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RESEARCH ARTICLE

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Geoengineering and the blockchain: Coordinating Carbon Dioxide Removal and Solar Radiation Management to tackle future emissions

Abstract Geoengineering is a proposed response to anthropogenic global warming (AGW). Conventionally it consists of two strands: Solar Radiation Management (SRM), which is fast-acting, incomplete but inexpensive, and Carbon Dioxide Removal (CDR), which is slower acting, more expensive, and comprehensive. Pairing SRM and CDR offers a contractually complete solution for future emissions if effectively-scaled and coordinated. SRM offsets warming, while CDR takes effect. We suggest coordination using a blockchain, i.e. smart contracts and a distributed ledger. Specifically, we integrate CDR futures with time and volume-matched SRM orders, to address emissions contractually before release. This provides an economically and environmentally proportionate solution to CO2 emissions at the wellhead, with robust contractual transparency, and minimal overhead cost.

Our proposal offers a 'polluter pays' implementation of Long & Shepherds SRM 'bridge' concept. This 'polluter geoengineers' approach mandates and verifies emissions-linked payments with minimal friction, delay, or cost. Finally, we compare alternative market designs against this proposal, finding that this proposal offers several advantages. We conclude that blockchain implementation of the 'polluter geoengineers' approach is attractive and feasible for larger wellhead contracts. We also identify a handful of advantages and disadvantages that merit further study.

Keywords Geoengineering, Solar Radiation Management, Carbon Dioxide Removal, futures markets, smart contracts, blockchain

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1 The role of CDR & SRM in the low carbon transition

Over the next few decades, anthropogenic climate change will present an increasingly urgent challenge for humanity, requiring significant financial outlay (Stern et al., 2006; IPCC, 2013; IPCC, 2018). Addressing the considerable social, political, scientific, cultural and physical challenges will be costly and has already required both hard-won international agreements and domestic compromises needed to restrain the expected rises in global temperatures. Breaking the link between energy generation and CO_2 emissions requires a wholesale transformation of global energy system – which is both expensive and unpalatable to many electorates. Moreover, despite the fact that energy and (to a lesser extent) surface transport are beginning to de-carbonise rapidly, this is offset to some extent by the steady demand for petrochemical products in developed economies, as well as rapidly growing demand in emerging markets, and the steep increase in demand for high carbon food sources (especially meat) in newly emergent middle-income countries (Hamilton and Turton, 2002; Carlsson-Kanyama and González, 2009; Broeren et al., 2014). The technology needed to produce bio-based bulk chemicals and low-carbon meat sources are in their infancy (Hermann et al., 2007; Galloway et al., 2008; Chen and Patel, 2012). The historic delays in de-carbonising energy and the longer-term time horizons for de-carbonising other sectors have both sparked a revival of interest in geoengineering- both as alternative, and as an addition to, mitigation and adaptation efforts.

In its modern incarnation, geoengineering is construed as the deliberate modification of the climate system. As a discipline, geoengineering has two key strands: Solar Radiation Management (SRM); and Carbon Dioxide Removal (CDR), or Greenhouse Gas Removal (GGR) more generally. Many geoengineering technologies remain theoretical, and, with the exception of afforestation (tree-planting) programmes, no large-scale geoengineering projects have yet been deployed. Nonetheless, most experts agree that some CDR/GGR and SRM schemes do not pose insurmountable technical barriers; some forms, like space mirrors, remain prohibitively expensive or impractical given current technological capabilities, but other forms of SRM and CDR are currently undergoing commercial or other development.

This paper explores the theoretical possibility of using blockchain technology to facilitate the coordination of SRM and CDR, in order to offer a contractually complete solution for managing future emissions. The relevant SRM and CDR technologies themselves and their challenges and limitations are introduced below, as are the use of carbon credits in facilitating mitigation through a range of theoretically possible market designs.

