Towards Ontology and Blockchain Based Measurement, Reporting, and Verification For Climate Action

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Abstract

Efforts like carbon credits that incentivize GHG emissions reduction are hampered by an inability to account for quantity and impact of emissions in transparent and uniform ways. Authoritative entities like the UN have espoused blockchain's potential to address transparency and novel Measurement, Reporting, and Verification (MRV) systems for climate action constitute the state-of-the-art in research and industry to use blockchain to address the transparency need. However, impact of such efforts are diluted if there is not sufficient uniformity: Different blockchains idiosyncratically quantifying carbon credits and reporting them based on standards not widely adopted may offer only some improvement over the status quo. In this paper, we specify a top-level architecture that uses Semantic Web ontologies to complement a blockchain-based MRV system to address the need for uniformity and sharability. We pose this within the context of the real-life *Reciclo Orgánicos* project, an international collaboration to reduce GHG emissions from Chile's municipal waste sector. Our design conceptualizes transforming "smart standards" that are efficiently designed and harmonized using IT into ontologies of quantification methodologies and verification standards, which in turn can be used develop smart contracts executable on, and interoperable between, different blockchain platforms. Though preliminary, our design makes a potentially important contribution towards a Digital MRV system that effects impactful climate action.

1 Introduction

GHG (Greenhouse Gases) emissions from human activity are accumulating in the Earth's atmosphere and have increased 46 percent above pre-industrial levels. Carbon pollution including industrial gas with over 10000x the environmental impact of CO_2 is contributing climate disruptions like massive hurricanes, longer droughts, devastating forest fires, and the spread of diseases and invasive species. The province of Quebec in Canada suffered an enormous flood in 2017, the third straight year experiencing what was heretofore a once-in-a-hundred-year event. Places like Middle East and India are experiencing prolonged extreme heat in excess of 45°C, putting added pressure on mass migration of environmental refugees (Baumann, 2018).

Although government-coordinated market mechanisms like emissions trading of carbon credits have been experimented with to incentivize adoption of clean technologies and mitigate carbon emissions, results have been disappointing in both environmental and business terms. Inefficient program design and implementation, high administrative costs, and inadequate resources (e.g. expertise, data) to scale the market are the main reasons. Also, approaches are fragmented and inconsistent at the macro level: Varying standards across the world lead to different carbon accounting units (Baumann, 2018). For example, a ton of CO_2 reduced in Canada does not necessarily have an equivalent *mitigation value* to a ton of CO_2 reduced in India (Shekhar et al., 2016). That is, efforts to award credits and incentives to those that reduce emissions or mitigate their impact are hampered by an inability to account for the quantity and impact of emissions in **transparent** and **uniform** ways.

Blockchain constitutes a novel technology for providing much needed transparency to GHG mitigation and indeed many have undertaken such work. In this paper, we describe work that extends blockchain efforts further: We conceptualize using computational ontologies to innovatively apply carbon emission standards to data on the blockchain as part of a Digital MRV (Measurement, Reporting, and Verification) system essential for tracking and management of climate-related information and activities. Our work promises to complement blockchains providing transparency with ontologies providing uniformity and standardization, thus benefitting climate action efforts in carbon mitigation and other climate actions.

2 Review of Blockchain Research in Climate Change and Sustainability

Recognizing the importance of addressing climate change, the 2015 Paris Agreement declared a "moon shot" to decarbonize and shift to a clean economy by 2050. Blockchain is recognized as a emerging technology to help achieve this goal.

> "The United Nations Framework Convent on Climate Change (UNFCCC) secretariat recognizes the general potential of Blockchain technology. In particular, transparency, cost-effectiveness and efficiency advantages, which in turn may lead to greater stakeholder integration and enhanced creation of global public goods, are currently viewed as the main potential benefits. The secretariat, therefore, specifically supports initiatives that lead to innovation at the intersection of Blockchain and climate" (United Nations Framework Convent on Climate Change (UNFCCC), 2017)

Since this UNFCCC recognition, there have been numerous research efforts at applying blockchain to different areas under the umbrella of "Climate Change and Sustainability." A dichotomy of blockchain for a financing system vs. blockchain for an operations system (Kim, 2018; Treiblmaier et al., 2020) presents a useful means of classifying these efforts. The precept for this dichotomy is that a blockchain for financing (for e.g. ICO's or working capital loans) and a blockchain for operations (for e.g. provenance tracking) ought to be designed complementarily and more tightly coupled: By coupling a blockchain for operations that recognizes and penalizes moral hazard behaviour with a blockchain for financing that offers contingent actions to lessen the effect of adverse selection, heightened productivity and effective allocation of resources are possible. Below we use the dichotomy to characterize some representative blockchain research efforts in Climate Change and Sustainability[1].

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[1] Note that these topics are not mutually exclusive and there is overlap between them.

Climate change and sustainability topics	Blockchain for Operations	Blockchain for Financing
Carbon emission	Public disclosure of carbon emissions (Fu et al., 2018); tracking carbon credits from generation to redemption (Ashley & Johnson, 2018)	Matching buyers and sellers (Khaqqi et al., 2018; Schletz et al., 2020) in carbon emissions trading; Emission Trading System design using permissioned (Yuan et al., 2019) and permissionless (Willms, 2017) blockchains; Using blockchain as an improved business process management for a national (Australian) carbon registry (Hartmann & Thomas, 2020).
Green Energy	Tracking actual energy consumption to report to market participants in transactive energy framework (Saxena et al., 2020); providing secure charging services for electric vehicles (Su et al., 2019)	Incentive markets and reputation management system for electric grid operators to incentivize microgrid operators and individuals to regulate energy consumption and production (Saxena et al., 2020); bookkeeping credit transfers for homes within a microgrid (M. C. Lacity, 2018); mechanisms for public charging (consumer pays) and discharging (consumer paid) to/from electric vehicles (Su et al., 2019)
Resilient and low carbon supply chains	Research issues in blockchains for sustainable supply chains (Saberi et al., 2019); exploring more complex supply chains (Manupati et al., 2020)	Financing transparent supply chains using blockchains (Chod et al., 2020)
Waste management	Blockchain-based smart contracts use for more efficient management of waste management business processes (Gupta & Bedi, 2018)	Crypto, “green” coins paid to volunteer waste collectors (França et al., 2020)
Circular economy	Blockchain use in plastics recycling (Sankaran, 2019)	Valuating and tokenizing recycled/reused/reduced products as they change form (Narayan & Tidström, 2020)
Wildlife conservation	Blockchain-based data management framework to provide near real-time reporting to donors of conservation projects (e.g. progress of efforts to protect endangered species) (Dryga et al., 2019)	Using blockchain for ecosystem services (“eco-credits”) to Africa and Global South (Oberhauser, 2019); Finding buyers for oversupplied Reducing Emissions from Deforestation and Forest Degradation

		(REDD+) credits generated in tropical forest regions (Howson et al., 2019).

