HOW BLOCKCHAIN CAN BE USED FOR CREATING A MARKET FOR ENERGY SAVINGS CERTIFICATES

by

Churong Feng, Keith Glassbrook, Songyun Lee, Jenna Weiner

Dr. Timothy L. Johnson, Adviser

April 19, 2019

Masters project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of Duke University

Acknowledgements

The authors also thank the following individuals for offering their insights and perspectives to this work. (Listed alphabetically.)

John Buley (The Fuqua School of Business, Duke University), Anita Castledine (Public Utilities Commission of Nevada), Matt Eastwick (Clean Capital), Sam Hartnett (Energy Web Foundation), Timothy L. Johnson, Ph.D. (Nicholas School of the Environment, Duke University), Mark Laabs (Modern Energy), Wai Yee Leong (SP Group), Jaclynn Lukach (PJM-EIS), Jason Massey (ndustrial.io Inc.), Todd Mohney (Gust), David Mulcahy (Modern Energy), Andrew Seelaus (PowerGen), Francois Sonnet (SolarCoin), Lisa Sundeen (Duke Graduate Student, former Energy Web Foundation Intern), Kevin Quilliam (InClime), Chris Wedding (IronOak Energy Capital)

Executive Summary

This paper explores use of blockchain technology to establish an effective energy savings trading market. Building an energy savings certificate (ESCert) trading market is expected to promote energy savings activities and investments, which is critical for decarbonization. Based on our analysis of blockchain applications in renewable energy certificate (RECs) markets, carbon credit markets, and supply chain applications, we designed a blockchain-based ESCerts trading system.

Energy efficiency practices are an effective and economical tool for decarbonization. While energy efficiency projects have been historically under-invested in, establishing energy savings trading markets can facilitate energy saving activities and enhance investment prospects. An effective energy savings trading market requires supportive regulations, a trustworthy marketplace, accurate measurement and verification, thorough tracking, and credible auditors.

Currently, only few energy savings markets exist globally, and there are four main barriers to building an energy savings trading market. First, the measurement and verification of energy savings is costly with complex calculations and the need for credible auditors. Second, it is difficult to confirm that an energy efficiency project is additional due to the ESCert trading market. Third, setting an impactful target is difficult as it is influenced by other factors such as a political pushback. Lastly, defining a geographic boundary for the energy efficiency program to avoid leakage is challenging.

To address these four challenges, this report examines an emerging technology, blockchain, and its applications. Blockchain is a distributed ledger technology where transaction data are saved in a block and can be traced. The blocks are linked to other blocks with relevant transactions and validated through consensus of network participants. The immutable and traceable data in blockchain are synchronized among all nodes in the system. Blockchain replaces the need for trusted intermediaries who store data and coordinate transactions with transparency. Tokens and smart contracts are important features of a blockchain system. Tokens may contain information about the assets. It can also be assigned to an owner and traded between different parties. A smart contract checks the previously encoded conditions and executes qualified transactions automatically. It improves transaction security and reduces transaction time and costs.

Blockchain has been applied in comparable cases to the ESCert markets, such as RECs, carbon credits, and supply chain applications. REC markets suffer from lack of transparency, high administrative costs, high brokerage fees, and inconsistencies across different markets. Blockchain streamlines the trading process, improves transparency and accuracy of data, and clarifies REC trading standards. Carbon markets have issues with carbon leakage, transparency, efficiency, liquidity, and inconsistencies between carbon credits' intrinsic value and the observed price. In carbon markets, blockchains can improve transaction transparency and verification. It also enables trading of smaller units of carbon credits and thereby attracts smaller market participants, which improves the liquidity in the market. Supply chain applications face challenges with linking the physical world with the digital world to ensure accurate data when moving to a blockchain based system.

Based on our analysis of the blockchain use cases, blockchain technology partially addresses the four main challenges to creating an ESCert trading market. For measurement and verification, blockchain does not address measurement concerns but can improve verification. Blockchain can help with measuring the impacts of other energy efficiency policies but cannot confirm additionality as it fails to verify a counterfactual. Blockchain may have limited influence on setting impactful targets since other factors such as policy have a large impact on setting targets. Also, blockchain can address the leakage issue only if worldwide trading policies are set.

Based on the analysis of blockchain use cases and the four main challenges, we designed a blockchain-based ESCert trading system. While the new ecosystem has the same basic flow of the existing market structure, tokens and smart contracts make the system less costly and time-consuming via digitalization and automation. A token represents an energy savings certificate. One token is equal to 1kWh of energy saved. Tokens are stored in the blockchain system and can tracked by market participants. Three main smart contracts - token issuance contracts, token transaction contracts, and token retirement contracts - enable the automatic issuance, trading, and retirement of ESCerts. This system improves the verification and tracking of ESCerts, streamlines the trading and auditing process by replacing paperwork and intermediaries, and increases participation in the market.

However, the blockchain-based ESCert trading system does not address the four main challenges to creating an ESCert trading market. Other market design issues such as oversupply and complex certification process cannot be solved by blockchain alone. Furthermore, this system requires costly digital infrastructure, which is currently lacking. For further study in the future, the effectiveness of an ESCert markets compared to other energy efficiency policies can be examined as well as M&V methodologies in the blockchain system.

For more information contact leesongyoon@gmail.com, churongfeng@hotmail.com, glassbrook.keith@gmail.com, jennaweiner@bellsouth.net

Contents

1 Introduction

The cheapest and cleanest kilowatt-hour is the kilowatt-hour not used. According to the American Council for an Energy-Efficient Economy, the average cost of saving a kilowatt-hour (kWh) is 2.8 cents, whereas the average retail cost of electricity in the U.S. is 10 cents.[1] Thus, energy efficiency is an important tool for decarbonization.

Since the 1980s energy intensity in the U.S. has fallen by approximately 50%.[2] This was in large part due to energy efficiency policies, such as appliance standards, information disclosure requirements, auto fuel economy standards, building codes, and tax rebates. While these policies have been extremely effective, the need to further decarbonize calls for an even stronger push for energy efficiency.

Some believe that a market for trading energy savings can increase the volume of energy efficiency projects undertaken.[3] However, there are four main challenges to establishing an energy efficiency trading market: (1) measurement and verification of energy savings, (2) confirming that projects undertaken are a result of the program rather than projects that would have been completed without incentives, which is referred to as additionality, (3) setting impactful targets, and (4) defining a geographic boundary for the program.[4] These are described in more detail in the following sections.

In this paper, we examine whether blockchain technology, a distributed and decentralized ledger, can be used to address these issues to create a successful market for trading Energy Savings Certificates, which represent energy savings resulting from energy efficiency investments. Our analysis shows that blockchain can help address the measurement and verification issue, but does not directly address concerns related to confirming additionality, setting impactful target, and defining a geographic boundary. Therefore, we do believe blockchain is an adequate tool to overcome only some of the barriers to creating a market for trading Energy Savings Certificates.

This paper provides an analysis of the blockchain application for an Energy Savings Certificates trading market. First, we give background on energy efficiency trading markets and blockchain. Then, we examine how blockchain is or can be used in comparable markets, including Renewable Energy Certificates, Carbon Credits, and supply chain applications. Following, we provide an analysis of if and how blockchain can solve the four main challenges to establishing an energy efficiency trading market. Before closing with the conclusion, we discuss potential blockchain system designs for an energy efficiency trading market, offer some technical recommendations, and outline the potential benefits of our proposed blockchain system.

2 Background

2.1 Energy Savings Certificate Markets

Presumably, profit-driven companies will seek cost-saving energy efficiency projects naturally. However, research has shown that energy efficiency markets are subject to market failures that result in sub-optimal investment. This phenomenon is called the energy efficiency gap.[5] Due to these market failures, policies to incentivize energy efficiency investments are necessary. There is much debate over what policies should be used to address this market failure. One proposed solution is a trading market for Energy Savings Certificates.

Energy Savings Certificates are also known as ESCerts, White Certificates, or White Tags. ESCerts are typically expressed in megawatt-hours or 1 tonne of oil equivalent and are tied to energy savings from an investment in an energy efficiency project or practice. Creating an involuntary market involves the government setting a mandate for energy savings with a penalty if the mandate is not met and also allowing trading of ESCerts to meet the target mandate. Companies that have a low marginal cost to create an ESCert can create excess ESCerts to sell to companies that have a marginal cost of energy efficiency above the price of the ESCert.

The goal of creating a market for trading ESCerts is to incentivize energy consumers to invest in energy efficiency projects. If a unit of energy savings has a price then it can be traded, which will incentivize innovation and investment in ways to save energy. For example, a company may be more willing to invest in energy efficient equipment if selling the excess ESCerts reduces the payback period of the investment. However, the trading price and volume is proportional to the amount of undertaken energy efficiency projects. Thus, the market depends on some of the participants not investing in energy efficiency.[6]

There are three notable energy efficiency trading markets: (1) France, (2) Italy, and (3) India. Italy and France were the leaders in creating a market for energy efficiency targeted at residential and commercial energy efficiency. Italy's program started in 2005 and France's program began in 2006.[7,8] In both programs the mandate was imposed on the electric and gas utilities. However, the utilities need to source the energy savings in their territories by the residential and commercial customers rather than in their own facilities.

In order to meet its mandated target, a utility either implements energy saving projects for its customers, such as distributing LED light bulbs, to earn ESCerts or the utility purchases ESCerts from other utilities that have earned excess White Certificates. The markets in both France and Italy don't have significant trading volume due to oversupply and low demand.

India's Perform Achieve Trade (PAT) scheme has a very different structure from Italy's and France's programs, and it was announced by the Indian government in 2008 with the aim to improve energy efficiency in energy intensive sectors.[9] The PAT scheme sets a mandate on a per plant basis from eight energy-intensive sectors, including aluminum, cement, chor-alkai, fertilizer, iron and steel, pulp and paper, textiles, and thermal power plants. These sectors make up approximately 60% of India's total energy consumption.[10] In the first phase the plants were required to meet a plant-specific target reduction from 2012 to 2015. The average reduction was 5.3%, which exceeded the target of 4.1%. In 2015, auditors determined which plants fell short or exceeded their targets and awarded those that exceeded their targets with ESCerts. Approximately 3.8 million ESCerts were awarded and there was only demand for 1.5 million ESCerts.[11] After the first phase, trading began in mid-2016, and similar to France and Italy, ESCerts are thinly traded due to oversupply.

Creating and managing these programs requires substantial governmental oversight and resources. Effective energy efficiency trading markets necessitate detailed regulation, a credible marketplace, complex measurement and verification, careful tracking, and trustworthy auditors. Building a program that meets these requirements is typically prohibitively expensive and difficult to scale. Markets run most efficiently when there are the largest number of possible participants and available projects.[12] Potential participants could include energy utilities, energy service companies, cities, transportation providers, industrial and commercial companies, appliance manufacturers, individuals, and real estate developers. More participants should make the market more efficient, but in reality more participants increase costs of monitoring the market. Thus, the transaction costs of an energy efficiency trading market must come down in order for it to scale and run effectively.

Currently, the U.S. has few energy efficiency trading programs. There are 27 states with Energy Efficiency Portfolio Standards (EEPS).[13] These EEPSs typically set a mandate that the electricity sector must meet by reducing energy consumption in the utility's territory. No states have particularly aggressive targets. There are five states, including Connecticut, Massachusetts, Michigan, Nevada, and Pennsylvania, that allow trading of ESCerts to comply with its EEPS.[14] However, Pennsylvania is the only state with active trading, and certificates are traded at a price of less than $1 per credit because the certificates are oversupplied. Additionally, the Pennsylvania energy efficiency certificates are not traded on their own trading platform, but instead traded as a small subsect of the renewable energy credits trading program. In 2009 and 2010, Democrats attempted to introduce several bills to set a national EEPS. However, none of the bills passed.[15] With any climate related policy being a contentious issue, it is unlikely that both parties will come together in the foreseeable future to pass a national EEPS, and any movement towards creating and establishing an energy efficiency trading market will most likely need to happen in each individual state.

Figure 1 is a generic illustration of how the energy efficiency certificate market currently functions in the U.S. Energy efficiency programs are implemented through a utility's demand-side management (DSM) program. Utilities can obtain ESCerts by either investing in their own energy efficiency projects or purchasing ESCerts directly from customers or in the market. Before an investment in an energy efficiency project is made, the utility or an Energy Service Company (ESCO) will forecast a baseline, which is the status quo of what the energy use would be without the investment. Then they forecast how much savings a particular investment would produce in order to decide if it is a cost-efficient project. An example of an energy efficiency investment is installing energy efficiency appliances, such as LED light bulbs. If an ESCO is hired to implement the project, the customer will pay the ESCO for its services only if the energy savings are realized. Energy savers need to have their savings measured and verified by a trusted third party, such as a Measurement and Verification Provider. After the energy savings are verified from a third party, the savers will obtain ESCerts for the saved amount and sell them in either the market or directly to utilities. The utility must then report its ESCerts to regulators in order to comply with a pre-set target.