1.1 SRM

Techniques described as SRM are based on the principle of the alteration of the Earth's radiation balance through reflection of sunlight. Proponents of SRM have suggested a variety of schemes, including space mirrors, white roofs, and stratospheric sulfur aerosol injection (SAI), which replicates the cooling caused by volcanic hazes. SRM techniques do not offer a complete solution to greenhouse gas emissions: SRM is both temporary and imperfect in its restorative potential, with effects differing between regions (Heyen et al., 2015). The resulting global climate would typically experience less precipitation than the pre-SRM world of the same average temperature, and the remaining increased CO_2 levels would cause widespread changes in Earth-system processes. There are therefore both scientific and technological risks, as well as political controversies, that make policymakers reluctant to deploy SRM at scale.

Despite the lack of deployments to date, geoengineering has a place in current climate change advocacy discourses and in policy debates. The expectation of viable CDR is becoming embedded in international agreements. The recent Paris treaty implies large-scale deployment in the second half of the current century (Lewis, 2016). By contrast, SRM is not part of the current policy mix. This may change, as SRM techniques can be cost effective. McClellan et al. (2012) estimate the operational costs of SAI to be as modest as \$1bn/year. – but contrasting estimates are available (Moriyama, et al., 2017). These cost estimations could be reduced further by delivery via drone aircraft, and potentially by robotic rather than human groundcrew, as automation technologies are evolving quickly. As the level of atmospheric GHGs rises, more aggressive interventions will be needed, but the upper bound, according to McClellan, still costs little more than \$2bn/year (McClellan et al., 2012). Either way the total direct costs of SRM are negligible when considered as a percentage of total global GDP.

Future deployment of geoengineering technologies may be by profit-seeking commercial firms (Lockley, 2016), or by states acting in the interests of publics and the wider economy. Likewise, two models for the future commercial purchase of geoengineering exist– depending on whether states, or private actors, are the customers. For clarity, we do not include explicit discussion of the state as a supplier of SRM or CDR at any point in this paper – although we note that the state may indeed be a supplier. However, our analysis is fully-applicable to the state as a customer for geoengineering services. As nation-states are major greenhouse gas (GHG) emitters, we would hope that our analysis is accepted by state actors.

A risk of SRM is 'termination shock', which would occur if the deployment were suddenly to cease (McCusker et al., 2014). This is due to the short atmospheric lifetime of SRM aerosols. Sudden SRM termination is inherently dangerous, as the rate of change of global temperature is a significant risk factor for the biosphere (MacMartin et al., 2014). Accordingly, any regulatory processes for SRM must ensure that any exit from a program is orderly, and therefore does not expose the climate to any avoidable risk of termination shock. One method for achieving this is a smooth transition to CDR. In this case, SRM technology merely acts as a bridge. Its job is to constrain temporary temperature rises, while CDR deployment is awaited.

SRM is not fungible–one ton of carbon offset by one SRM method or locus is not exactly equivalent to that ton offset by any other method or locus. Various classes of SRM are fundamentally different: Stratospheric Aerosol Injection (SAI) is global and persistent for about two years; Marine Cloud Brightening (MCB) is locally-controllable and persists for days (Latham 2002); cirrus stripping is also an option. The latter is far less well-studied – and is not strictly SRM, although it has a range of similarities, and is therefore often grouped alongside SRM (Mitchell and Finnegan, 2009).

SAI deployments are inherently global in nature, tending to be spread rapidly on zonal winds (Brühl et al., 2015), and transferred more slowly poleward by stratospheric air movement – i.e. the Brewer-Dobson circulation (Keith, 2010). SAI broadly remains within the meridional hemisphere of injection (Haywood et al., 2013). Any hemispheric imbalance in injection patterns causes significant disruption to the Inter-Tropical Convergence Zone (ITCZ) - and thus major disruption to the equatorial climate (Dai et al., 2018). MCB and cirrus stripping are more locally-specific- although climatic teleconnections in the climate system mean that they do not have a cleanly-isolated effect (Jones et al., 2010). Further, SAI and MCB are expected to have differing effects on precipitation – a difference which will vary according to the specific injection regime (Hill and Ming, 2012). Nevertheless, in this paper we do not consider the specific practicalities of managing this heterogeneity; others have considered how such a private-sector SRM program could be managed in detail (Lockley, 2016). Moreover, some recent authors regard

SRM as a viable means of carbon sequestration, though this is highly contested (Ming et al., 2014; Lockley, 2016). This paper assumes that carbon sequestration is not the main objective of SRM; such an assumption is consistent with the recent IPCC recommendations which omit SRM from any discussion of how to achieve technological CDR (IPCC 2018).