There are numerous works in blockchain for climate change and the table does not represent an exhaustive survey; these can be found at (Bao et al., 2020; Baumann, 2018; Mollah et al., 2020). In particular, we note the collaborative consortium efforts of (Climate Chain Coalition, 2020; Climate Ledger Initative, 2020; Dong et al., 2018, 2018; Hyperledger Foundation, 2020; Yale OpenLab, 2020). Nevertheless, there are interesting insights gleaned from conducting this survey. For example, of the topics presented in the table, sheer number of efforts in carbon emission and green energy dominate. Other insights stems from juxtaposing carbon emission efforts vis-à-vis green energy ones. For example, a representative effort to use blockchains to regulate contribution of electricity from renewable source micro grids and individuals to main grid operators – and vice versa for consumption of electricity from main to micro grids – encompasses both blockchain for financing and blockchain for operations. Of the three objectives of the blockchain design of (Saxena et al., 2020),

i) *Maintaining an auditable reputation rating for each agent that is increased proportionately with each mitigation of a voltage violation* entails measuring, tracking and calculating energy consumption and production by agent (microgrids or individuals on a microgrid) and constitutes facets of an **operations** system
ii) *Automating the negotiation and bidding of agent services by implementing the contract net protocol (CNP) as a smart contract* entails establishing a market mechanism and tokenizing transfer of value and constitutes facets of a **financing (or payment)** system
iii) *utilizing smart contracts to enforce the validity of each transaction and penalize reputation ratings in case of a mitigation failure* entails enabling measurement and tracking of agent behaviour to inform to financing decisions, and enabling financing decisions to incentivize agents operate in compliance to financing agreements. This constitutes a **tight coupling of financing and operations** systems.

For carbon emissions, these would be akin to blockchain use for:

i) *Transparent Data Management.* That is, data from a facility's databases and sensors would be stored on the blockchain and used for data management **operations** functions such as public disclosure of emissions (Fu et al., 2018).
ii) *Registries for carbon reporting of earners and purchasers of carbon credits* could be maintained as distributed ledgers using blockchain (Hartmann & Thomas, 2020). Registries complement *Emissions Trading Systems (ETS)* that provide markets for trading carbon credits. There are several examples of ETS enabled using blockchain (Willms, 2017; Yuan et al., 2019). Registries and ETS constitute **financing** systems that provide monetary incentives to emissions mitigation efforts.
iii) If implemented using blockchain, *carbon auditing and accounting systems* constitute a **tight coupling of financing and operations** systems. Data from sensors and other sources can be "rolled up" to calculate carbon credits that can be registered and traded. Moreover, carbon standards and requirements that dictate how emissions are recognized, and credits, calculated, can be "rolled down" for reporting and verification. Using smart contracts, a blockchain-based carbon accounting and auditing system can execute aspects of this roll-up from the data management and

roll-down from carbon standards. Interestingly, there does not appear to be much research into blockchain-based carbon accounting and auditing systems, lagging blockchain-based data management, registries, and ETS in number of research efforts. This then is a research opportunity

In sum,

- UN Secretariat for Climate Change and other authorities believes that blockchain and the transparency provided by its use – as well as its value to catalyze financing of climate action projects – is useful to address climate change. And indeed, there are numerous efforts at the intersection of blockchain and climate change.
- These blockchain efforts can be classified under topics of carbon emissions, green energy, resilient and low-carbon supply chains, waste management, circular economy, wildlife preservation, and green finance. Carbon emission and green energy are most studied by blockchain researchers.
- Using a framework that classifies research efforts into those for operations (e.g. provenance tracking), financing (e.g. cryptocurrencies), and coupling between operations and financing, blockchain-enabled transactive energy systems to incentivize and operate microgrids that generate renewable energy – a green energy example – has elements of all three classes of systems.
- A parallel for carbon emissions is data management for operations, carbon registries and Emission Trading Systems (ETS) for financing, and carbon auditing and carbon accounting for coupling between data management and registries and ETS. Interestingly, the novel opportunity lies in research blockchain-enabled carbon auditing and accounting systems.

The transactive microgrid example we examined is much less complex than a carbon emission system. Data gathered from sensors and recorded on a microgrid's blockchain needs much less aggregation, transformation, and interpretation than carbon emissions data. For instance, the microgrid is paid per kilowatt-hours of electricity produced at a given data/time. The unit of measurement for what is collected and what is paid for is straightforward and entails an "apples-to-apples" comparison. Contrast that with how data from an emission reporting system – e.g. what is the overall emissions and what component of that is "green" – needs to have standards as well expertise of auditors and accountants applied so that carbon credits can be attributed. Interpretations can vary widely not just by auditors but also from one national standard to another and from one standards body to another. To have a blockchain enabled carbon emission system that is as tightly integrated as the state-of-the-art in microgrids requires all those standards and auditor and accountant judgements to be somehow encoded as smart contracts that execute on managed data and registry/ETS systems. To that end, next we provide some background on smart contracts and ontologies and outline how ontology-based smart contracts can be used for this aim.