When creating a market where participants can trade ESCerts, there are four main challenges that must be addressed. First, the measurement and verification of energy savings poses a large cost. The energy savings must be verified to ensure that the savings actually happened. To measure the savings, a baseline must first be established before implementing an energy efficiency project. Once the energy efficiency project has been implemented, the new energy usage is compared to the baseline. All of this requires time and complex calculations and it must be determined by credible and trustworthy auditors.

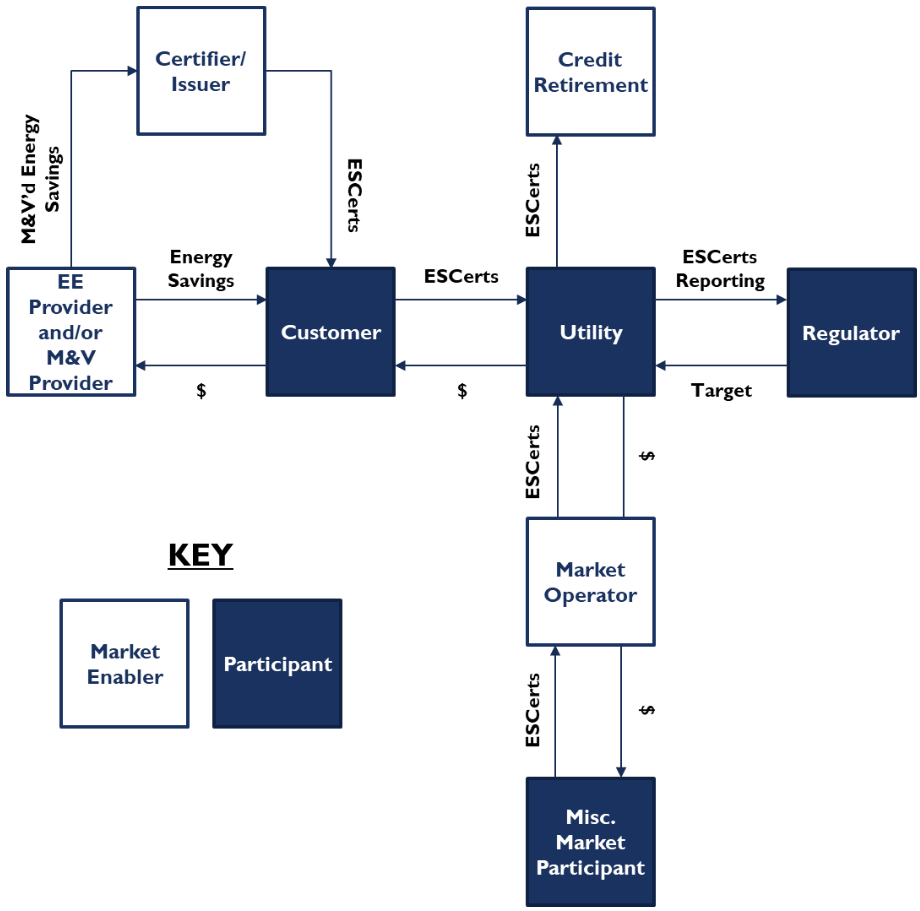

Figure 1. Generalized Market Structure

Second, confirming that the energy efficiency project is additional is extremely challenging. Additionality is the idea that an activity is additional, meaning that the intervention has an effect compared to the baseline. The mandate target should only be met by energy efficiency projects that are additional and not projects that would have been undertaken anyways. Additionality is essentially impossible to determine because it is based on a hypothetical question of what would have happened in the absence of the program. For example, it is impossible to prove that an investment in LED lightbulbs was a result of the program or if it would have happened without incentives from the program. Making additionality more complex to measure in the U.S. is that included in the baseline are impacts from the other energy efficiency policies, such as tax credits and product subsidies, which need to be accounted for. If energy savings that would have happened anyways are allowed to count towards meeting the mandate, then that would create a windfall to the receiver and an oversupply of ESCerts in the market. This would decrease the price of ESCerts making it cheaper for other firms to purchase ESCerts rather than investing in energy efficiency projects that it would have otherwise invested in, which would undermine the entire program and reduce actual energy savings.

Third, setting a target that is aggressive enough to make an impact is a difficult feat. A substantial target over the business-as-usual case will create a scenario where firms have varying marginal costs, which is necessary to encourage trading. In Europe, India, and the U.S., low trading volumes indicate that targets are unimposing and companies are able to reach targets on their own accord. Across all programs there seems to be a trend of over-allocation and lax targets. This is possibly due to a political pushback where regulators can only enact mandates if the targets are not substantial enough to require a change in behavior.

Fourth, defining the geographic boundary of the program is important to avoid leakage. Carbon leakage occurs when a company moves its production outside the system boundaries to avoid aggressive targets. The same concept can occur with energy efficiency if the boundary is not properly set. Contracting out energy intensive aspects of a business and the ease of shipping makes these types of markets easy to manipulate. Additionally, with interstate trading, states with lower targets could sell to states with higher targets, undermining the stricter state's program.

While there has yet to be an effective energy efficiency trading market set in place, new technology, such as blockchain, can help address some of the issues outlined above to get a step closer to creating a well-functioning market.

2.2 Blockchain

The recent hype in blockchain stems from a white paper released by Satoshi Nakamoto in 2009, and it is most commonly known for being the underlying technology in the Bitcoin network. Blockchain is a distributed ledger that tracks transactions, and stores information about these transactions, including sellers, buyers, terms, and other details in blocks. These blocks are linked to blocks of prior transactions and are validated through consensus by network participants before being recorded. Each node within the network stores and synchronizes a copy of the ledger. Unlike conventional centralized systems where a single organization controls the access to the data, all participants can access and audit data on a blockchain since the information is synchronized among all the nodes. Thus, blockchain replaces the need for a trustworthy third-party as an intermediary to store data and provides transparency and efficiency.

In addition to the efficiency afforded by the distributed ledger, the data stored in the blocks are traceable and immutable. Each block contains data about transactions, including the hash value of the previous block. A hash value completes a block and it is the output of a function that takes all the information inside the block as inputs. A unique hash value is given to each block, which is then carried over to the next block, creating a chain. The hash value acts as the fingerprint or identification number of a block. A hash value is generated by a miner, and once a miner claims to have generated a block by calculating an adequate hash value that meets specified requirements, it must be verified by peers in the network. There may be multiple miners working on creating the same block, and the miner that is able to create a verified block first may receive token rewards.

Since the hash value of a current block is calculated from the function that contains the hash value of the previous block, after the current block is added to the chain, any modification within the current block invalidates the hash values, and consequently invalidates all the following blocks. To make any modification valid, one needs to calculate and change the hash value in all following blocks in a time shorter than block generation intervals, which is infeasible. Thus, this ensures that data stored in blockchain is immutable and safe from bad actors seeking to manipulate the data.

Figure 2 provides a description of the blockchain creation process.[16] The process includes five key steps. First, several nodes broadcast transaction requests with information such as the number of tokens to be transferred. Second, miners, or nodes which participate in creating a block, gather all the transaction requests within a specified time interval and create a block through finding the hash value. Third, miners who have successfully created the block broadcast the block to the entire network. Fourth, other nodes act as validators to verify whether the block contains authentic information and broadcast the approval decision to the entire network. Fifth, the fastest approved block within this time interval is added to the chain, the miner of which can receive a reward.

Occasionally multiple blocks are generated at almost the same time, leading to the divergence of the existing chain. In this situation, miners may choose to build the following blocks on whichever branches they first see. Eventually, the time difference becomes evident as one branch will become much longer than the other, and the shorter branch will be abandoned.

The above description is a general process of block creation in the network. However, based on different needs, there can be many variations of the steps. For example, some blockchains include smart contracts, which automatically execute complied conditions and terms in the verification process or use different types of consensus mechanisms to determine the verification process and how the successful miners are rewarded.

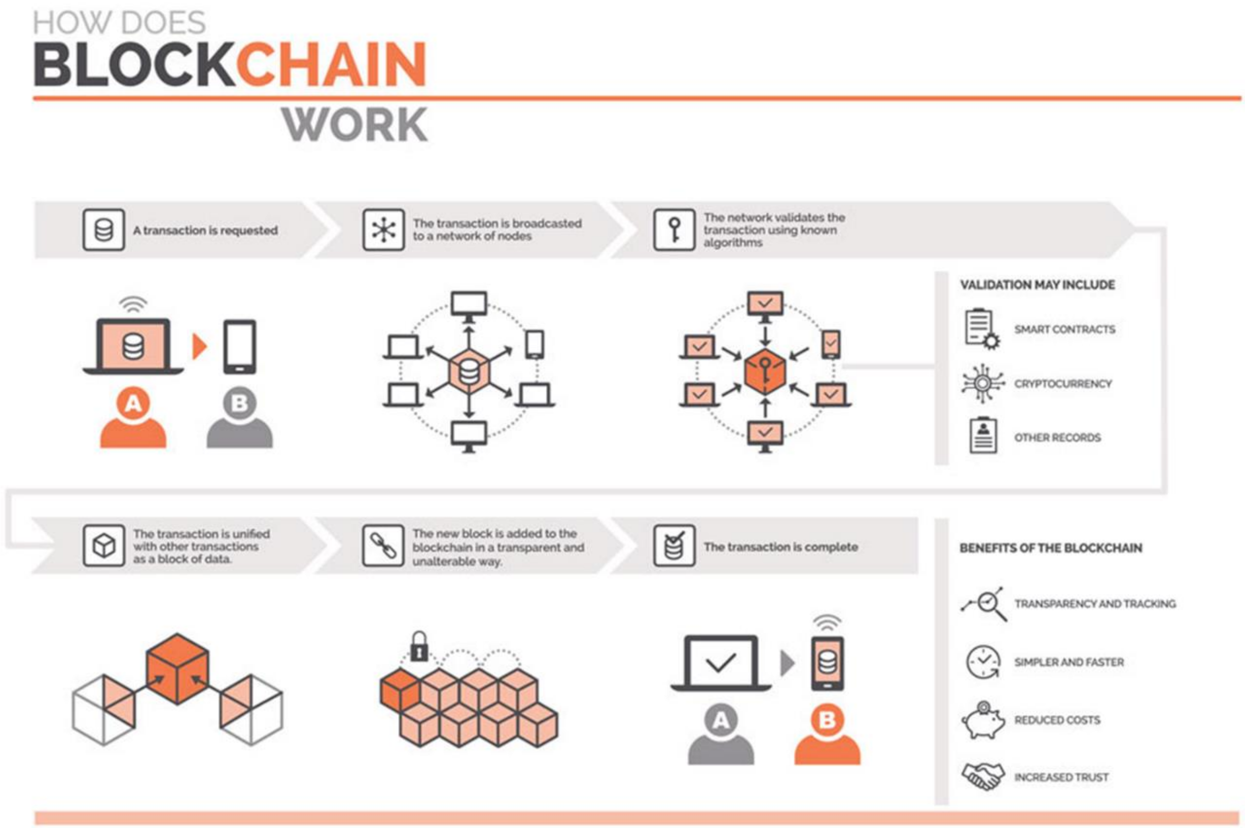

FIGURE 2. BLOCKCHAIN NETWORK OPERATION[16]

2.2.1 Participation Permissions and Openness of Code

In addition to variation in how blocks are created, there are also different categories of blockchain systems. Blockchain systems can be categorized in two ways: (1) participation permissions and (2) openness of the underlying code.

First, there are two levels of participation permissions: public, consortium or private. A public blockchain network is accessible by anyone on the internet. Once a participant accesses the public blockchain and obtains a wallet and valid address, the participant is allowed to transact, create blocks, and earn rewards.[17] Since no trust is previously established among participants, public blockchains rely heavily on cryptography verification algorithms and an appropriate consensus mechanism to create incentives for participants to govern the network and resist attacks from malicious nodes. Allowing anyone to participate makes the public blockchain the most decentralized when compared to consortium or private blockchains. Bitcoin network and Ethereum are the most well-known public blockchains.

A consortium blockchain or a private blockchain only provides the rights to access, read, and write on the blockchain system to members from specific entities.[18] For example, some real-world blockchain applications require tokens to gain access to the system and to participate in mining. Since permission is needed before a node can participate, trust has been partly established among the nodes. While a consortium blockchain or a private blockchain may adopt appropriate consensus mechanisms, miners who create new blocks can also be internally selected by the network nodes. A consortium blockchain or a private blockchain can achieve higher efficiency, shorter block processing time, and lower costs than public blockchains as they are able to bypass some of the complicated algorithms and consensus mechanisms necessary to defend against bad actors in a public blockchain where there is no assumed previous level of trust. Therefore, consortium blockchains or private blockchains are typically used in business cases that target improvements in transparency and traceability.