1.2 CDR/GGR

CDR refers to removal of CO_2 from the atmosphere – either directly (via chemical Direct Air Capture – DAC), or indirectly by methods such as Enhanced Weathering (EW) of rocks. More generally, GGR includes removal of secondary GHGs generally (methane, etc.) (Lomax et al., 2015). GGR/CDR offers a theoretically complete solution to CO_2 emissions. However, delays in enacting CDR after emissions can leads to interim temperature increases, which may cause permanent harm (e.g. extinctions). In the CDR case, cost is the major barrier to implementation (a figure of 50 EUR/ton CO_2 for Bio-Energy with Carbon Capture and Storage (BECCS) is suggested by IEAGHG, giving roughly $200 per ton carbon (IEAGHG, 2011). Figures for individual technologies may vary widely (Bui et al., 2018).

Evaluating CDR impacts and efficacy is a complex matter, of which we offer the following brief explanation. CDR may take several forms, and these vary widely in their effects. One such continuum is environmental impact. Some proposed methods are expected to have significant, disruptive effects on ecosystems (e.g. Ocean Iron Fertilisation- OIF) (Martin et al., 2013). By contrast, others such as Direct Air Capture, if properly conducted, are more environmentally benign (Lackner et al., 2012). Secondly, different strategies involve varying levels of future risk. Enhanced mineral weathering offers essentially perfect, benign storage, notwithstanding any local environmental impacts (Kohler et al., 2010). Other techniques pose a serious long-term management problem – e.g. shallow storage of pressurized CO_2 (such as after DAC) incurs a risk of dangerous leakage, potentially necessitating careful future observation and management of injection sites (Celia et al., 2009).

Finally, biosphere storage (such as afforestation) results in only temporary carbon storage. With biosphere reservoirs, little guarantee can be offered of the stability of resulting carbon reservoirs beyond the century timescale (Locatelli and Pedroni, 2004). Our discussions, therefore, should not be construed as recommending biological storage. Timing is critical here. Consider, for example, a tree-planting scheme. The economic activity takes place when the land is purchased, and the trees are planted. However, carbon uptake is slow initially, as the sampling are small. Later, it accelerates as young trees grow rapidly. Finally, it tails off – as mature woodland reaches its climax state. As such, there is a significant delay between the economic activity and the carbon removal – leading to a gap where warming is untreated, save for the addition of a separate bridge solution.

1.3 The SRM bridge

Long and Shepherd (2014) proposed that SRM, to be replaced by CDR in the long term, may best be considered as one element of a portfolio of complementary responses to climate change – although the authors do not drill down to a transactional level. Shepherd's famous 'Napkin Diagram' is the best illustration of what they had in mind (Long and Shepherd, 2014).

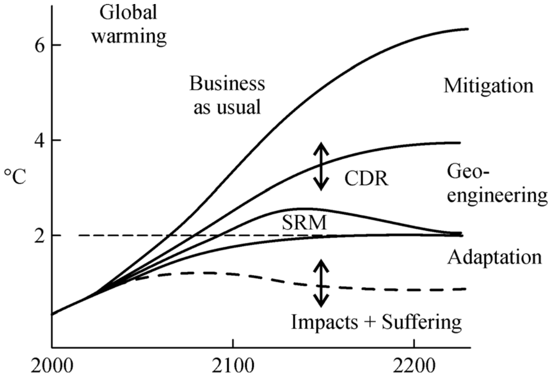

Fig. 1 Shepherd's Napkin Diagram of SRM bridge

This paper extends their discussions, adding in a level of transactional and executional detail, which was missing from their predominantly geophysical analysis. Central to this is a 'polluter pays' approach, implemented through contracts (similar to carbon credits) to dispose of emissions through an appropriate package of geoengineering interventions – so that the polluter geoengineers (albeit it by proxy).