3 For Digital MRV: Smart Contracts and Ontologies

There is a term that is inclusive of emissions data management, standards and requirements, and carbon auditing and accounting: Measurement, Reporting, and Verification (MRV). It encompasses an operations system and can offer coupled links to financing systems such as external national registries and ETS's. The term MRV is used within other climate action efforts beyond carbon emissions in cases where:

- Climate data is **measured**

- Aggregated data is **reported** as per financial *and* non-financial accounting standards specified for a climate action industry class (e.g. carbon emissions, green energy, etc.)
- An external audit of a facility that **verifies** that reporting adheres to industry accounting standards and that the facility functions adhere to industry standards on operational characteristics is performed

There has been a fragmented proliferation of MRV standards[2] since the 1990's (World Bank Group, 2016). Well over a thousand MRV standards have been developed by various stakeholders such as: National (e.g. US, UK, EU countries) and sub-national (e.g. California, Alberta) government programs; industry associations (e.g. oil and gas, transportation, waste); voluntary initiatives (e.g. GHG Protocol, Gold Standard, Verified Carbon Standard, American Carbon Registry, Assessing low-Carbon Transition – ACT, Science Based Targets - SBTs); international organizations (e.g. Intergovernmental Panel on Climate Change); standards bodies (e.g. International Organization for Standardization - ISO, British Standards Institution); and research institutes and academia (e.g. life cycle, sector, and macro-economic models). The UNFCCC Clean Development Mechanism (CDM) includes over 200 MRV methodologies for large-scale projects, small-scale projects and standardized baselines.

Most MRV standards were developed by various actors during the early phase of climate policies and carbon markets, and resultingly, standards are not only fragmented but lack harmonization into a user-friendly system (Baumann & Kollmuss, 2010; Gasiorowski-Denis, 2017). Companies expend major resources to apply the standards, and yet the results vary from jurisdiction to jurisdiction. Furthermore, an MRV methodology can cost hundreds of thousands of dollars to develop, and an international standard can cost one million dollars per page to develop as well as three to four years until it gets published.

If smart contracts that execute upon data collected from sensors and databases and stored on the blockchain codify climate action accounting and auditing rules as specified in the above-mentioned standards, then automation and efficiency gains can be added along with transparency as compelling reasons to use blockchain.

A smart contract is merely a computer program that executes in a blockchain environment. The term "smart contracts" is a misnomer. There is nothing inherently "smart" nor contract-like about a blockchain smart contract, though a well-written smart contract can autonomously enforce a contractual obligation—e.g. automatically sending payment from a payer once the recording of a service provided by the payee as per the logic programmed in a smart contract is verified on the blockchain. Smart contracts are functionally expressive: For instance, the Solidity programming language widely used to code smart contracts in Ethereum is Turing complete. There are however differences compared to more fully expressive languages like Java and Python. Certain paradigms like dynamic typing and non-deterministic execution are not permitted in smart contracts as they are inconsistent to cryptographically secured and tamper proof design principles of blockchain.

There is a caveat to the effective use of blockchain and smart contracts for a carbon MRV system, however. The computer-encoded standards must themselves reflect standardization[3]. That is, if the standards are codified in a haphazard way, it is akin to auditors and accountants interpreting the

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[2] Standards is a used as a general term to encompass also methodologies, guidelines, protocols and other "rules"

[3] Standards will also drive the AI-powered wave of auditing and accounting (for climate and other applications)

standard in idiosyncratic ways that may be unfaithful to precepts of the standards. What is the point of ensuring that raw data is transparently and immutably maintained on the blockchain if how carbon credits are assigned from the data is opaque and not uniformly applied? The role of Semantic Web ontologies in this context is to ensure the required standardization and sharability and interoperability.

The Semantic Web refers to models, standards, tools, and methods that extend the World Wide Web to make the Internet machine-readable. Its key technology is ontologies, which is used to represent the rules sharable and executable throughout the Internet that would allow, for example, Internet-enabled calendars, phones, clocks, and providers' databases to automatically coordinate and schedule a medical appointment between multiple parties (Berners-Lee et al., 2001).

Before the pseudonymously named Satoshi Nakamoto launched Bitcoin and blockchain with their whitepaper (Nakamoto, 2008), there were already thriving communities developing decentralized systems that could inter-operate in the absence of an intermediary—the ontology and open data communities. The development premise for these communities assumes that data from disparate sources is "open" to being shared, and that semantics in the form of ontology representations and meta-data are required to unambiguously interpret data that is processed for inter-organizational business processes and Web services. The premise for Bitcoin and traceability blockchains assumes that blockchain is needed because data is closed for sharing; that is, it is assumed that self-interested intermediaries tend to hoard and close-off data about network members' transactions or complex business networks like supply chains tend to have no natural intermediaries and hence there is no network-wide record of transactions.

Interestingly, given this seeming synergy, there have not been that many works that examine blockchain and ontologies. One area of investigation has been in developing a characterization of blockchain concepts and technologies as ontologies. These works present an ontology of blockchain as a natural language characterization of blockchain constructs – e.g. "What are the different kinds of blockchains?" (Glaser, 2017; Tasca & Tessone, 2019). Or, commit further to representing an ontology of blockchain as conceptual modelling formalism – e.g. representing that "an EconomicAgent initiates a Transaction, which is governed by a SmartContract" in UML notation (de Kruijff and Weigand 2017a)(de Kruijff and Weigand 2017b).

Rather than developing an ontology of blockchain, other works endeavor to represent ontologies of enterprise or general concepts within a blockchain context, and furthermore, commit to prototypical implementations. A comprehensive treatise on integrating blockchain and ontologies is the BLockchain ONtology with Dynamic Extensibility (BLONDiE) project (Hector & Boris, 2020). The BLONDiE ontology is implemented in OWL and interfaces with Bitcoin and Ethereum networks as well as Hyperledger. The implementation answers competency questions such as "Who was the miner for each block?" and "How many transactions were included in each block?" The project also presents a Decentralized Supply Chain Application (DeSCA), which is a prototype where different companies along a supply chain would use a common blockchain as source of data, and inter-organizational business processes would entail use of ontologies represented using an RDF framework. Another work proposes and develop a prototypical implementation of an ontology of traceability as an Ethereum smart contract for a supply chain provenance use case (Kim & Laskowski, 2018).