Second, there are two levels of openness of the underlying code: open-source and closed-source. An open-source blockchain makes its underlying code accessible to anyone, which means the code, as well as the blockchain features, are public and subject to review, discussion, and community-based decision-making processes for changing blockchain features. An open-source blockchain provides a high degree of transparency and can benefit from contributions made from all participants to improve the system.

A closed-source blockchain does not share its underlying code with the public, and any decisions on changing blockchain features are made internally by the system creator. A closed-source blockchain may not be transparent, nor subject to public supervision. However, this type of blockchain is more efficient in the decision-making process since it does not require input from a majority of the participants.

There are no firm boundaries between different categories and types of blockchain systems. Any one category of blockchain may not satisfy the needs of specific real-world application and hybrid approaches are sometimes necessary to adopt important features from multiple blockchain categories.[19]

2.2.2 Consensus Mechanisms

Different types of blockchains create different environments, which can impact the design of consensus mechanisms and other essential features.[20] Consensus mechanisms refer to the methodologies or algorithms that determine how nodes reach consensus in approving transactions or verifying data updating requests in the blockchain network. Consensus mechanisms guard against security issues, such as node failures, unresponsive nodes, message delays, data corruption, and malicious nodes.[21] There are four main types of consensus mechanisms: (1) Proof of Work, (2) Proof of Stake, (3) Proof of Authority, and (4) Delegated Proof of Stake. All consensus mechanisms face the "impossible triangle," which is that it is impossible to achieve perfect efficiency, decentralization, and security, and each consensus mechanism trades-off certain features to achieve more of one. Deciding which consensus mechanism to use in a blockchain system depends on how the creator of the system prioritizes efficiency, decentralization, and security.

Proof of Work (PoW) was first introduced and used in the Bitcoin network. Its effectiveness in preventing malicious nodes has been proven robust. Under PoW, miners (nodes) compete to create a block by solving a mathematical function (finding the hash value), which requires time and computational power. The fastest node can add its block to the chain after receiving approval from peers who verify the block's hash value, and the node is rewarded with block creation fees and transaction fees. PoW makes fraudulent activity extremely expensive and unlikely to succeed because malicious nodes need to add consecutive blocks in order to make the fraudulent block valid and verified. Unless this malicious node has hardware and computational power that is far greater than other miners', being the first one to generate consecutive blocks is impossible. Therefore, every miner within the blockchain network has an incentive to remain honest under PoW. However, PoW has several drawbacks. PoW consumes a lot of energy because many nodes use computing power to compete for rewards. Additionally, PoW encourages pooled-mining. Pooled-mining is when miners with high-quality hardware make alliances with other miners with superior hardware, and as an alliance they have more opportunity to successfully add blocks compared to other individual miners who lack the same computational resources. Pooled-miners share the costs and rewards, and it could eventually lead to the imbalance of computational power distribution as well as coin aggregation.

Proof of Stake (PoS) is another commonly adopted consensus mechanism. PoS consumes fewer resources and can more efficiently verify and process new blocks when compared to PoW. With PoS, the blockchain system applies a lottery-like algorithm that assigns permission of block creation among nodes. Usually, the more resources a node has invested in the blockchain system, or the more cryptocurrency the node holds, the higher the probability is for it to be chosen to create a block. Thus, PoS dramatically reduces the time and energy used in a blockchain network by using less computational power and reducing the time needed to find the hash value. Unlike PoW, which rewards miners with both a block generation fee and transaction fees, PoS only rewards miners with transaction fees in the block. Therefore, the blockchain system does not have to continuously generate new cryptocurrency to motivate block creation, and the pool-mining problem does not exist since investing in hardware has no added benefits.

PoS is also effective in preventing fraud. In order to ensure selection, a node needs to aggregate over 50% of the coins in the system. Buying such a large amount of coins is expensive, and as the number of participants in the system increases, the possibility of a node getting more than 50% of coins drops significantly. Besides, such an attempt may cause inflation. If one node does accumulate a large number of coins through fraudulent activities, the risk of devaluing the coins is also higher as the other nodes will sense the fraud. Thus, the malicious node will end up with coins that have no value. Therefore, coin holders have an incentive to be honest. The major drawback of PoS is that the distribution of coins may eventually become increasingly imbalanced. Since the more coins a node holds increases the node's chances to mine and win coins, the distribution of coins may eventually end up in the possession of only a few nodes.

Proof of Authority (PoA) is not as widely used as PoW and PoS, and it was first introduced to address spam on the Ethereum network. Under PoA, a group of validators (block creators) are preselected, and the network will randomly assign a node from the preselected group to create a block. The selected node will gather the transaction information and assemble it into a block, before broadcasting it to the network to be approved by the other validators. Once it is approved, the creator can add it to the chain.[22] The network can continuously update the list of preselected validators and block creators as they enter and exit the system.

The main advantages of PoA are that it is efficient and scalable.[23] Compared to PoW and PoS, PoA does not make nodes compete to create a block, rather the system assigns the block creator. This simplifies the communication process for reaching consensus, which significantly increases the system efficiency. Additionally, PoA can easily scale-up in a large network to handle high transaction volume. The main disadvantages of PoA are that it introduces the potential of centralization and damage from malicious validators.[24] The assigned validators illustrate the nature of centralization within this mechanism, which undermines blockchain's attribute of decentralization. In addition, PoA may be vulnerable to malicious validators since only a small group of nodes are included in the validation process. Therefore, the chances for a validator to cheat is larger than with the other consensus mechanisms.

The last consensus mechanism is **Delegated Proof of Stake (DPoS)**. Under DPoS, the distributed nodes vote and elect a group of nodes to generate blocks. The elected nodes follow prescribed rules to compete in creating a block. The elected nodes are also responsible for making decisions such as transaction fees and block size. DPoS is a promising mechanism as it guarantees relatively fair participation of each node in block creation and decision making, as well as choosing the trustable nodes within the network. However, there is the risk of centralization when there is a low volume of nodes voting.[25]

2.2.3 Tokens

Tokens are another important feature in a blockchain system. Tokens contain information and can be assigned to an owner and exchanged between different parties. Tokens are categorized by functionality as either (1) utility tokens or (2) asset-based tokens.[26]

Utility tokens, also known as intrinsic tokens, are created by the blockchain platform and aim to provide incentives for participating as a validator and a block creator. The Bitcoin is an example of a utility token that is created by the Bitcoin network and is used to reward miners for successfully adding a block to the chain. Utility tokens can also help reduce transaction spam if used for transaction fees. When a transaction fee for a transaction is higher, the network prioritizes the transaction, so it takes less time to settle the transaction. Therefore, making the transaction costly helps avoid redundant transactions. Utility tokens are created and recorded by software algorithms and may or may not have economic values since the utility tokens are not backed by assets. Asset-backed tokens are issued by a specific issuer and provide proof of ownership of the underlying asset. Asset-backed tokens store the information about the underlying asset and are easy to track and trade in the blockchain network. A blockchain system can utilize either token or both types of tokens at the same time depending on other technical features the blockchain system adopts.

2.2.4 Smart Contracts

As blockchain has developed, the ability to write and include smart contracts has become a key feature enabling more complex blockchain applications. A smart contract is code that can automatically enforce the content of an agreement between multiple parties. A smart contract is similar to a traditional legal contract in that it also contains information outlining an agreement, but it is entirely compiled as computer code. In other words, a smart contract is a software program added to the blockchain system that checks the conditions and executes qualified transactions.

To deploy a smart contract in the blockchain system, a smart contract must be assigned a unique address and uploaded to the blockchain system before the transaction is initiated. The smart contract will perform the information it receives and execute the codes automatically. For example, when an agreement is reached between two nodes that a certain number of tokens will be transferred from one to the other on a specific date, the agreement will be written in computer algorithms with several conditions: the number of tokens, delivery date, output address, and input address. The smart contract will automatically check whether the conditions are satisfied, and if they are satisfied, the smart contract will settle the transaction by broadcasting the transaction request to the blockchain network. Once deployed, a smart contract cannot be changed without employing a complicated voting mechanism.

The objective of a smart contract is to improve transaction security and to reduce transaction time and costs.[27] A smart contact can help avoid lawsuits because once an agreement is made neither party can change or delay the agreed upon actions. In addition, the execution of a smart contract does not require supervision and it automates the process for either party to fulfill their obligation. However, to ensure the effectiveness of smart contracts, they must be bug-free. Loopholes in codes can cause severe losses to the associated parties and even the entire blockchain network.

3 Blockchain Applications in Comparable Markets

We analyzed blockchain applications in comparable markets to better understand how blockchain can be used to create a market for trading ESCerts. In this section, we examine three different blockchain applications: (1) Renewable Energy Certificates, (2) carbon credits, and (3) supply chain applications.

3.1 Renewable Energy Certificates

3.1.1 Overview

A Renewable Energy Certificate (REC) is a tradable, market-based tool that assigns ownership to the attributes of renewable electricity generation and use in renewable energy markets.[28] One REC is issued to the generator when one MWh of electricity is generated from a renewable source and delivered to the electricity grid.

RECs facilitate a larger adoption of renewable energy for power producers by providing an additional revenue stream along with revenues from power sales and tax credits in both voluntary and mandatory REC markets. Under each state's Renewable Portfolio Standards (RPS), the power suppliers must acquire a required percentage of energy from renewable sources through either producing on their own or purchasing from other producers in mandatory REC markets.[29] Regulators of the mandatory market set targets and penalties. To avoid the penalty and meet their targets, obligators are incentivized to purchase RECs when they cannot reach their target with their own generation. A penalty price or alternative compliance payment sets the price ceiling in compliance markets where RECs are traded. A REC holds important data attributes to account, track, and assign ownership of renewable electricity generation and uses, such as certificate data, certificate type, tracking system ID, renewable facility location, and project name.[30] Buyers in a REC market can either purchase unbundled RECs, which does not include electricity sales, buy green power from an electricity service provider (a bundled REC product), consume green power from its own onsite project with RECs, or buy RECs through a power purchase agreement with an onsite/offsite project. U.S. Voluntary Green Power Market trades renewable energy products like RECs, independent from a compliance REC market to meet a state's RPS. In a voluntary market, a REC price is determined by a supply and demand balance in the market. The demand for RECs in voluntary markets have been rising as increasingly more companies purchase RECs to meet their sustainability or carbon offset goals. In addition, the supply of unbundled RECs in the U.S. Voluntary Green Power Market has been growing as a result of increasing residential and small commercial customers.[31]

The current REC market requires several steps and involves different entities. First, the renewable generator produces electricity and passes data to certificate-creating entities. Certificate-creating entities authenticate electricity generation from renewable sources and issue certificates. For trading, brokers aggregate small certificates into larger bundles and source buyers or disaggregate larger bundles into smaller ones. Brokers are also active in the RECs trading in addition to renewable generators and certificate buyers. Brokers connect buyers and sellers for a fee as well as aggregate and disaggregate supply into customized offerings. Either by renewable generators themselves or the broker/aggregator, certificates are traded either on a certificate exchange (Intercontinental Exchange for the U.S.) or in over-the-counter deals. Finally, load serving entities purchase and retire certificates. Certificate issuers must go through an annual audit by the certification entity.

There are several pain points in REC issuance, trading, tracking, retirement, and reporting under the current model. The most notable pain points in the REC market include a lack of transparency, high administrative costs, high brokerage fees, inconsistencies across different markets, and overall difficulty of meeting one's needs. Firstly, certification systems must verify whether renewable generators are in compliance, and the REC issuing process is burdensome and requires a lot of paperwork. In addition, an annual audit is required to make sure there is no double counting of certificates. Finally, tracking systems to ensure compliance with policy mandates is a time-consuming and costly process. Under this complex system, it's hard for small retailers or small renewable generators to participate in the market. Electricity companies in mandatory markets often buy RECs in large quantities, disincentivizing sellers with a small REC quantity to participate. The transaction costs such as fees for auditors and brokers amount to 5% of the certificate's value.[32] REC market participants, mainly renewable energy developers and buyers, must go through an expensive, complex and vague process, which differs from market to market and depends on obsolete trading platforms.[33] This acts as a barrier for market participants without adequate resources or tools to overcome the process.

Blockchain technology is expected to streamline the trading process of RECs, and thereby enable more secure, lower cost, and integrated markets. In many cases, REC trading is highly specialized and opaque.[34] Blockchain technology eases the process by enabling real-time settlement, replacing intermediaries, reducing internal administration and auditing costs, and tracing renewable energy generation with improved accuracy.[35] Under the current system, it requires time and money for certification entities to verify a renewable generator's compliance and audit for double counting of certificates. Smart contracts, which automatically enforce an agreement between parties, can automate certificate issuance, tracking, and retirement.