For clarity, this obligation need not exist for all pollution. It may be required only for emissions above a cap, or for a proportion of total emissions, or in certain industries or jurisdictions. Depending on policy priorities and the amelioration of physical or technical constraints on transaction volumes, the obligation could also be laid on consumers rather than producers (Larsen and Hertwich, 2009).

1.4 Carbon credits

Carbon Credits schemes may be used in a variety of ways to mitigate emissions. Credits schemes fall into two categories: Statutory (e.g. EU Emissions Trading Scheme or ETS), and Voluntary Carbon Offsets or VCO (Bayon et al., 2012; Tilmes et al., 2013). Generally, we consider only VCOs –noting that our proposed measures may ultimately be afforded statutory weight. There is a significant and inglorious history of interplay between geoengineering and the VCO market. Early firms like Planktos and Climos have attempted to profit from geoengineering via this market (Courtland, 2008; Lockley, 2016), and recently Climeworks has begun offering carbon credits for DAC and rapid mineralisation strategies (Gutknecht et al., 2018). Their intended geoengineering intervention was CDR by Ocean Iron Fertilization (OIF). This technique that has largely fallen out of favor, based on concerns about the stability of the carbon removal, and the resulting ecosystem disruption (Martin et al., 2013).

The carbon credits market is highly variable in the legitimacy and permanence of the offsets offered. Additionally, and in no small part causally, it is heterogeneous in its regulation. Accordingly, there is a lack of a single framework to ensure equivalence and validity of offsets (Corbera et al., 2009). In extremis, 'offsets' have been offered against non-existent mitigation. This notably occurred in the corruption of the EU ETS, involving Ukrainian credits (Kollmuss et al., 2015). In other cases, impermanent CO_2 storage gives rise to a marketable credit-a major risk in forestry projects. Impermanent storage provides a mere pause in warming, not a genuine offset – and is therefore somewhat akin to SRM in its temporary nature. In this paper, we suggest only geological storage of carbon, not biological – as the latter is fundamentally impermanent.

The VCO market has also previously been considered as a vehicle through which to trade SRM services (Sargoni and Lockley, 2015). This is based on the insight that SRM is predicted to have an indirect (but quantifiable) effect on the global carbon cycle (Keith et al., 2017). It is nevertheless also possible that direct purchase of SRM may happen without reliance on the VCO market – and it is this type of commission which we principally focus on. Specifically, we do not invoke the use of SRM for the generation of VCOs/carbon credits. By contrast, we do consider the use of VCOs as a mechanism for quantifying CDR activities – with the blockchain-mediated market for CDR services functioning to allocate VCOs/carbon credits. Nevertheless, our in-principle discussion does not require thorough consideration of these instruments.

1.5 Approaches to Carbon Dioxide Removal market design

Other studies have examined the possible use of both futures contracts and tradeable put option (TPO) contracts in CDR markets (Coffman and Lockley, 2017; Lockley and Coffman, 2018). TPO contracts are currently used by the World Bank's Pilot Auction Facility; but in both cases, we found significant political and economic risks when these instruments were used at scale. Long-dated futures seemingly offer polluters contractual guarantees of future CDR delivery at a low price – because the long date assumes costs reductions through technical innovation and scaling, in the intervening years. However, unrealistic pricing on the part of suppliers may render these undeliverable – leading to dangerous, market-wide under-provision of CDR, and resulting wholesale failure of carbon markets. By contrast, TPOs allow nascent CDR firms a guaranteed market for their services (for a small fee) – to support the technical development process. However, TPOs must be underwritten by a reliable institution, and do not offer any security of CDR delivery to the option writer. Similarly, there is a temptation to overlook the lack of enforceability for writers, and thus to assume delivery will occur. Regardless of market design, any unexpected technological or economic issues may lead to a total failure of CDR provision. Technological risk of CDR failure is another reason why the SRM Bridge is so important.