In sum, much of the transparency benefits of blockchain use is lost if data on the blockchain cannot be calculated, aggregated, and transformed in uniform, repeatable – i.e. standardized – ways. It is not merely that the proliferation of standards is problematic in climate action; even if one of the standards is agreed upon by many as appropriate, the smart contracts that operate on the data stored on a blockchain may not be so agreed. Inasmuch as there may be too many standards, there are not enough computer encoded versions of these that can “talk” to the blockchain. In a space that is so heavily dependent on standards to valuate and reward effective climate actions, this paucity may neuter the highly touted promise of blockchain use. Next, we propose an architecture that augments ontologies to resolve this issue.

4 Architecture for an Ontology-Based MRV Blockchain for Climate Action

4.1 Background

An overall digital MRV system that supports carbon mitigation as well as other climate action efforts such as green energy and green finance – and which is implemented using blockchain, ontologies as well as other emerging technologies such as AI and Internet of Things – is an ambitious effort espoused by (Baumann, 2018; World Bank Group, 2018). In this section, we propose an architecture for such a system with specific focus on ontologies and blockchains for climate action auditing and accounting.

The first precept of this architecture is the importance of interoperability. Recall that a key issue in climate action is proliferation of standards and methodologies. A digital MRV system must be flexible enough to account for this proliferation; it must facilitate reasonable interoperability between systems using similar classes of standards and methodologies. As applied to blockchain, interoperability can be characterized as follows: “An interoperable blockchain architecture is a composition of distinguishable blockchain systems, each representing a unique distributed data ledger, where atomic transaction execution may span multiple heterogeneous blockchain systems, and where data recorded in one blockchain is reachable, verifiable and referenceable by another possibly foreign transaction in a semantically comparable manner ” (Yaga et al., 2018, p. 50).

Recognizing the relevance of interoperability for our efforts, we use the following framework as a guide for further work.

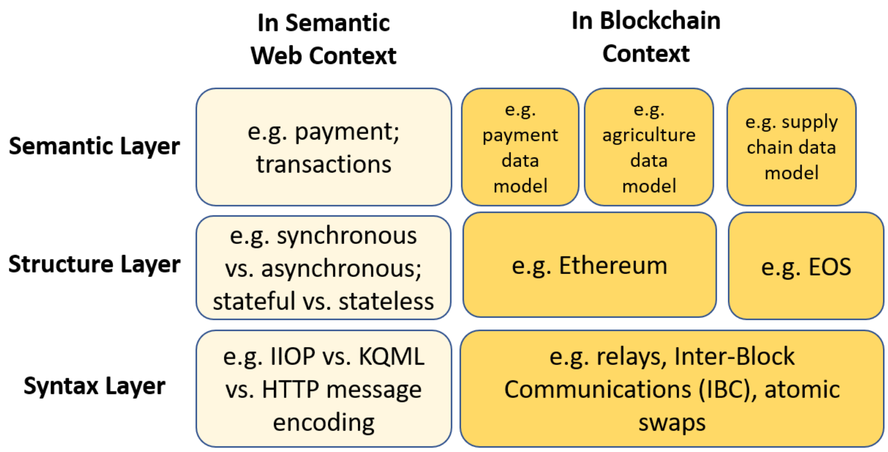

Figure 1: Interoperability in Semantic Web and Blockchain Contexts[4]

Figure 1 disambiguates blockchain interoperability into its various types (Kim et al., 2020). We are concerned with the top, the semantic layer. There are a few climate action data models in the blockchain context. However, they only offer partially semantic interoperability. It is not enough that terms, variables names, and other constructs – all of which constitute the data model – stored on the blockchain be standardized; so too must smart contracts that encode the rules of carbon standards. As we discuss later, we posit that though interoperable blockchain data models may be possible, interoperable smart contracts require an architecture that relies additionally upon the Semantic Web, most especially ontologies.

There are some building blocks with which to develop an effective blockchain-based Digital MRV system, nevertheless. A starting point is markup languages, namely XBRL (eXtensible Business Reporting Language), which specifies a detailed and standardized vocabulary and format such that financial reports can be encoded in XBRL. Once encoded, reports in XBRL can be registered within bodies like the US Securities and Exchange Commission (SEC), and then used as data sources for Web services that can query across multiple reports or automate report management business processes. “Interest expense,” “Deferred Tax Assets, Net,” and “Financing Receivable, Allowance for Credit Losses, Write-downs” are some of the estimated 15,000 XBRL elements that can be instantiated to report the financial status of a company. XBRL is a key initiative of International Accounting Standards Board (IASB) and represents the internationally standardized means of computer encoding financial accounting reports. Though XBRL is meant for use in financial reporting, the Global Reporting Initiative (GRI) is working to provide non-financial, accounting extension to XBRL, encompassing elements like “Non-Renewable Fuel Consumed,” and “Direct Economic Value Generated” (GRI, n.d.).

The renewable energy and solar spaces have taken a lead on this with the Orange Button Taxonomy, an effort funded by the US Department of Energy’s Solar Energy Technologies Office to develop information standards for interoperability between various solar Photovoltaic (PV) power generators and energy storage plants on the smart grid. The Orange Button Taxonomy is like GRI’s in that it extends XBRL, but is even more detailed in its specification of concepts like “Environmental Site Assessment,” and “Zoning Permit” (SunSpec Alliance, 2018). In fact, there appears to be efforts to implement the taxonomy onto a public blockchain platform called the Energy Web Chain (Ledger Insights, 2020). At first glance, this appears an ideal exemplar for a blockchain-based Digital MRV system. However, there are a few issues of note with this approach. Energy Web Chain is a somewhat obscure platform that entails payments – e.g. for grid operators paying for solar-energy produced “local” electricity – in its cryptocurrency. Energy Web Token’s market cap is less than 1% of ethers[5]. Therefore, it is unlikely that the Energy Web Chain will become a de facto standard platform. Additionally, a platform that necessitates cryptocurrency use will be a source of possibly insurmountable friction for platform adoption (Eyal, 2017).