Transparency and accuracy of data can be greatly improved through blockchain-based REC systems as well. Immutability is one of the essential characteristics of blockchain technology with cryptography, recording of every change in blocks, and distributed consensus mechanisms. With immutable data on a blockchain-based system, transparency and accuracy in tracking and trading data can be enhanced. In addition, smart contracts enable real-time retirement of RECs, avoiding the risk of double-counting.

Not limited to the U.S. REC market, an open-source, global blockchain infrastructure can facilitate standardization among regional voluntary markets.[36] This will be invaluable for trading across countries and regions, especially in voluntary markets. Currently, REC markets in each region and country require different regulatory intermediaries and brokers with specific knowledge of the local complex market. Blockchain will enable standardizing across borders and eliminate the need for intermediaries. Participants from markets which have not been functioning well due to the high transaction cost and complex system can have another option to trade their REC in the global market.

3.1.2 Case Studies

SP Group REC Marketplace

Singapore's REC market is currently facing problems, such as high certificate verification costs and issues with tracking RECs. This has led to low trade volume in the market.[37] The Singapore government expects to solve the REC double counting and low trade volume problems through the recently launched global blockchain-based voluntary REC trading marketplace by Singapore's energy utility, SP Group. This will improve transparency and lower costs by eliminating the costs incurred by intermediaries for verifying and tracking RECs. Local, regional, and international RECs are eligible to be traded in the marketplace. Buyers can set their preference on asset types and location. The platform automatically matches buyers with sellers all over the world.

The blockchain technology not only benefits market participants by saving time and costs, but also accommodates smaller producer and consumer market participants. With blockchain, the minimum size requirement per transaction is drastically lowered from 1000kWh to 1kWh.[38] In addition, blockchain allows small energy consumers and producers to participate with lower transaction costs. This enables small scale sellers and buyers to participate in the market. Moreover, a blockchain-based REC system is expected to scale up the market and increase trade volume by matching cross-border demand and supply beyond the geographic territory. SP Group's REC marketplace helps companies meet their sustainability target with greater security, facilitates renewable energy integration on the grid, and supports Singapore's climate target under the Paris Agreement at COP21.[39]

Energy Web Origin

PJM Environmental Information Services (PJM-EIS) has been developing and testing a blockchain-based platform called Energy Web Origin for the Generation Attribute Tracking System (GATS) for renewable and carbon markets with the Energy Web Foundation.[40] The blockchain-based GATS pilot is currently being tested for voluntary REC markets.

PJM expects that blockchain will enhance the security, transparency, and transaction costs of its REC trading market.[41] Additionally, blockchain is expected to enable trading in smaller units of RECs and facilitate peer-to-peer trading between small-scale renewable energy producers.[42] A blockchain-based system makes the processing of payments quicker as payments can be processed and tracked on the chain. Moreover, it can potentially provide the service of matching buyers and sellers in voluntary markets. Standard, automated processes for physical asset registration, asset authentication through digital signatures, secure data logging, REC creation and validation, REC ownership registration, and REC retirement can be streamlined by using blockchain technology.[43] However, a blockchain system does not address issues related to burdensome certification processes required by most states.

3.2 Carbon Credits

3.2.1 Overview

A carbon market is a market solution that addresses climate change. Carbon credits are issued to entities that achieve reductions in Greenhouse Gas (GHG) emissions. Carbon credits can also be traded in the carbon market. A carbon price is determined by the price that carbon credits are traded for in the market. Regulators can use the carbon price as a signal to determine emissions targets, and institutional participants can make decisions about investing in emission-abatement projects or technologies based on the observed carbon price.

While carbon markets effectively engage polluters in achieving environmental goals with lower administrative and compliance costs, problems still exist in the market and impede the process of reducing GHG emissions. There are three main problems faced by carbon markets: (1) carbon leakage, which refers to polluters relocating outside a certain regulatory boundary or to a region with less strict constraints on emissions,[44] (2) lack of transparency, inefficiency, and illiquidity, and (3) inconsistencies between carbon credits' intrinsic value and the price observed in the market, which makes it difficult for investors to understand the true value of a carbon credit.[45] First, carbon leakage is a result of the inconsistency between regional regulations. Carbon leakage happens when a company relocates its polluting factories or purchases products outside the jurisdiction boundary to avoid emissions fees. In this situation, no GHG abatement methods are applied and emissions are simply transferred to the other location. Therefore, the amount of emissions remains the same or even increases at the global scale, and carbon markets fail to reduce emissions. Second, carbon credit markets lack transparency, efficiency, and liquidity, especially in secondary markets. Many carbon markets track each credit or allowance through paperwork, which is inefficient and prone to error. As a result, there are issues regarding double-spending where the same credit is sold to multiple entities. Because of the lack of transparency and inefficiency, investors are less interested in holding carbon credits, which results in low trading volume and illiquidity issues. Third, because of the market failures in the carbon markets, carbon prices do not reflect the true cost of carbon emissions, including externality costs. In addition, currently carbon prices are specific to regional markets, so there is no global carbon market, which would have a carbon price that reflects the pollution cost at a global scale.

Blockchain can address problems related to the lack of transparency in carbon markets. Carbon credits and allowances, as well as the associated transactions, are permanently recorded in the blockchain network and the blockchain technology guarantees immutability of approved records. Each credit or transaction can be encrypted with a unique identification number (hash value), which provides an efficient way to verify each transaction and to track the credits. Such processes can establish trust among the participants in the market. In addition, each verified carbon credit can be divided into smaller portions for smaller transactions while still being trackable. This feature can be useful for attracting smaller market participants and improving the liquidity of the market.

Another important feature of blockchain that can be useful for carbon credit markets is the ability to eliminate intermediaries. Participants use the blockchain network to request transactions, while also accepting the responsibility of governing the market by verifying peers' transaction requests. While the regulator can be an active participant in the blockchain system to support the carbon market, blockchain technology reduces regulators' burden of supervising the market by simplifying the administrative process and improving efficiency. As an additional function in a blockchain system, a smart contract can help streamline the carbon credits issuing process by automatically issuing qualified units to participants, and the smart contract can be applied to transaction execution as well. Compared to the traditional documenting process, the time of issuance and transaction execution is drastically shortened. This not only improves the accessibility of market information about real-time supply and demand, but it also helps participants make smarter decisions about when to buy or sell credits and emissions-abatement investments.

3.2.2 Case Studies

As the emerging carbon markets prove to be effective, several companies have proposed business models using blockchain technology to facilitate greater participation in carbon markets. Though blockchain seems to be a promising application in carbon markets, there has not yet been a mature or large-scale application thus far and most companies are only in the initial phases of raising funds.

Xarbon Sustainability Limited[46]

Located in Seychelles, Xarbon Sustainability Limited (XSL) is a company targeting sustainability programs. Based on XSL's white paper, the business model contains two major components. First, XSL files and conducts sustainable projects, such as rainforest protection to obtain various certified carbon dioxide reduction units from the United Nations Framework Convention on Climate Change (UNFCCC) and other governmental bodies. Second, XSL generates revenue by digitizing the certified carbon dioxide reduction units and selling them to consumers through blockchain technology. At the same time, XSL also promises to reinvest a fixed portion of its revenue to sustainable projects. XSL uses New Economy Movement (NEM), an open software platform as the infrastructure to launch its blockchain network, and issues its own token "OCO" for carbon credit trading.

In addition to directly selling certified carbon units to institutional consumers who need the credit for meeting carbon offset targets or sustainability branding, XSL created a secondary market on its blockchain-based platform. This secondary market allows peer-to-peer trading among different consumers. Individuals and small retail customers can participate in the carbon market by buying carbon credits from the secondary market or buying credit-embedded products.

By creating digitized carbon credits and the associated trading platform and market, XSL intends to improve transparency, reduce transaction costs, and incentivize small consumers to participate in the market. Once carbon credits are digitized in the blockchain system, they are encrypted with information, unique identification numbers, and trading timestamps, which makes the units traceable even when the units are circulating in the secondary market. This improvement in transparency also prevents the double-spending problem. Additionally, each carbon credit can be divided into partial units for trading, making it easier for smaller participants to transact in the market.

New Era Energy Ltd[47]

Based on New Era Energy Ltd's (NERA) white paper, NERA deployed a blockchain program to raise awareness about green energy utilization and to incentivize other green initiatives in Southeast Asia. Instead of obtaining certified carbon reduction credits from authorized institutions, NERA aims to develop its own methodology of quantifying the contribution of various green behaviors, such as renewable energy production, energy consumption savings, food-waste reduction, plastic-waste reduction, and green campaigns. NERA also issues Emission Reduction Units (ERU) as a "proof-of-green" measurement through blockchain to its community members. ERUs are tradable within NERA's blockchain network, the price of which is determined by observed carbon credit prices from reputable programs, such as the Clean Development Mechanism (CDM) program of UNFCCC and the International Renewable Energy Certificates (iREC) program. NERA developed the blockchain network based on the Ethereum blockchain and issued NERA tokens for trading ERUs and buying green products and services from merchant participants.

Target participants are merchants and cities that are implementing green projects. Each participant is recognized as a "green node" in the blockchain network. The blockchain network uses the consensus mechanism by which three green nodes are randomly chosen to verify a green project. Only when all the three nodes approve the project, can the comprehensive project information, such as activity type, geographic information, amount of energy savings or carbon offset, timestamp, and identification number, be added to the blockchain system.

Through this blockchain program, NERA aims to address problems related to the burdensome carbon credit certification process, lack of incentives for environmentally conscious behaviors, and lack of transparency and accountability. Issuing digitized ERUs avoids the complicated and paperwork-intensive process of certifying carbon credits. At the same time, intermediaries that traditionally certify the credits are replaced by the blockchain system and participants can be immediately rewarded with ERUs after completing green projects. NERA also tries to extend its quantifying methodology to include more behaviors that contribute to sustainability. Lastly, through the blockchain system, NERA hopes to establish trust among investors to accelerate the financing of green projects.

3.3 Supply Chain Applications

Many old and new organizations are exploring ways to implement supply chain applications of blockchain. These applications will need to surmount similar obstacles faced by possible energy efficiency blockchain applications. They must (1) connect the physical world with the digital world and (2) ensure information stored in the blockchain is accurate. Below we examine how blockchain projects in sea shipping and seafood supply chain attempt to apply blockchain to address core industry challenges. We also explore implications for possible energy efficiency blockchain applications.

3.3.1 Sea Shipping Case Studies

Large organizations like AB InBev, Hyundai, Samsung, Maersk and IBM are developing or piloting blockchain-based systems for the shipping industry.[48,49] Startups like CargoX are also participating.[50] The overarching issue these organizations hope to address with blockchain projects is the challenges created by the dominance of paper documentation in the sea shipping industry. These organizations believe blockchain is the technology that could bring digitization to the analog sea shipping industry. First, we explore TradeLens, a partnership between Maersk, a global shipping giant, and IBM. Second, we explore CargoX, a startup that has developed a blockchain-based Bill of Lading. Both systems are operational.[51,52]

TradeLens

TradeLens started as a partnership between Maersk and IBM in 2017 to develop a blockchain-based system to digitize the shipping industry. In a 2017 IBM press release about the partnership, IBM notes that "costs associated with trade documentation processing and administration are estimated to be up to one-fifth of physical transportation costs."[53] In other words, paperwork and associated processing and administration expenses are very high. TradeLens is an attempt to reduce these expenses and increase system efficiency with an "open, neutral platform underpinned by blockchain technology."[54] More specifically, TradeLens is addressing: (1) data inconsistencies and data sharing challenges, (2) "blind spots" across organizations and geographies, (3) "complex, cumbersome, and often expensive peer-to-peer messaging," (4) manual, time-consuming processes that increase costs and time to ship cargo, and (5) processes that are open to fraud.[55] Details about how TradeLens addresses the issues above are scarce. However, we can glean a few basic concepts about how it works. TradeLens describes itself as consisting of three components: (1) the network, (2) the platform, and (3) applications and services.[56] The network is essentially all the organizations utilizing TradeLens in some way; the platform is the blockchain system; and the applications and services build on top of the platform and give TradeLens its functionality.

TradeLens envisions the applications and services component to be an "open medium where anyone can build, use, and sell applications to their customers to fit the [TradeLens] ecosystem's needs now and into the future."[57] The platform is a private, permissioned blockchain based on Hyperledger Fabric that utilizes smart contracts.