1.5.1 An overview of CDR futures and options markets

To explain the various proposals for the design of carbon markets, it is necessary to review the general principles behind futures and options markets in contemporary economic life. In modern finance, both forward and futures contracts allow buyers and sellers to agree a current price for a transaction executed at a specific later date, e.g. the sale of 100 bushels of grain. Technically, these are called 'time bargains' as they are to be settled in the future (Poitras, 2009). A producer may forward-sell before the harvest in order to be assured of a future income stream, which can in turn be used to arrange trade credit. Those who buy and sell commodities use forward contracts to transfer risk, reduce the cost of trade finance, and hedge against future price fluctuations. The farmer controls the risks from falling grain prices; the miller hedges against rising grain prices. Alfred Marshall commented: 'The hedger does not speculate: He insures' (Marshall, 1919; Coffman and Lockley, 2017). Forward contracts are used to bind two parties in a bilateral agreement, though assignment of the obligation may be possible if permitted in the contract language. Futures are exchange-traded, assignable forward contracts. Options contracts are derivative contracts that create the right, but not the obligation, to complete the transaction. A put option confers upon the holder the right to sell the optioned asset (thereby binding the writer to buy the optioned asset, if the option is exercised), whereas a call option confers upon the holder the right to buy the optioned asset (thereby binding the writer to sell the optioned asset, if the option is exercised).

Organized trading in futures and options contracts has a long history in Europe, dating back to sixteenth-century Antwerp (Poitras, 2009). Grain futures trading in the United States dates from the second half of the nineteenth century (Levy, 2006). The Chicago Board of Trade (CBOT) has dominated the global market for wheat and maize corn futures since the early twentieth-century; by the 1920s, CBOT futures were ordinarily cash settled, avoiding physical delivery (Hoffman, 1941; Saleuddin and Coffman, 2018; Saleuddin, 2018). Futures are thus more suited to speculation; forwards simply organize bilateral trade.

Exchange-trading of futures means that the exchange demands assurance that eventual counterparties can perform. Accordingly, either contracts require significant (and extensible) deposits, or regulation of market participants must ensure solvency. To ensure futures performance, exchange deposits are typically 2% – 10% – now adjusted daily ('mark-to-market'). The high costs of maintaining central clearing houses and of complying with relevant legislation in the early 20-first century have combined to encourage market consolidation (Liebenburg, 2002; Lockley and Coffman, 2018; Duffle and Zhu, 2011). For the purposes of this article, the main distinction between futures contracts and forward contracts is that futures contracts are exchange-traded and cash-settled.

Cash settlement makes futures contracts less vulnerable to market abuse, such as corners (attempts to control supply) in a parallel spot market (Pirrong, 2001). Settlement aims to restore the parties' financial position, as if physical performance had occurred, allowing economically efficient outcomes and thus creating a viable instrument for price insurance. This works best over the short time horizons characteristic of futures markets. Long-dated forward contracts, particularly in energy markets, are considered very risky and in foreign exchange markets have largely been superseded by currency swaps (Takezawa, 1995; Brennan and Crew, 1997; Routledge et al., 2000; Coffman and Lockley, 2017).

Blockchain architectures are already being deployed as a way to improve transparency in a variety of over-the-counter forward and swap markets (Peters and Vishnia, 2017), and have been proposed as building blocks of the evolving financial architectures of extant securities and commodities exchanges (Kiviat, 2015; Walch, 2015).

1.5.2 Blockchains

Distributed ledger technologies (blockchains) are a system for storing transactional-ledgers in a distributed manner, thus enabling digitally-supervised markets to operate without a central clearing authority. These are inherently resistant to falsification, as transaction histories are stored on multiple, tamper-resistant nodes throughout the network. Accordingly, transactions carried out on the blockchain are intrinsically secure. They are best-known as being the technology underpinning cryptocurrencies, such as bitcoin. Various blockchains exist, and each may support a variety of contractual systems implementations (Antonopoulos 2014; Noroozi et al., 2018). Colloquially, 'the blockchain' is often taken to mean the bitcoin blockchain technology – but various comparable technologies are becoming increasingly popular. The Ethereum blockchain is widely used, having generally more flexible capabilities than the bitcoin blockchain.