Within the limited scope of the solar energy space, the proposed implementation of the Orange Button Taxonomy – which extends XBRL to enable representation of non-financial data relevant for climate reporting (especially in the solar space) – with the public, cryptocurrency-driven, Energy Web Chain platform provides an intriguing exemplar. Even though this platform is unlikely to

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[4] Published with permission from authors

[5] Energy Web Token’s $365M vs. Ethereum’s ethers at $43B, as of August 26, 2020.

become a dominant, never mind a de facto, standard platform, it can be a part of an interoperable ecosystem of blockchains, a business landscape and technical architecture espoused for a variety of industries and applications (Hardjono et al., 2019; Tapscott, 2020). Next, we describe on-going climate action project in Chile that has developed a prototype for a blockchain based MRV system, and use that as a Motivating Scenario to specify our architecture that could be used as the prototype is scaled-up.

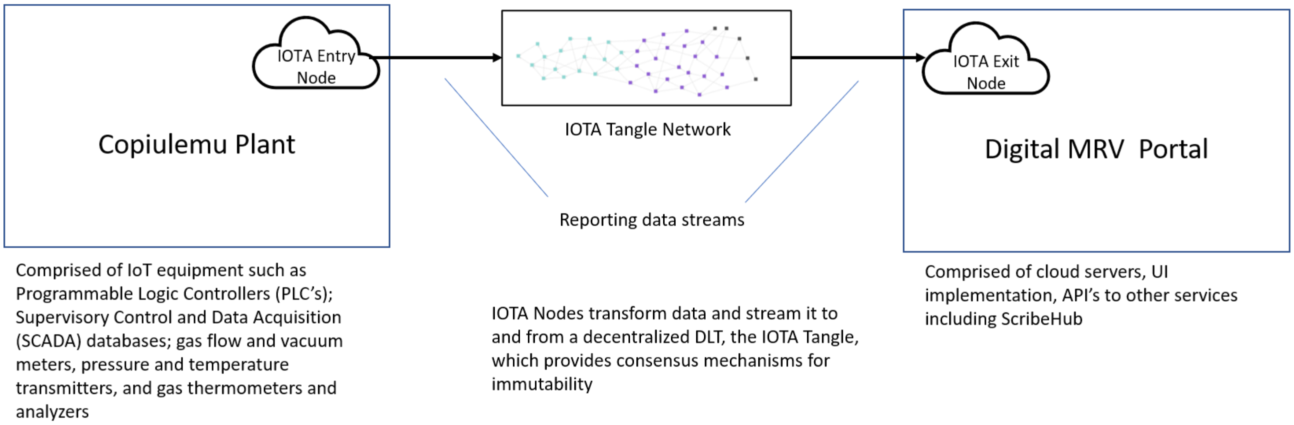
4.2 Motivating Scenario: Digital MRV System for Reciclo Orgánicos Landfill Gas Project in Chile

The Ministries of Environment of Canada and Chile as well as partnering companies Arcadis Canada, ClimateCHECK, and the IOTA Foundation are collaborating on the . They are developing a pilot MRV project at Copiulemu Landfill Gas (LFG) site. The objective of the pilot is to demonstrate the feasibility of a digital MRV system to reduce costs and time as well as improve the utility of the data and reports for stakeholders. The main stakeholders are:

- Project manager/owner as the source of most project information and project data, which include Arcadis Canada and the municipality that operates the Copiulemu site. These stakeholders provide the GHG project information and data to the GHG consultant, ClimateCHECK.
- ClimateCHECK collects and then inputs information to write the GHG project report, and then performs the GHG calculations as per the LFG methodology. For the Digital MRV system, data collection, quality assurance/control and calculations are all automated with the the Digital Ledger Technology (DLT) developed from the IOTA platform. The vernacular term DLT is used for this project to describe its use of the IOTA blockchain. For example, the system checks on inputs, processing, and outputs, and manages related resources (e.g. meter maintenance and calibration, quality performance monitoring). ClimateCHECK is responsible for reporting based off this data as well as qualitative data about the project.
- A GHG auditor performs the GHG verification using a verification standard like ISO 14064-3 and writes the GHG verification report. ScribeHub™, an online tool to develop and customize applicable standards and automate verification against those standards, is used by the auditor.
- GHG information user such as government of Chile or Canada, a carbon credit program, carbon credit buyer/seller, or project partner reviews the project data on the DLT and reviews the project information for the GHG report and GHG audit report in ScribeHub, which can then be followed by steps to register, certify, or transact carbon credits.

There are four distinct artifacts that these stakeholders use: two software applications – IOTA DLT and ScribeHub; and two sets of documentation – LFG Methodology and verification standards. The development and integration of the applications as well as the machine-encoding and automation of rules and logic specified in the documentation constitute the core of the Digital MRV System. ClimateCHECK serves a carbon accounting function in applying the LFG Methodology to calculate and report on carbon credits earned and GHG auditors serve a carbon auditing function in applying GHG standards to verify that the calculations and reporting adhere to those standards.

The purpose of the Motivating Scenario is to describe the context within which a blockchain and ontology based Digital MRV can be developed. Here is a high-level solutions architecture of the first pass pilot.



Comprised of IoT equipment such as Programmable Logic Controllers (PLC's); Supervisory Control and Data Acquisition (SCADA) databases; gas flow and vacuum meters, pressure and temperature transmitters, and gas thermometers and analyzers

IOTA Nodes transform data and stream it to and from a decentralized DLT, the IOTA Tangle, which provides consensus mechanisms for immutability

Comprised of cloud servers, UI implementation, API's to other services including ScribeHub

Figure 2: Copiulemu LFG Pilot Digital MRV Solutions Architecture

Inasmuch as this design constitutes arguably state-of-the-art in applying blockchain technologies for climate action, there are key areas for further improvement. This design automates and systemizes manual and very subjective processes so efficiency gains can be realized. Furthermore, blockchain use provides immutability. However, though transparency is gained from documenting rules used by accountants and auditors precisely enough to be programmed, these rules are opaque to external purview as they are "hardwired" into the Digital MRV system. For the Copiulemu pilot, the LFG Methodology for accounting for and measuring carbon credits and GHG verification standards used by the auditors do not exist as standalone modules but rather are directly written into the MRV code. This means that the code is not designed to be understandable to external parties or reusable by them. This design is not as transparent – and certainly not standardized – as it could be. Below, we propose an architecture which relies upon ontologies to provide this additional transparency and standardization.