CargoX

While TradeLens is focused on wide industry transformation, CargoX is more narrowly focused. CargoX's primary focus is the Bill of Lading (B/L). Investopedia defines a B/L as a "legal document between a shipper and carrier that details the type, quantity, and destination of the goods being carried" and notes that it also "serves as a shipment receipt when the carrier delivers the goods at the predetermined destination."[58] Essentially, whoever has the B/L owns the associated goods.[59] There have been attempts to digitize B/L, but none have been widely adopted.[60] CargoX hopes to change that.

B/L is generally a paper document and must be sent via courier to various parties involved in a shipment transaction. As a result, there are several problems associated with B/L that CargoX attempts to address with its Smart B/L based on blockchain technology.[61] First, B/L are slow to transport, taking from 5 to 10 days on average to reach their final destination. Second, they are expensive to transport. Third, they can get lost, misplaced, damaged, or stolen. Finally, they are open to fraud and forgery.

CargoX's Smart B/L runs on the Ethereum blockchain, a public blockchain, meaning B/L transfers of ownership are publicly visible.[62] However, because sensitive business information could be stored in a B/L, the details of the B/L are permissioned.

CargoX's systems uses smart contracts to create and transfer B/L. Use of the CargoX application is free to all users; however, entities that want to create a B/L must pay CargoX.[63] These customers can pay in fiat currency (e.g., USD or EUR) or with CXO tokens, a fungible, ERC20[a] compliant token. CargoX defines the CXO token as a utility token. It is used to run CargoX's B/L creation smart contract. It can also be used as a means of payment within CargoX's system. In addition, because CXO tokens are ERC20 compliant, they could theoretically be used as a means of payment outside CargoX's system. Lastly, CargoX is working on

[a] ERC20 (or ERC-20) is a technical standard that describes the "functions and events that an Ethereum token [smart] contract has to implement." It is the technical standard for fungible tokens on the Ethereum blockchain. (from https://theethereum.wiki/w/index.php/ERC20_Token_Standard, accessed March 13, 2019)

a non-fungible, ERC721[b] compliant token that could be used for transfer of digital ownership (e.g., Smart B/L transfer).

3.3.2 Seafood Supply Chain Case Studies

One of the biggest problems in the seafood industry today is overutilization of resources. By one estimate, about 90% of the world's fish stocks are either fully fished or overfished.[64] This is compounded by waste in the supply chain—with up to 50% of caught fish being discarded or wasted within the supply chain—and stolen seafood through illegal, unreported, and unregulated activities.[65] Many in the industry believe improving transparency and traceability[c] will help.[66] However, the seafood industry is highly fragmented and suffers from information silos.[67] Enter blockchain. Below we explore two examples of how blockchain is being applied in the seafood industry.

Blockchain Supply Chain Traceability Project

World Wildlife Fund (WWF) is leading a project it calls the "Blockchain Supply Chain Traceability Project" focused on building a system for traceability and trust in the seafood supply chain.[68] WWF notes that electronic/digital supply chain traceability is not new; however, existing systems rely on centralized systems and trust in a managing authority for data and verification. They believe blockchain's decentralized nature solves this problem.

Phase 1 of the pilot project started in tuna fishing in Fiji. WWF worked with Viant, a "tool to make Ethereum more accessible and useful for supply chain asset tracking," TraSeable, a supplier of traceability software, and Sea Quest, a small, Fijian fishing company.[69] The project functions on the Ethereum blockchain, which uses the proof of authority consensus mechanism. Like CargoX, the WWF project utilizes data permissions to protect participant's identities and sensitive information.

During phase 1 of the project, the team relied on supply chain actors scanning radio-frequency identification (RFID) tags and quick response (QR) codes to track the fish through the supply chain. Supply chain actors also had to input relevant data—often referred to as key data elements (KDE) in the industry—through TraSeable's system. Crudely, Sea Quest and other supply chain actors collected and

---

[b] ERC721 (or ERC-721) is technical standard similar to ERC20. However, ERC721 is the technical standard for non-fungible tokens on the Ethereum blockchain.

[c] Traceability is essentially "a system of records designed to track the flow of a product through the production process or supply chain." (from http://futureoffish.org/content/traceability-101, accessed March 13, 2019)

input data into TraSeable's system, which shared the data with Viant's platform, which then recorded the data to the blockchain.

WWF notes the project faced a major data authenticity challenge. In the seafood supply chain, it is difficult to verify the authenticity of data being recorded, but blockchain offers the "ability to 'see' what previous actors have recorded and so it is possible to identify where supply chain actors may have entered false data into the supply chain."[70] In other words, because the data is now available, which it wasn't previously, it allows for supply chain actors to police the system by flagging incorrect and fraudulent information. As WWF notes, "the permanence of the blockchain allows instantaneous auditing of a historic record that could help identify patterns of ongoing fraud very quickly."[71] Given the phase 1 project's data authenticity challenge, current versions of WWF's project are focused on utilizing passive data collection techniques—the "collection of information without an explicit action by a supply chain actor."[72]

Fishcoin

Eachmile Technologies is the team behind Fishcoin, a platform utilizing the Ethereum public blockchain to increase transparency and traceability in the seafood industry.[73] Fishcoin describes itself as existing in two major parts: the Fishcoin ecosystem and the Fishcoin network. The Fishcoin ecosystem can be understood as the high-level system design that could enable more transparency and traceability in the seafood industry. The Fishcoin network is the open source tools and software kits that enable supply chain actors and others to utilize the Fishcoin ecosystem. The Fishcoin network utilizes several interconnected smart contracts to track data flow and exchange Fishcoin tokens.

At a high level, the Fishcoin ecosystem works in the same way as the WWF project: the data follows the seafood down the supply chain to the consumer and is tracked on the blockchain. The main difference between the two platforms is how each handles questions of data validity. The WWF project relies on members of the system self-policing by flagging incorrect or fraudulent data, and in the extreme case, no longer doing business with bad actors in the supply chain. Fishcoin, on the other hand, uses the Fishcoin tokens and its utility within the Fishcoin ecosystem to incentivize data validity.[74]

In the Fishcoin ecosystem, there are two things that happen in each transaction: (1) seafood is exchanged for fiat currency and (2) data is exchanged for Fishcoin tokens.[75] Seafood and data flow down the supply chain, while fiat currency and Fishcoin tokens flow up the supply chain. The first part of the transaction is the same as it would be without blockchain, but the exchange of data for Fishcoin tokens is novel. Fishcoin tokens represent a cost to the buyer of the seafood and the associated data. Therefore, according to Fishcoin, the buyer's willingness to exchange Fishcoin tokens for data indicates data accuracy because inaccurate data would prevent further transfers of data down the supply chain and possibly the sale of the seafood if a buyer requires the data for purchase.[76] Furthermore, Fishcoin notes that they have designed the ecosystem such that the economic burden of data falls on downstream actors (e.g., hotels, restaurants, and retailers) who benefit the most from the data through selling traceable fish at a premium.

An interesting feature of the Fishcoin ecosystem is token flow. Because Fishcoin tokens flow from buyers to sellers, they accumulate near the point of harvest. Producers are often small fishing outfits in developing countries where prepaid mobile data plans are heavily utilized.[77] To incentivize producers to want Fishcoin tokens, Eachmile Technologies has partnered with a mobile data plan top up service that enables Fishcoin tokens to be exchanged for mobile data top-ups.

3.3.3 Supply Chain Application Takeaways

Previously, we noted that supply chain applications of blockchain faced similar challenges as energy efficiency applications: they must (1) connect the physical world with the digital world and (2) ensure information stored in the blockchain is accurate. One takeaway from the sea shipping industry examples is a clear transition from an analog (paper) to digital (blockchain) medium, enabling a strong connection between the physical goods being shipped and the data in the digital tracking system. It is unclear how the sea shipping applications ensure information stored on the blockchain is accurate, but blockchain does make fraud and theft of shipping documents more difficult.

Our study of the seafood supply chain examples also has important takeaways. First, blockchain alone does not overcome the challenge of connecting the physical to the digital. There are important off-chain considerations (ecosystem design considerations) that support blockchain technology implementation to overcome this challenge. Even still, connecting the physical to the digital is hard because the blockchain systems must rely on actions that take place off-chain (e.g., properly scanning seafood). Second, blockchain alone does not overcome the challenge of ensuring information stored on the blockchain is accurate. Again, there are important ecosystem design considerations that support blockchain. For example, WWF's project utilizes self-policing to ensure data validity, while Fishcoin relies on Fishcoin tokens as an incentive for data validity.

The most important takeaway from studying sea shipping and seafood supply chain applications of blockchain is that ecosystem design is distinct yet connected to blockchain technology design. One clearly cannot have a blockchain ecosystem without blockchain technology. But more notably, one cannot have a viable blockchain technology platform without a clear ecosystem supporting it.

4 Analysis

4.1 Blockchain's Suitability to Address ESCert Market Hurdles

Recall from Section 2.1 that there are four common challenges associated with creating a market for trading ESCerts: (1) measurement and verification, (2) confirmation of additionality, (3) setting impactful targets, and (4) defining the geographic boundary. Utilizing insights gained from studying the technical aspects of blockchain (Section 2.2) and blockchain applications in comparable market (Section 3), we analyze how blockchain can or cannot solve the four main challenges listed above.

4.1.1 Measurement and Verification

Below, we outline several ways in which attributes of blockchain can help solve the measurement and verification challenge—developing a system to measure and verify savings to ensure they actually happened. Of the four common issues to be overcome in creating a market for trading energy efficiency credits, measurement and verification can be most fully addressed with blockchain.

Blockchain cannot influence measurement of energy savings, however, it can help with verification. Measurement would be done through some type of metering technology that occurs off-chain. Verification of savings can be facilitated through smart contracts. The basic idea is to: (1) input the energy consumption data and energy baseline[d] onto the blockchain (this could be done automatically by devices connected to the blockchain) and (2) run this data through smart contracts to verify savings. This last step could be performed by multiple nodes for increased trust. Once verified, the savings could be automatically turned into tokens representing savings credits.

[d] Note, specification of energy baselines for a blockchain system is outside the scope of this report. We simply treat the baseline as a black box. If a blockchain-based system were to be implemented, relevant parties (regulators, regulated entities, energy savings, etc.) would need to come to an agreement about what the baseline entails.

A supporting feature of blockchain is the ease with which it can be used for tracking. Because energy data and associated credits are on a blockchain, a regulator can more easily audit a subset of savings and credits to ensure greater accuracy when compared to a non-blockchain system.

Tokens could also be used in another way to address the measurement and verification challenge. Recall from the Fishcoin example (Section 3.3.2) that Fishcoin tokens are used as an incentive for truth telling in the seafood supply chain. In the energy efficiency supply chain, tokens could be used in the same way. For example, a separate utility token could be used to unlock the transfer of tokenized credits. If the credit buyer does not believe in the credits they are purchasing, then they would not "pay" to unlock their transfer. In theory, this would incentivize credit holders to ensure their credits are properly measured and verified, thus increasing trust in the system.

4.1.2 Confirmation of Additionality

The issue of additionality is a common issue faced with any policy. In order to prove that something is additional, one would need to prove a counterfactual, which is impossible. For example, it is impossible to say that a manufacturing facility would not have retrofitted with LED lightbulbs in the absence of the ESCert market.

While blockchain does not have the ability to verify a counterfactual, it can theoretically help with measurement in cases where there are multiple energy efficiency policies. For example, in instances where rebates on new equipment are provided, one cannot claim the rebate and the energy efficiency certificate. Smart contracts can be used to either retire a token issued for an energy efficiency credit or only issue a fraction of a token if a rebate is used. The difficulty with this would be verifying if a rebate were used. The smart contracts are only as effective as the information it receives. Thus, in most circumstances it would not be a practical application. However, in the case where another policy has a geographical characteristic, such as a tax benefit to incentivize investment in energy efficiency projects, a smart contract could verify and measure the impact from the other policy based on the location associated with the energy efficiency certificate.

In general, blockchain cannot confirm additionality because it is not able to verify a counterfactual. However, in very specific circumstances blockchain can help with measuring the impacts of other energy efficiency policies.

4.1.3 Setting Impactful Targets

Blockchain has a limited impact on setting targets for energy savings. As mentioned, blockchain will contribute to improved measurement and verification of energy savings. In addition, blockchain will enable entities with smaller energy savings to join the market at a lower cost by simplifying procedures. This helps the regulating entity to count the small participants' savings which were previously ignored in setting targets. This improved precision in verifying and accrediting previously omitted data helps regulators to more accurately observe the current status of energy savings and forecast future improvement.

However, accurate data is just one component of setting energy savings targets. There are multiple crucial factors affecting the target setting, such as the will of regulators, citizen's engagement in setting the goal, and opposition from relevant industries. Accuracy of current data helps identify the gap between the target and the current status, but it does not directly affect how ambitious the target ought to be.