The robust and efficient nature of blockchain has already resulted in postulated uses in the literature for emissions trading (Al Kawasmi et al., 2015; Chapron, 2017; Chen, 2018; Chitchyan and Murkin, 2018; Galenovich et al., 2018; Zhang et al., 2018). Those who work in this area are well aware of the carbon footprint of the Bitcoin and Ethereum blockchains, and have proposed both practical and regulatory measures for addressing it (Truby, 2018). We are, however, the first to propose application to SRM. The application of blockchain technology in small-scale energy distribution has already been demonstrated in practice (Rutkin, 2016). Such resources show that an application to carbon-related markets is indeed feasible – even if the specific pollution-management use case and consequential performance-verification issues remain unexplored in this instance. As well as security, the lack of dependence on a central clearing authority affords the market robustness against several other problems, which may otherwise be introduced by unreliable central authorities. These notably include: Fees escalations; abolition of the clearing house; corruption; and inadvertent loss of records (e.g. by fire).

Blockchains are now being used for a very wide variety of transaction types well beyond cryptocurrencies – for example land registries (Lemieux, 2016). Deprecating the relative importance of any single ledger helps to reduce the risk of fraud – which is (as discussed above) a serious and recurring problem in the carbon offset market. Missing Trader Fraud (MTF – where traders buy goods VAT-free, and then sell them on before absconding with the VAT they collect) alone is believed to have been responsible for 1.3 bn Euros of Carbon Market fraud (Frunza et al., 2011). Interpol provides a list of carbon credits fraud types (Interpol, 2013).

Another feature of blockchain transactions is that they constitute so-called 'smart contracts'; this means that the architecture of the blockchain serves inherently to verify contractual performance – rendering many steps in a traditional transaction unnecessary. With this self-verification and resistance to falsification comes a commensurate reduction in compliance costs. However, a significant IT cost overhead exists. Because of the highly-distributed nature of blockchains, IT transactions costs are inherently higher than for equivalent central-ledger systems (Giungato et al., 2017).

When evaluating real expected transaction costs, the artificially adjusted levels of current bitcoin transaction fees must be considered (Kaskaloglu, 2014). Nevertheless, subdivision into relatively tiny units of cryptocurrency is possible – with the unit of a hundred-millionth of a bitcoin being known as a Satoshi. The use of very small trades implies large aggregate transaction volumes. These dramatically increase the resources required in maintaining the blockchain infrastructure.

Transaction rates are a significant limitation for blockchains. To permit individual instances of the distributed ledger to require modest IT overhead, transaction volumes must be kept low – in the order of low tens of transactions per second. This compares unfavorably with card networks, such as Visa or Mastercard, which are several orders of magnitude higher. Although larger transaction volumes are a goal of bitcoin technology upgrades, our proposal does not rely on high transaction frequency – instead choosing large transaction sizes to get around this limitation.

2 Proposal

2.1 Problem statement

Continuing CO_2 emissions threaten dangerous warming, and geoengineering offers a potential solution, albeit an imperfect one. Long and Shepherd (2014) propose a period of SRM geoengineering (colloquially referred to as a ‘bridge’ or stop-gap) while waiting for CDR, which effects a lasting solution to the emissions. Assuming consent for such an approach, the challenge of implementation is to create a practical system for executing the necessary contracts, so that geoengineering activity can be linked very closely to emissions, by ensuring i) time-of-effect – thus avoiding transient over- or under-cooling; ii) a ‘polluter pays’ commercial linkage; iii) an accurate match between the physical amount of geoengineering ordered and the pollution that mandated its use – thus avoiding permanent over- or under-cooling.