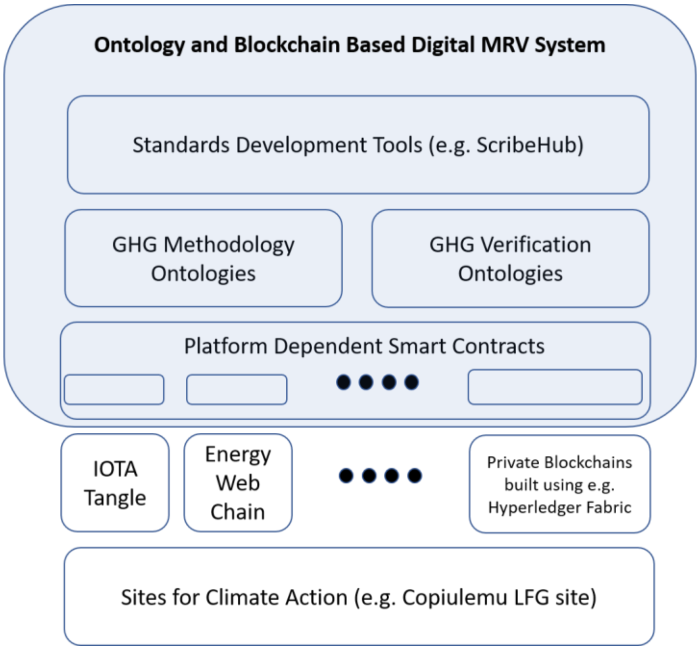


Figure 3: High Level Architecture for Ontology and Blockchain Based Digital MRV System

This design disambiguates the “hardwired” interaction in the Copiulemu LFG pilot between the blockchain (i.e. IOTA Tangle) and Digital MRV system into the following distinct components

- A standards development tool like ScribeHub for collaboratively developing GHG standards should be a distinct module that is coupled with the Digital MRV system. That is, it is not necessarily embedded in the system and hence can be accessed by external applications.
- Distinct set of ontologies for GHG Methodologies should be coupled with the Digital MRV. System. At Copiulemu, the specific methodology is called the Chile LFG GHG Quantification Protocol, and it provides eligibility rules, methods to calculate reductions, performance-monitoring instructions, and procedures for reporting project information. This protocol is designed to ensure transparent, accurate, and conservative quantification of GHG emission reductions and concomitant earned carbon credits. The ontologies represent machine-executable (hence much more precise), blockchain platform-independent transformation of standards and protocols developed using a tool like ScribeHub.
- Distinct set of ontologies for GHG verification standards should be coupled with the Digital MRV System. Standards like ISO 14064-3 specify principles and requirements and provides guidance for verifying and validating GHG statements. If GHG methodologies (or quantification protocols) specify how GHG emissions should be calculated and reported, GHG verification standards are used to audit the calculations and reporting as well as validate the systems and organizational processes in place.
- These ontologies in turn must be transformed into smart contracts native to different blockchain platforms. IOTA Tangle, Energy Web Chain, different implementations in Hyperledger Fabric, as well as other platforms have been reported for use in climate action. These smart contracts will ensure that some business processes of GHG accounting as per an applicable methodology/protocol and GHG auditing as per an applicable verification standard can be automated while allowing for flexibility for different blockchain platforms to be used.

It should be noted that the ontologies aren’t absolutely necessary for the development of these smart contracts. The Copiulemu project is an example where natural language standards are embedded into the logic of the IOTA application. However, that is hardwiring. By developing ontologies as distinct modules, this hardwiring is avoided. With our design, there is greater transparency of the transformation from natural language to smart contracts as code would not need to be broken apart to understand this transformation. Furthermore, ontology representations are specifically designed to be used like building blocks so developing subsequent ontologies should require less development time, resulting ultimately in less time to develop smart contracts using different platforms or at different facilities. Finally, the ontologies may be useful for applications other than MRV and may be used even in the absence of blockchains – say for ESG reporting from Enterprise Resource Planning databases.

4.3 Architecting Interface Ontologies, and Blockchain and Smart Contracts

The Digital MRV System ought to be scalable for use at different facilities that use different blockchain platforms. This scalability is only is possible if we can rely upon blockchain interoperability. That is, if we can maintain some code that can be used across multiple platforms then time for development at a new facility requiring carbon action would be reduced over time. Interoperability would also mean that integrating data from different facilities that may use different platforms for more complex accounting and auditing would be possible.

Indeed, there are many efforts at enabling inter-chain interoperability (del Castillo, 2017; Hardjono et al., 2019; M. Lacity et al., 2019; Litwin et al., 1990; Miah, 2019; O'Neal, 2019) and two of the most developed are Cosmos (Kwon and Buchman 2017) and Aion networks (Higgins, 2017; Spoke & Nuco Engineering Team, 2017). Cosmos is conceptualized as an Internet-like network of public blockchains organized in hubs and zones, where each zone maintains its own blockchain and "plug" into hubs. Aion network connects both public and private blockchains, but rather than a hub-and-zone architecture, it acts as a common translation blockchain that inter-operates between heterogeneous blockchains. There are many differences between Cosmos and Aion, but what they have in common is their emphasis on protocol-level details of blockchain interoperability such as mechanisms for achieving consensus that data transported from one blockchain to another has been verified in the destination blockchain and tokenization of an inter-blockchain cryptocurrency system used to incentivize third party verification. What is hardly addressed though is semantic interoperability. This means that in the approach of Aion and Cosmos a piece of data can be verified and transported from one blockchain to another – and a third party may receive cryptocurrency payment for verification – without the semantics of its proper use transported as well.