Levying energy saving targets, as well as determining which entities must comply with the target, is a highly sensitive issue that can elicit strong opposition from relevant entities. Setting impactful targets has been an issue in carbon markets as well. For example, the EU Emission Trading Scheme (ETS) had low carbon emissions prices and low trading volume in its initial phases due to its redundant allocation. The redundant allocation was partially due to strong opposition from regulated entities. Also, Korea's ETS has loosened its emission reduction target as a result of intense disapproval from industries, such as steel, which are concerned about being disadvantaged compared to their unregulated global competitors.

The ETS cases show the complexity of setting targets in other markets that trade certificates of environmental value. Though blockchain addresses the accurate data issue, it is unlikely to have a meaningful impact on setting targets due to the political and economic implications of setting strict targets.

4.1.4 Defining the Geographic Boundary

The geographic boundary of ESCert markets matters when trading occurs between different states with inconsistent energy efficiency targets. To avoid undermining ESCert markets in the state with stricter goals, a trading boundary needs to be defined before uploading data to the blockchain system. In this case, the blockchain can be used to track each ESCert's origin, as the tokenized ESCert is tagged with the project's information such as the geographical location. When a transaction of ESCerts is requested, a smart contract can check and approve the transaction if the ESCert's location information shows that the transaction is within the boundary.

Defining a geographic boundary can create a "leakage" problem, similar to that in the carbon market. Utilities or industrial companies can locate their energy-inefficient facilities outside the policy boundary. The leakage problem can only be solved by a global market under universal policies. The blockchain system, especially a public blockchain system where entities around the world have equal access, can potentially provide a world-wide trading platform. However, this solution is unrealistic because cooperation between governments is infeasible and enforcing the target would be impossible. Therefore, blockchain is unlikely to address the leakage problem for ESCert markets.

4.2 Blockchain System Design for ESCert Markets

4.2.1 Overview

Although an ESCert trading market based on blockchain does not address many of the hurdles faced by ESCert markets, there are some clear benefits to the verification process. Thus, we designed a potential blockchain system for trading ESCerts. As illustrated in Figure 3, our design includes a variety of actors, such as utilities, customers, regulators, market operators, energy efficiency providers, auditors, and miscellaneous market participants. Regulators require utilities or regulated entities to meet an energy savings target. Customers (sellers), utilities (buyers), and other market participants are the main actors that trade the ESCerts. When a utility obtains ESCerts to satisfy the target, the certificates are retired by smart contracts and reported to the regulator. Tokens represent the amount of energy saved and make it possible for ESCerts to be traded on the blockchain system. Smart contracts streamline the verification and trading process and lower the barrier for small and new energy savers to enter the market.

4.2.2 Actors

Utilities/ Regulated Entities

In a regulated market, utilities are often required to meet the energy savings target set by regulators. In this system, it was assumed that utilities and other entities under compliance must meet the specific energy savings target set by regulators and are the final buyers of ESCerts before retirement.

There are various measures for utilities to meet their requirement such as demand-side management (DSM), peak demand reductions, building codes, combined heat and power (CHP), and self-direction. The ESCert market only includes energy saving measures that achieve permanent energy saving and emission reductions such as the installation of energy efficiency products. ESCerts would not include means that save energy temporarily such as peak demand reductions where energy consumption shifts in time.

Utilities comply with their target through either their own energy savings programs or purchasing certificates from other energy savers. After they attain the target amount of energy savings certificate, they report to regulators and the certificates (tokens) are burned accordingly. Utilities benefit from the reduced transaction costs by replacing costly administrative work with automated smart contracts.

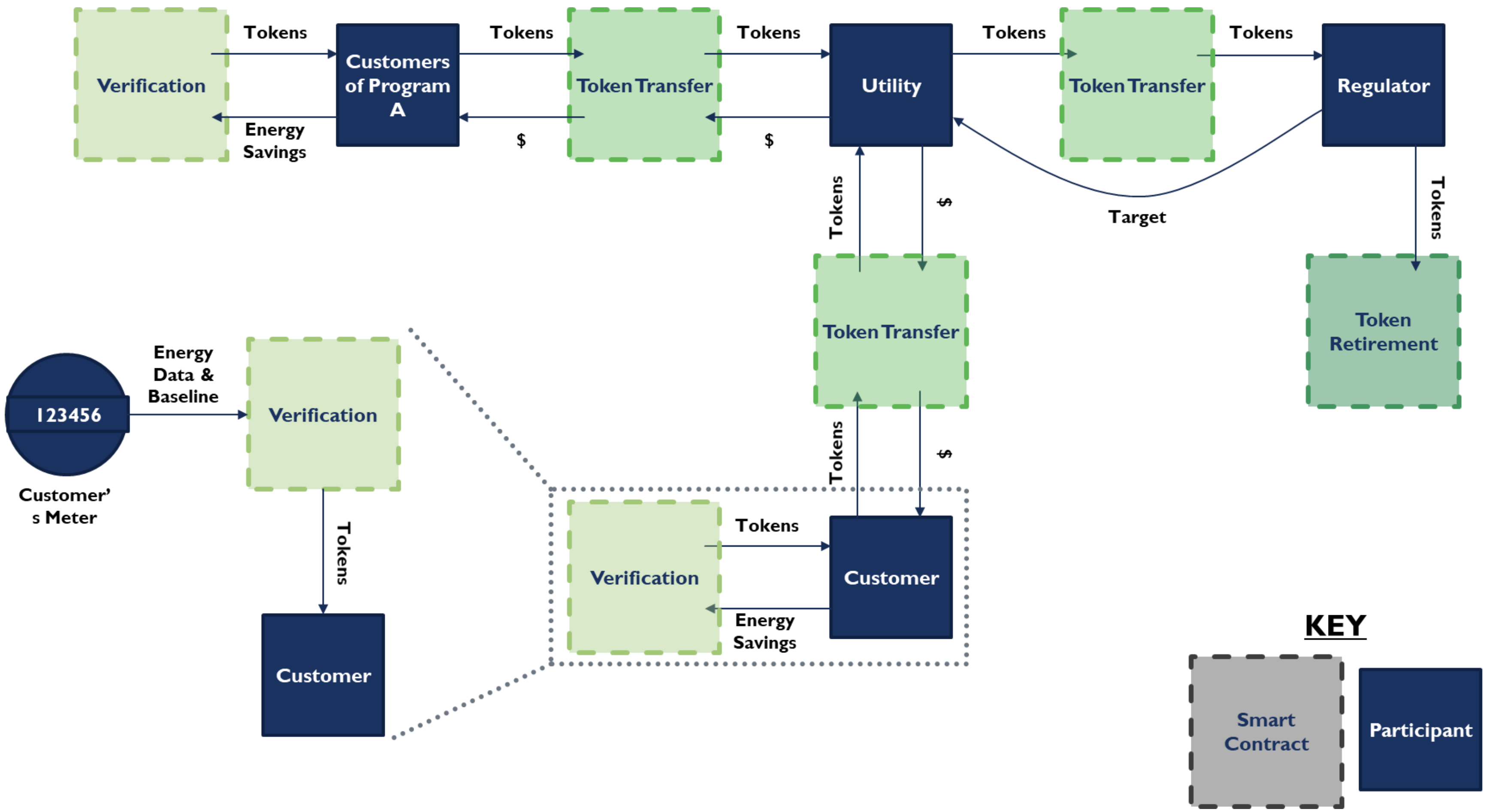

FIGURE 3. ECOSYSTEM DESIGN

Customers (Energy Savers, ESCert Sellers)

In the existing ESCert market, there are two major energy savers: (1) utilities and (2) private companies. Utilities save energy mainly through their demand side management programs. Private companies that consume a large amount of energy, such as manufacturing companies, implement energy savings projects voluntarily to reduce their energy bills. Their energy savings projects do not fall under the utilities' demand side management program. For a private company's energy savings project, the company confirms the plan suggested by the ESCO and compensates the ESCO for the project implementation. These energy savings are closely tied to each energy savings project and not traded in the market.

In our blockchain-based ESCerts system, both utilities and private companies can participate and trade in the same market as energy savers. Energy savers are any entity that saves energy relative to its baseline scenario, and they can receive ESCerts that correspond to the saved amount, which can then be sold in the market. An energy saver's energy savings, which are currently verified by a trusted third-party, such as M&V provider, can instead be verified through a smart contract.

Regulators

Regulators set the energy savings target for regulated entities and make sure the entities achieve the target within the specified period. Regulators receive information about how much energy the utility saved and how it met the target by looking at the information saved on blockchain instead of directly asking utilities. With more timely and accurate information, regulators can better forecast baseline scenarios and reflect that information in setting the future target. Through a blockchain-based energy savings trading system, regulators can ensure no double counting of certificates and data accuracy.

Energy Efficiency Providers and/or Measurement & Verification Providers

Energy efficiency providers and/or measurement & verification providers participate in the market indirectly by providing energy efficiency services to customers, including utilities. The verification of energy savings is replaced by smart contracts in the blockchain-based system. Their roles are limited to helping energy savers determine baselines and/or develop smart contract codes for M&V of their energy savings projects.

Miscellaneous Market Participants

Miscellaneous market participants do not directly engage in creating ESCerts through saving energy but instead participate in selling and buying ESCerts. They can profit from buying ESCerts at low prices and selling when the prices rise.

Auditors

Auditors do not directly take part in trading ESCerts, but they do participate in the system. They have access to market data that they need in order to perform an audit through token retirement smart contracts.

Market Operators

Market operators run the trading exchange platform for ESCerts, coordinating between buyers and sellers of ESCerts. However, their role is minimized under the blockchain system. The smart contracts can automate matching buyers with seller, which essentially eliminates the role of market operators.

4.2.3 Energy Savings Tokenization

Energy savings are tokenized by the blockchain system, which means ESCerts are issued as tokens on the blockchain. ESCert tokens are traded among individual and institutional participants on the blockchain system. One token represents one ESCert, or 1kWh of energy saved, and the tokenization process is automatically completed by the smart contract using smart-meter data. First, the smart meter or other Internet of Things (IoT) devices[e] create checkpoints to record real-time energy consumption several times per day and upload the data to the blockchain regularly. Second, smart contracts measure energy savings by comparing the metered data to the encoded baseline of energy consumption, while ensuring the conditions written in the smart contracts are satisfied. Then, the blockchain system automatically issues tokens to the energy savers. ESCert tokens can be traded to generate revenue for participants.

Tokens can be divided into fractions while remaining traceable. For example, one token can be divided into two half tokens, and these two half tokens can be traded and traced in different transactions. This feature is also helpful in accounting for other financial incentives, such as tax benefits for investments in

[e] Internet of Things (IoT) devices, equipped on an object or a network, is able to collect data from the object and automatically transfer the data to the other object through the Internet.

energy efficiency projects. In this case, the energy saver would receive a fraction of a token to avoid double counting the benefits.

Every token is traceable in the blockchain system. Besides technical information for traceability such as hash values, a token is tagged with the project name, year, related contracts, site of origin, and other relevant information at its creation. The geographical information of the tokens may be used to restrict token trading within the defined boundary. Table 1 is an example of project-specific information that would be tagged to a token.

TABLE 1. TOKEN INFORMATION TAG

Category	Information
Project Profile	Project Name Project Developer Project Owner Project Geographical Location Project Implementation Time Project Baseline and Alternative Scenario Information
Energy Saving Profile	Total Amount of Energy Saving within the Same Period of This Token
Time Checkpoints	Time Checkpoints of Energy Saving Data Associated with This Token
Smart Meter/IoT Device Profile	Smart Meter/IoT Device Serial Number Smart Meter/IoT Device Provider Smart Meter/IoT Device Location of Installation Load Components of Reading
Smart Contract	(Historical) Smart Contracts with This Token
Transaction	Historical Transactions with This Token

4.2.4 Smart Contracts

To serve different types of data exchanges and transactions between various stakeholders, the blockchain system employs three categories of smart contracts for issuing, trading, and retiring tokens. Within each category, more tailored smart contracts are available to serve specific stakeholders and their needs.

Token Issuance

Token issuance smart contracts are encoded with the content from energy saving measurement and verification models and agreements on tokens received by each associated entity. In the current system, the baseline for an energy saving project is set by an ESCO. ESCOs set the baseline by measuring an entity's energy consumption for a certain period, taking into account related variables, such as historical consumption, weather, and forecasted consumption. In a blockchain-based system, this process can be automated by smart contracts. If there is no previous metering data available for a project in the blockchain system, the ESCOs can access historical energy consumption data from the content in the smart contracts. However, for renewal projects that already have metering data recorded in the blockchain system, the ESCO can access the data directly and renew the content of the smart contracts to call the records. Metering data uploaded to the blockchain goes directly through the smart contract for tokenization, and the smart contract will transfer tokens based on the agreement.

