They lack exploring the full potential of blockchain technology to tackle all the challenges facing the present scheme. Our work is providing a total solution in the form of a three-level framework consisting of two types of blockchains (public and private or consortium). The CHBETS extensively utilized smart contracts' codes to provide an automated carbon trading mechanism and carbon asset management and accounting with full integrity. Recent up-to-date technologies were proposed as design solutions for the CHBETS such as Ethereum, Hyperledger, Polkadot, Interledger, and others. The result is a trustworthy, advanced, unified, global, effective, and practical carbon emission trading market.

CRediT authorship contribution statement

Alia Al Sadawi: Conceptualization, Investigation, Formal analysis, Writing – original draft. **Batool Madani:** Visualization, Investigation, Writing – original draft. **Sara Saboor:** Methodology. **Malick Ndiaye:** Supervision, Writing – review & editing. **Ghassan Abu-Lebdeh:** Project administration.

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