We posit that between protocol-level inter-operability designed with focus on issues like consensus and tokenization mechanisms and semantic level inter-operability with focus on knowledge engineering and representational language there is a protocol/semantic interface. Ugarte insightfully recognized the need for this layer. He stated that there are three possible approaches to "semantify" the blockchain: 1) Encode RDF class definitions within the blockchain, or maintain the definition elsewhere "off-chain" but place hashes of those definitions only on the blockchain; 2) Extend data interchange protocols of an interoperating network like Aion or Cosmos to represent RDF constructs; or, 3) Map blockchain data instances directly onto appropriate RDF classes that are not on the blockchain (i.e. off-chain).

It appears that Ugarte uses the last approach in his DeSCA prototype. In the context of Aion and Cosmos's protocol level inter-operability focus, the difficulty of Ugarte's approach is that this mapping would not necessarily be maintained by Aion or Cosmos when they transport data between blockchains. In order to preserve these mappings, Aion or Cosmos would need to be able to access and process RDF encoded ontologies off-chain, and not only do they not facilitate this now but are unlikely to do so because their focus is primarily at the blockchain protocol level. What we are proposing with our work is an approach that is more complementary to their efforts, and which entails a hybrid of approaches 1) and 2). We propose to: Encode ontology constructs within the blockchain at the protocol level as specially tagged hashes that point to semantics (ontology definitions and axioms) kept off-chain.

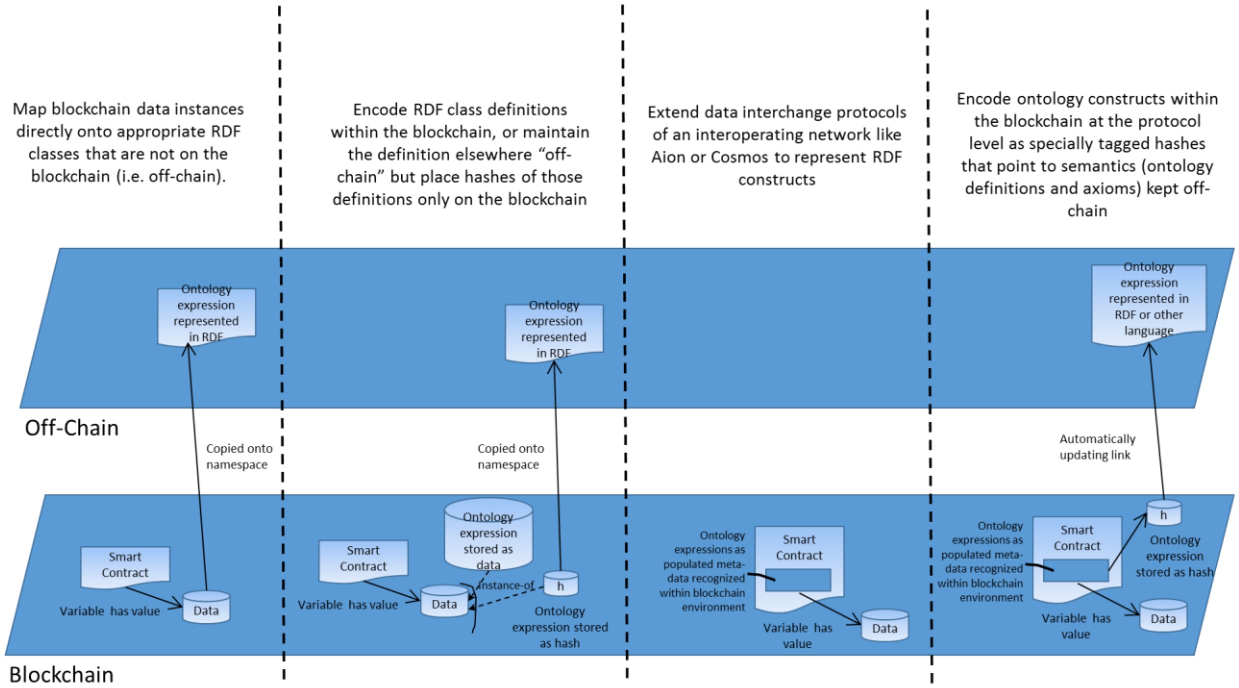


Figure 4: Schematic of Different Approaches to Representing Semantics for Blockchain

5 Concluding Remarks

No less an authority than the United Nations Framework Convent on Climate Change (UNFCCC) secretariat has espoused the use of blockchain for transparency, cost-effectiveness and efficiency advantages for initiatives in carbon emissions mitigation, green energy, resilient and low carbon supply chains, waste management, enhancing the circular economy, wildlife preservation, and green finance. After surveying the academic literature regarding these initiatives, we identified green energy and carbon emissions mitigation as two topics most discussed. Using a framework that recognizes that functional uses of blockchain can be delineated into (i) blockchain for financing (e.g. Initial Coin Offerings and decentralized finance), (ii) blockchain for operations (e.g. provenance tracking), and (iii) tight coupling of blockchains for operations and financing, we noted that blockchain-based carbon emissions mitigation lacks applications that integrate all three functions, whereas blockchain-based micro-grids do. We surmised that the larger scope of effort required for carbon emissions mitigation is the key reason for this lack. This seems worthy of further enquiry.

This enquiry starts with detailing that the three functions for carbon emissions mitigation would correspond to the following.

i) *Transparent Data Management*, wherein data from a facility's databases and sensors would be stored on the blockchain and used for data management operations functions such as public disclosure of emissions.
ii) *Registries for carbon reporting* of earners and purchasers of carbon credits and complementary *Emissions Trading Systems (ETS)* that provide markets for trading credits constitute blockchain-based financing systems that provide monetary incentives to emissions mitigation efforts.
iii) If implemented using blockchain, *carbon auditing and accounting systems* constitute a tight coupling of financing and operations systems. Data from sensors and other

> sources can be “rolled up” to calculate carbon credits that can be registered and traded. Moreover, carbon standards and requirements that dictate how emissions are recognized, and credits, calculated, can be “rolled down” for reporting and verification. Using smart contracts, a blockchain-based carbon accounting and auditing system can execute aspects of this roll-up from the data management and roll-down from carbon standards.