Token Transaction

Token transaction smart contracts can be used as bilateral contracts to settle token transactions at a given time for delivery. Once entities reach an agreement and code it as a smart contract, the contract will automatically execute, which ensures the rights and obligations of both entities are met without needing a third party to oversee the transaction. The transaction of tokens is documented in the blockchain system, rather than requiring trusted third parties to verify and track the exchanges. The smart contract also significantly lowers the risk of repudiation and ambiguous terms since the contents are recognized by the machine with accurate algorithms.

Token Retirement

Retirement smart contracts can help regulators verify if the utility meets the energy efficiency target and retire the corresponding number of ESCert tokens. Utilities that are required to meet energy saving targets must prove that they met the target by giving an equal number of tokens to the regulators. Tokens used to meet the energy saving target are not allowed to recirculate in the market. Therefore, those tokens will go through the retirement smart contracts, which first confirm the target is met and then retire the tokens (transfer the tokens to an internal address and lockup the tokens forever). Adding a smart contract to this process improves the inspection process and traceability of mandatory target compliance.

4.3 Technical Recommendations

4.3.1 Blockchain Platform

We do not recommend a specific blockchain for the proposed ESCerts trading system. A blockchain-based trading system is within the scope of a mandatory market and subject to regulation; thus, specific technical features are needed to address regulatory issues. Given that most existing blockchains have embedded technical features and allow limited flexibility in developing case-specific features, selecting a specific blockchain to launch this project is not advantageous at this stage. However, if the blockchain proposed in this project is further developed or implemented, it will be valuable to conduct a comprehensive review of existing blockchain platforms and consider integrating desirable features.

An alternative to selecting an existing blockchain platform is to develop a unique blockchain platform that suits the needs of ESCert market. Building a blockchain based on an open-source structure, such as Ethereum, is resource efficient as there is no need to code from scratch. Additionally, modifications can be made to implement desired features.

4.3.2 Type of Blockchain

We recommend a public blockchain as a foundation for several reasons. First, requiring smart meters and other IoT devices qualifies entities to participate in selling ESCerts, which acts as granting permission to ESCert creators to participate in the market. Second, restricting access creates hurdles to entering the market, which could adversely impact the level of participation in the market. Thus, a public blockchain ensures that anyone who wants to participate is allowed. Third, a public blockchain is beneficial for determining the intrinsic value of ESCerts. Removing barriers to entry will help reveal the true price, which is an essential reference for regulators to adjust energy efficiency targets.

One concern is that the mandatory ESCert market is highly regulated. Regulators still have the centralized responsibility to supervise and operate the market. However, choosing a public blockchain does not equal complete decentralization. Rights and restrictions can be applied to each stakeholder so that the system aligns with the current regulatory structure.

4.3.3 Permission Levels

Though participating in the blockchain system does not require additional permissions, there should be permissions for specific activities. Permissions can be embedded to allow only certain nodes to participate in specific smart contracts. For example, permissions to use retirement smart contracts can be applied to only the nodes representing regulators. Additionally, regulators may have the privilege of requesting smart contract modifications throughout the entire network to align with policy changes. Without this privilege, governance solely depends on network voting, which could lead to the system not complying with regulations.

Permission is also essential for off-chain governance. Through off-chain governance, participants can contribute to network performance improvements, such as adding new functions, modifying smart contracts, or adopting new processes of transactions. Proper permissions for off-chain governance develop voting mechanisms to ensure the voices of the most relevant stakeholders carry the most weight. For example, an attempt to modify a smart contract for direct transactions between homeowners and utilities needs to ensure that the homeowners and utilities' voices are weighted more heavily than other stakeholders, such as market brokers and aggregators.

4.3.4 Consensus Mechanisms

We recommend the Proof-of-Authority consensus mechanism because of its ability to uphold the regulatory requirements. Recall from Section 2.2, the PoA mechanism preselects a group of block validators. Using the PoA mechanism will allow regulators to select block validators off-chain. Regulators will also need to verify that the validators' nodes match their true identity. While this imposes additional off-chain work on regulators, it ensures that regulatory requirements are met. Validators would be selected for their computing resources, expertise in energy efficiency markets, and reputation. Validators can also help detect inauthentic information in transaction requests, especially smart contract-based transactions in the ESCert issuing process. In the event of a suspicious transaction, validators can either reject the transaction request or flag the nodes for off-chain auditing.

The PoA mechanism will improve network performance by decreasing the settlement time and reducing transaction costs for customers. Unlike the PoW mechanism, PoA mechanism does not employ competition for mining. Therefore, the transaction fees will not be inflated to incentivize the validators, and the use of a large amount of computational power will be avoided. Additionally, without mining competition and frequent communication for consensus, the system's performance and the overall efficiency would improve.

4.4 System Benefits and Limitations

4.4.1 Benefits

A blockchain-based ESCerts trading system is expected to have three main benefits: (1) improving the verification and tracking of ESCerts, (2) streamlining the trading and auditing process, and (3) increasing participation in the market. First, blockchain technology improves the accuracy and security of data. Information associated with each ESCert, such as the location of origin, smart contracts, and transactions, is saved in the block and traded with extremely low risk of manipulation. This also makes tracking and auditing ESCerts easier and helps to avoid double-counting issues. Second, the tokenization and digitalization of data replaces time-consuming and costly administrative work. Smart contracts streamline the ESCerts trading process through the automation of ESCert issuance, token-data exchanges, and transaction validation. Third, private entities can now participate in the ESCert market and are incentivized to save energy in order to sell ESCert tokens. The increase in market participation may lead to an increase in the number of ESCerts traded and consequently reduce overall energy consumption.

4.4.2 Limitations

Although there are some clear benefits to a blockchain-based system, there are significant limitations. As mentioned in Section 4.1, a blockchain-based system does not solve the main barriers to establishing an ESCert market, which include measuring energy savings, confirming additionality, setting impactful targets, or defining the geographic boundary. Until these issues are addressed, establishing an efficient market will be difficult.

In addition to not addressing the main hurdles to creating a market, a blockchain-based system requires significant digital infrastructure, such as smart meters and IoT. Currently, utilities do not take stock of digital equipment used for tracking energy savings below the substation level (e.g., internet of things devices).[78] However, a blockchain system relies on a digital system. Thus, significant digital infrastructure must be established for effective operation of the blockchain-based ESCert market.

Moreover, a blockchain-based system does not address market design issues, such as certification and the oversupply of ESCerts. Regulators still set the criteria for certifying ESCerts, and the criteria can vary greatly by state, as in the REC market.[79] In certain markets where states have stricter criteria for certification, small or new energy savers would still face hurdles to entering the ESCert market. Conversely, if a state has generous criteria for certification, this can cause an oversupply of ESCerts, which would lead to low prices and low trading volume.

5 Conclusion

The purpose of this paper was to determine if blockchain could be used to create a market for trading energy efficiency credits. First, we examined ESCert markets and identified the four main challenges to establishing an energy efficiency trading market: (1) measurement and verification, (2) confirming additionality, (3) setting impactful targets, and (4) defining a geographic boundary for the program. Next, we discussed blockchain and how the technology works.

We then examined blockchain applications in three comparable markets: (1) REC markets, (2) carbon credit markets, and (3) supply chain. We found several instances where blockchain could address pain points in each market. However, blockchain was not a panacea and could not address all concerns faced by each market.

Using information regarding blockchain's applications' in comparable markets, we were able to perform a thorough analysis of blockchain's ability to address the four main challenges to creating an energy efficiency trading market. We found that blockchain only helped address issues with verification, and it did not help overcome issues related to measurement, confirming additionality, setting impactful targets, and defining a geographic boundary.

After determining that blockchain does have potential for addressing some of the concerns related to creating a market for ESCerts, we outlined a system design and provided technical recommendations. Lastly, we discussed some of the potential benefits and limitations.

Ultimately, we concluded that while blockchain does not address all the hurdles to creating an energy efficiency trading market, it is a valuable tool and can be done. This paper is only meant illustrate how blockchain can be used to create an energy efficiency market and does not form an opinion on whether it would be the best policy to encourage investment energy efficiency projects and reduce GHG emissions.

We recommend three potential next steps. First, there should be a comparison of the effectiveness of an energy efficiency trading market to other energy efficiency policies to determine the best policy or combination of policies. Second, there should be an analysis of existing or possible future legislation that would be necessary to create a market. Third, there should be more research on the technical requirements for this type of blockchain application and more structure on what is coded into the smart contracts in order to comply with regulations.

Citations

[1] The Economist. “Invisible Fuel.” The Economist, January 15, 2015. https://www.economist.com/special-report/2015/01/15/invisible-fuel.
[2] Sachs, Noah M. “Should the United States Create Trading Markets for Energy Efficiency?” Washington D.C.: Environmental Law Institute, June 2016. https://www.eli.org/sites/default/files/elr/featuredarticles/46.10466.pdf.
[3] Jason Massey (ndustrial.io). Personal interview. October 2018.
[4] Sachs, Noah M. “Should the United States Create Trading Markets for Energy Efficiency?” Washington D.C.: Environmental Law Institute, June 2016. https://www.eli.org/sites/default/files/elr/featuredarticles/46.10466.pdf.
[5] Jaffe, Adam B., and Robert N. Stavins. “The Energy-Efficiency Gap,” October 1994. https://scholar.harvard.edu/files/stavins/files/the_energy_efficiency_gap.pdf.
[6] Sachs, Noah M. “Should the United States Create Trading Markets for Energy Efficiency?” Washington D.C.: Environmental Law Institute, June 2016. https://www.eli.org/sites/default/files/elr/featuredarticles/46.10466.pdf.
[7] International Energy Agency. “White Certificate Trading for End-Use Energy Efficiency,” November 3, 2017. https://www.iea.org/policiesandmeasures/pams/italy/name-22483-en.php.
[8] International Energy Agency. “White Certificate Scheme & Obligation,” November 3, 2017. https://www.iea.org/policiesandmeasures/pams/france/name-22969-en.php.
[9] Industrial Efficiency Policy Database. “IN-2:Perform Achieve Trade Scheme (PAT Scheme).” The Institute for Industrial Productivity. Accessed April 10, 2019. http://iepd.iipnetwork.org/policy/perform-achieve-trade-scheme-pat-scheme.
[10] Industrial Efficiency Policy Database. “IN-2:Perform Achieve Trade Scheme (PAT Scheme).” The Institute for Industrial Productivity. Accessed April 10, 2019. http://iepd.iipnetwork.org/policy/perform-achieve-trade-scheme-pat-scheme.
[11] International Energy Agency. “Perform, Achieve, Trade (PAT) Scheme,” February 2018. https://www.iea.org/policiesandmeasures/pams/india/name-30373-en.php.
[12] Sachs, Noah M. “Should the United States Create Trading Markets for Energy Efficiency?” Washington D.C.: Environmental Law Institute, June 2016. https://www.eli.org/sites/default/files/elr/featuredarticles/46.10466.pdf.
[13] Molina, Maggie. “What Will Massachusetts’ New Efficiency Targets Mean for Future Policy?” American Council for an Energy-Efficient Economy, November 1, 2018. https://aceee.org/blog/2018/11/what-will-massachusetts-new.
[14] Sachs, Noah M. “Should the United States Create Trading Markets for Energy Efficiency?” Washington D.C.: Environmental Law Institute, June 2016. https://www.eli.org/sites/default/files/elr/featuredarticles/46.10466.pdf.
[15] Sachs, Noah M. “Should the United States Create Trading Markets for Energy Efficiency?” Washington D.C.: Environmental Law Institute, June 2016. https://www.eli.org/sites/default/files/elr/featuredarticles/46.10466.pdf.
[16] Sancho9000. “Cryptocurrencies and Crypto Games: What’s the Deal?” Crypto Bit Games (blog), March 8, 2018. https://cryptobitgames.com/cryptocurrencies-and-crypto-games/.
[17] “Blockchain Technology: Definition, Types & Uses.” Study.com. Accessed April 17, 2019. http://study.com/academy/lesson/blockchain-technology-definition-types-uses.html.
[18] “Blockchain Technology: Definition, Types & Uses.” Study.com. Accessed April 17, 2019. http://study.com/academy/lesson/blockchain-technology-definition-types-uses.html.
[19] Andoni, Merlinda, Valentin Robu, David Flynn, Simone Abram, Dale Geach, David Jenkins, Peter McCallum, and Andrew Peacock. “Blockchain Technology in the Energy Sector: A Systematic Review of Challenges and Opportunities.” Renewable and Sustainable Energy Reviews 100 (February 1, 2019): 143–74. https://doi.org/10.1016/j.rser.2018.10.014.
[20] Andoni, Merlinda, Valentin Robu, David Flynn, Simone Abram, Dale Geach, David Jenkins, Peter McCallum, and Andrew Peacock. “Blockchain Technology in the Energy Sector: A Systematic Review of Challenges and Opportunities.” Renewable and Sustainable Energy Reviews 100 (February 1, 2019): 143–74. https://doi.org/10.1016/j.rser.2018.10.014.
[21] Baliga, Dr Arati. “Understanding Blockchain Consensus Models.” 2017.

[22] "The Energy Web Chain: Accelerating the Energy Transition with an Open-Source, Decentralized Blockchain Platform Version 1.0." Energy Web Foundation, October 2018. https://energyweb.org/wp-content/uploads/2018/10/EWF-Paper-TheEnergyWebChain-v1-201810-FINAL.pdf.
[23] "What Is Proof of Authority Consensus? (PoA) Staking Your Identity." Blockonomi, July 5, 2018. https://blockonomi.com/proof-of-authority/.
[24] "What Is Proof of Authority Consensus? (PoA) Staking Your Identity." Blockonomi, July 5, 2018. https://blockonomi.com/proof-of-authority/.
[25] "What Is Delegated Proof of Stake?" Lisk. Accessed February 2019. https://lisk.io/academy/blockchain-basics/how-does-blockchain-work/delegated-proof-of-stake.
[26] Lewis, Antony, and Antony Lewis. "A Gentle Introduction to Digital Tokens." Bits on Blocks, September 28, 2015. https://bitsonblocks.net/2015/09/28/gentle-introduction-digital-tokens/.
[27] N. O. Sadiku, Matthew, Kelechi Eze, and Sarhan M. Musa. "Smart Contracts: A Primer," June 1, 2018.
[28] OAR US EPA, "Renewable Energy Certificates (RECs)," Overviews and Factsheets, US EPA, February 5, 2016, https://www.epa.gov/greenpower/renewable-energy-certificates-recs.
[29] Anirudh Gautam et al., Sustainable Energy and Transportation (Springer, 2018).
[30] OAR US EPA, "Renewable Energy Certificates (RECs)," Overviews and Factsheets, US EPA, February 5, 2016, https://www.epa.gov/greenpower/renewable-energy-certificates-recs.
[31] Eric O'Shaughnessy, Jenny Heeter, and Jenny Sauer, "Status and Trends in the U.S. Voluntary Green Power Market: 2017 Data" (National Renewable Energy Laboratory, October 2018), https://www.nrel.gov/docs/fy19osti/72204.pdf
[32] Douglas Miller and Claire Henly, "Blockchain Is Reimagining the Rules of the Game in the Energy Sector," Rocky Mountain Institute, August 28, 2017, https://www.rmi.org/blockchain-reimagining-rules-game-energy-sector/.
[33] Douglas Miller and Claire Henly, "Blockchain Is Reimagining the Rules of the Game in the Energy Sector," Rocky Mountain Institute, August 28, 2017, https://www.rmi.org/blockchain-reimagining-rules-game-energy-sector/.
[34] Kevin Stevens, "Why Blockchain Will Power the New Energy Network," Utility Dive, October 23, 2018, https://www.utilitydive.com/news/why-blockchain-will-power-the-new-energy-network/540226/.
[35] Douglas Miller and Claire Henly, "Blockchain Is Reimagining the Rules of the Game in the Energy Sector," Rocky Mountain Institute, August 28, 2017, https://www.rmi.org/blockchain-reimagining-rules-game-energy-sector/.
[36] Douglas Miller and Claire Henly, "Blockchain Is Reimagining the Rules of the Game in the Energy Sector," Rocky Mountain Institute, August 28, 2017, https://www.rmi.org/blockchain-reimagining-rules-game-energy-sector/.
[37]Melissa Goh, "Blockchain Tech Is Taking on Renewable Energy Trading in Singapore," CNBC, November 7, 2018, https://www.cnbc.com/2018/11/07/blockchain-tech-is-taking-on-renewable-energy-trading-in-one-country.html.
[38]SP Group, "SP Group Launches One of the World's First Blockchain-Powered Trading of Renewable Energy Certificates," Press Release, October 29, 2018; SP Group, SP Group REC Marketplace, accessed April 5, 2019, https://www.youtube.com/watch?v=N1YopoPIqTg&feature=youtu.be.
[39] SP Group, SP Group REC Marketplace, accessed April 5, 2019, https://www.youtube.com/watch?v=N1YopoPIqTg&feature=youtu.be.
[40] "Collaboration to Build Blockchain Tool for U.S. Renewable Energy Market," Transmission & Distribution World, October 25, 2018, https://www.tdworld.com/utility-business/collaboration-build-blockchain-tool-us-renewable-energy-market.
[41] William Driscoll, "PJM Subsidiary to Test Blockchain for Trading RECs," PV Magazine USA, October 25, 2018, https://pv-magazine-usa.com/2018/10/25/pjm-to-test-blockchain-platform-for-trading-renewable-energy-certificates/.
[42] William Driscoll, "PJM Subsidiary to Test Blockchain for Trading RECs," PV Magazine USA, October 25, 2018, https://pv-magazine-usa.com/2018/10/25/pjm-to-test-blockchain-platform-for-trading-renewable-energy-certificates/.
[43] William Driscoll, "PJM Subsidiary to Test Blockchain for Trading RECs," PV Magazine USA, October 25, 2018, https://pv-magazine-usa.com/2018/10/25/pjm-to-test-blockchain-platform-for-trading-renewable-energy-certificates/.

[44] Anonymous. "Carbon Leakage." Text. Climate Action - European Commission, November 23, 2016. https://ec.europa.eu/clima/policies/ets/allowances/leakage_en.
[45] Glendhill, Richard, Jonathan Grant, and Lit Ping Low. "Review of Carbon Market." Briefing Paper. PricewaterhouseCoopers LLP, UK, 2008. https://www.theclimategroup.org/sites/default/files/archive/files/Carbon-Markets-Review.pdf.
[46] "We Bring the World Sustainability through Technology - Creating a Transparent Carbon Market for a Sustainable Future." Xarbon Sustainability Limited, 2018. http://xarbon.com/assets/Xarbon_Whitepaper_V1.1_EN.pdf.
[47] "A New Global and Trusted Standard for Recording, Measuring and Trading Your Clean Energy Footprint." New Era Energy Ltd, February 20, 2018.
[48] Maersk, and IBM. "Maersk and IBM Unveil First Industry-Wide Cross-Border Supply Chain Solution on Blockchain." IBM, August 9, 2018. https://newsroom.ibm.com/2018-08-09-Maersk-and-IBM-Introduce-TradeLens-Blockchain-Shipping-Solution.
[49] Park, Kyunghee. "Blockchain Is About to Revolutionize the Shipping Industry." Bloomberg, April 18, 2018. https://www.bloomberg.com/news/articles/2018-04-18/drowning-in-a-sea-of-paper-world-s-biggest-ships-seek-a-way-out.
[50] CargoX. "Business Overview and Technology Bluepaper," 2018. https://cargox.io/CargoX-Business-Overview-Technology-Bluepaper.pdf.
[51] White, Mike, and Marvin Erdly. "TradeLens: A Journey from Beta to Production in One Year." TradeLens, December 11, 2018. https://blog.tradelens.com/news/tradelens-a-journey-from-beta-to-production-in-one-year/.
[52] CargoX. "Business Overview and Technology Bluepaper," 2018. https://cargox.io/CargoX-Business-Overview-Technology-Bluepaper.pdf.
[53] Maersk, and IBM. "Maersk and IBM Unveil First Industry-Wide Cross-Border Supply Chain Solution on Blockchain." IBM, August 9, 2018. https://newsroom.ibm.com/2018-08-09-Maersk-and-IBM-Introduce-TradeLens-Blockchain-Shipping-Solution.
[54] TradeLens. "TradeLens Solution Brief, First Edition," August 1, 2018. https://www.tradelens.com/solution/.
[55] TradeLens. "TradeLens Solution Brief, First Edition," August 1, 2018. https://www.tradelens.com/solution/.
[56] TradeLens. "TradeLens Solution Brief, First Edition," August 1, 2018. https://www.tradelens.com/solution/.
[57] TradeLens. "TradeLens Solution Brief, First Edition," August 1, 2018. https://www.tradelens.com/solution/.
[58] Lim, Sandra. "Bill Of Lading." Investopedia, January 29, 2018. https://www.investopedia.com/terms/b/billoflading.asp.
[59] CargoX. "Business Overview and Technology Bluepaper," 2018. https://cargox.io/CargoX-Business-Overview-Technology-Bluepaper.pdf.
[60] Maanen, Marc van, and Iris Regtien. "E-Bills of Lading." Lexology, April 20, 2018. https://www.lexology.com/library/detail.aspx?g=453d225f-ca8b-404f-9b39-f39f4f0a7b90&l=8C0HPVK.
[61] CargoX. "Business Overview and Technology Bluepaper," 2018. https://cargox.io/CargoX-Business-Overview-Technology-Bluepaper.pdf.
[62] CargoX. "Business Overview and Technology Bluepaper," 2018. https://cargox.io/CargoX-Business-Overview-Technology-Bluepaper.pdf.
[63] CargoX. "Business Overview and Technology Bluepaper," 2018. https://cargox.io/CargoX-Business-Overview-Technology-Bluepaper.pdf.
[64] Cook, Bubba. "Blockchain: Transforming the Seafood Supply Chain." World Wildlife Fund for Nature, New Zealand, August 31, 2018. https://dj8xp7a0ejkvv.cloudfront.net/downloads/draft_blockchain_report_1_4_1.pdf.
[65] Fishcoin. "44. Fishcoin: A Blockchain Based Data Ecosystem For The Global Seafood Industry," February 2018. https://fishcoin.co/files/fishcoin.pdf.
[66] Cook, Bubba. "Blockchain: Transforming the Seafood Supply Chain." World Wildlife Fund for Nature, New Zealand, August 31, 2018. https://dj8xp7a0ejkvv.cloudfront.net/downloads/draft_blockchain_report_1_4_1.pdf.
[67] Fishcoin. "Fishcoin: A Blockchain Based Data Ecosystem For The Global Seafood Industry," February 2018. https://fishcoin.co/files/fishcoin.pdf.

[68] Cook, Bubba. “Blockchain: Transforming the Seafood Supply Chain.” World Wildlife Fund for Nature, New Zealand, August 31, 2018. https://dj8xp7a0ejkvv.cloudfront.net/downloads/draft_blockchain_report_1_4_1.pdf.
[69] Cook, Bubba. “Blockchain: Transforming the Seafood Supply Chain.” World Wildlife Fund for Nature, New Zealand, August 31, 2018. https://dj8xp7a0ejkvv.cloudfront.net/downloads/draft_blockchain_report_1_4_1.pdf.
[70] Cook, Bubba. “Blockchain: Transforming the Seafood Supply Chain.” World Wildlife Fund for Nature, New Zealand, August 31, 2018. https://dj8xp7a0ejkvv.cloudfront.net/downloads/draft_blockchain_report_1_4_1.pdf.
[71] Cook, Bubba. “Blockchain: Transforming the Seafood Supply Chain.” World Wildlife Fund for Nature, New Zealand, August 31, 2018. https://dj8xp7a0ejkvv.cloudfront.net/downloads/draft_blockchain_report_1_4_1.pdf.
[72] Cook, Bubba. “Blockchain: Transforming the Seafood Supply Chain.” World Wildlife Fund for Nature, New Zealand, August 31, 2018. https://dj8xp7a0ejkvv.cloudfront.net/downloads/draft_blockchain_report_1_4_1.pdf.
[73] Fishcoin. “Fishcoin: A Blockchain Based Data Ecosystem For The Global Seafood Industry,” February 2018. https://fishcoin.co/files/fishcoin.pdf.
[74] Fishcoin. “Fishcoin: A Blockchain Based Data Ecosystem For The Global Seafood Industry,” February 2018. https://fishcoin.co/files/fishcoin.pdf.
[75] Fishcoin. “Fishcoin: A Blockchain Based Data Ecosystem For The Global Seafood Industry,” February 2018. https://fishcoin.co/files/fishcoin.pdf.
[76] Fishcoin. “Fishcoin: A Blockchain Based Data Ecosystem For The Global Seafood Industry,” February 2018. https://fishcoin.co/files/fishcoin.pdf.
[77] Fishcoin. “Fishcoin: A Blockchain Based Data Ecosystem For The Global Seafood Industry,” February 2018. https://fishcoin.co/files/fishcoin.pdf.
[78] Hartnett, Sam (Energy Web Foundation). Personal interview. March 2019.
[79] Lukach, Jaclynn (PJM-EIS). Personal interview. February 2019.