Interestingly, there does appear to be some, but not much, research into blockchain-based carbon accounting and auditing systems, lagging blockchain-based data management, registries, and ETS in number of research efforts. We then explored this as a promising research opportunity. We first addressed nomenclature. The term *MRV* is used within other climate action efforts beyond carbon emissions in cases where: (i) Climate data is *Measured*; (ii) Aggregated data is *Reported* as per financial and non-financial accounting standards specified for a climate action industry class (e.g. carbon emissions, green energy, etc.); and (iii) An external audit of a facility that *Verifies* that reporting adheres to industry accounting standards and that the facility functions adhere to industry standards on operational characteristics is performed. That is, blockchain-based MRV is parallel to carbon accounting and auditing insofar as it also serves to tightly couple financing and operations systems but is a more general term that is inclusive of different types of climate action initiatives.

MRV systems require standardized methodologies for measurement, financial and non-financial accounting standards for reporting, and verification standards against which to audit the system of measurement and reporting. That is, MRV systems rely heavily upon standards. If smart contracts that execute upon data collected from sensors and databases and stored on the blockchain codify climate action accounting and auditing rules as specified in the above-mentioned standards, then automation and efficiency gains can be added along with transparency as compelling reasons to use blockchain. Hence the promise of a blockchain-based MRV system. However, the historical proliferation of MRV standards represents an obstacle: Rather than different carbon accountants and auditors haphazardly applying their niche standards, smart contracts can more efficiently, but just as haphazardly, apply standards on data stored on the blockchain. Much of the transparency benefits of blockchain use is lost if data on the blockchain cannot be measured, reported, and verified in uniform, repeatable – i.e. standardized – ways.

An approach that seeks to systematically transform standards that are in natural language to machine-encoded representations of these standards that can be applied to blockchain data is quite promising. That is, business rules and requirements expressed in standards can be specified as smart contracts that automate the processing of blockchain data subject to these rules and requirements. For example, the Orange Button Taxonomy supported in part by the US Department of Energy’s Solar Energy Technologies Office extends and customizes data elements of the widely adopted financial reporting language, XBRL. The cryptocurrency-based blockchain platform Energy Web Chain is said to implement the taxonomy as data elements and smart contracts. The issue however is that this enforces uniformity only if the same blockchain is used. It would overly constrain the MRV system to use one platform, and a relatively obscure one at that. Recognizing that a potential remedy is to use Semantic Web ontologies, which enable data and the semantics required to interpret that data to be shared amongst diverse actors, we then outlined a top-level architecture for a blockchain *and* ontology based MRV system for climate action.

We analyzed a state-of-the-art blockchain-based MRV implementation of the *Reciclo Orgánicos* project – an initiative supported by the Ministries of Environment of Chile and Canada to reduce GHG emissions from Chile’s municipal waste sector and industry firms and piloted at the Copiulemu

Landfill Gas (LFG) site. Other project stakeholders include: ClimateCHECK as consultants who apply a standardized LFG methodology to measure, quantify, and report carbon output; a different entity that acts to audit the application of the methodology against verification standards; and IOTA as the platform provider of the DLT/blockchain for the project.

Integrating our literature survey and findings, we propose the following architectural augmentations for the next version of the pilot:

- *Refine the "smart standards" aspects*. In the current pilot, a tool called ScribeHub is used to document the LFG methodology and verification standards. It is also used by the consultant to report against the methodology, and by the auditors to report against verification standards. Though it is beyond the ontology and blockchain scope of this paper, we espouse further development to enable semi-automated transformation – using e.g. NLP – of these natural language standards into using Semantic Web ontology representations in RDF and OWL.
- *Develop an ontology layer*. In the current pilot, rules specified in the methodologies and standards are manually interpreted by an expert who works with software developers to ensure faithful coding of the rules on a particular blockchain platform. Not only may this lead to applying standards haphazardly, it also leads to an incongruence in that the data on the blockchain is transparent, but the rules applied to the data are not. By developing modularized ontologies of methodologies and standards, rules are stand-alone, not hardwired, and represented independent of any particular blockchain. It is very unlikely that Energy Web Chain, IOTA, or another will become a de facto platform for climate action, so having a decoupled ontology layer ensures against over-reliance on a platform. These ontologies are constructed as building blocks with terms and rules defined in terms of fundamental terms and rules more core to climate action concepts. Thus, different standards that have similar domain and application can be represented using the same set of building block ontology representations. A well constructed and populated set of ontologies can be coupled with a well-refined smart standards system to systematically represent and classify similar standards. Through this coupling/coordination, commonalities and differences between proliferating standards can be explicitly represented, ultimately enabling semi-automated harmonization between standards.
- *Develop an ontology-blockchain interface*. Ontology representations must be transformed to platform specific smart contracts. These smart contracts represent the programmatic code that applies the "ontologized" methodologies to measure, quantify, and report as well as the "ontologized" verification standards to audit that the measurement, quantification, and reporting occurred in compliance to the standards. This layer is also used in inter-operation where some MRV functionality requires applying rules to data from different blockchains. We outline high level design alternatives for architecting this interface and state our preference: Encode ontology constructs within the blockchain at the protocol level as specially tagged hashes that point to semantics (ontology definitions and axioms) kept off-chain.

Though rather preliminary, our work contributes to both academic literature and industry initiatives in that it promises to complement blockchains providing transparency with ontologies providing uniformity and standardization, thus benefitting climate action efforts in carbon mitigation and other climate actions. The key limitation of this work is that it is merely a conceptualization, and we are admittedly far from a proof-of-concept both in terms of a research prototype or an industrial proof-of-concept. Nevertheless, we put forth that the potential contribution to climate action can be impactful and that spurs us towards further progress.

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