Article 6 of the Paris agreement envisages a transnational approach to meeting individual-nation targets – potentially offering legitimacy to an international market in geoengineering services. The nature of SRM is that it is geographically heterogeneous yet transboundary – and therefore any deployment must be carried out in an orderly global fashion, without artificial attempts to constrain its extent for political reasons (Lockley, 2016; Nalam et al., 2018). CDR is, by contrast, geographically fungible, at least to the extent that geography and geology permits the necessary activities. In this paper, we propose and analyze a system of smart contracts – organized and executed on the blockchain, to achieve the objectives stated above.

2.2 Methods and scope

We discuss the potential use of smart contracts, implemented via a blockchain, to enact Long & Shepherd’s proposed link between SRM and CDR geoengineering along five dimensions. First, we consider how Long & Shepherd’s SRM-CDR bridge concept be commercially implemented on an individual, polluter-pays basis, by which we mean to provide a mechanism that encapsulates and disposes of the climate effects of a given unit of pollution. Second, we ask whether or not the blockchain offers unique advantages in connecting CDR with an SRM bridge. Third, we investigate whether or not the blockchain is feasible for realistic transaction volumes. Fourth, we consider if blockchain-based systems offer regulatory advantages and evaluate their resistance to fraud. Finally, we compare our proposal with commonly-discussed alternative schemes.

3 Discussion

3.1 Constructing the bridge: Sample transactions and market microstructure

A given emitter could, in theory, fully mitigate the warming caused by constructing an instance of Long and Shepherd’s bridge through individual initiative. This could be done by purchasing a combination of both SRM and CDR futures credits at the time of emission. The market might generally resemble the market for VCOs, although an element of compulsion may later be introduced – as in state-mandated ETSs (Papageorgiou et al., 2015).

Commercially packaged reliable short- or medium-term CDR futures, coupled with an SRM bridge, offer a convenient product to the buyer – potentially allowing them to reduce the transaction costs associated with constructing a bespoke SRM bridge. The key to this is an understanding that the market for CDR-derived credits would be both heterogeneous (especially regarding time-of-action) and in continual flux (in common with other global commodity markets). Accordingly, it is a non-trivial task to purchase a best-value contract and match it to an appropriate SRM bridge.

Structuring and commercially packaging the SRM bridge could be done without a blockchain. However, the use of a well-designed blockchain potentially allows rapid, automated purchase of the necessary permits or offsets, thereby further reducing transaction costs, as well as offering escrow capabilities and a transparent public record. A decentralised, blockchain-based system offers infrastructure that lacks single points of failure- and is less vulnerable to central authorities that are inept, impermanent, overloaded or dishonest (Subramanian, 2017). These characteristics explain the widespread adoption of blockchains in markets unrelated to their original cryptocurrency implementations. Blockchains have inherent transaction volume limitations – but, by placing the commensurate obligations on high-volume ‘wellhead’ contracts, the transaction costs become essentially trivial compared to the value of the fuels and offsets traded.

A significant difference exists between the use of blockchain for cryptocurrency applications, and for the purposes of verification of geoengineering activities. In the former case, the ‘proof of work’ is computational – and it needs no central regulation authority to validate the initial ‘mining’ activity (Dwork and Moni, 1993). The much-discussed carbon footprint of blockchain technology is because of this ‘proof of work’ feature (Giungato et al., 2017). In contrast, blockchains for geoengineering would be an efficient means of trade – but would not necessarily offer any validation in the form of an inherent ‘proof of work’. As we discuss elsewhere in this paper, such a proof could be designed-in to the system, monitoring the actual operation of machinery – as opposed to relying on ad hoc inspections, or the bona fide of licensed operators. The role of regulatory authorities in verifying the bona fide of operators, and the environmental legitimacy of geoengineering interventions – particularly SRM – is matter of governance of licensees, not of market microstructure for trading offsets (Lockley, 2016).

Nevertheless, a complexity of this strategy for dealing with emissions in this way is the time delay. As discussed above, CDR is inherently slow. Even if the economic activity occurs rapidly, the biogeochemical processes may be slow – e.g. in ‘enhanced weathering’ (Kohler et al., 2010). Delayed CDR deployment carries significant economic risks, which become systemic at scale (Coffman and Lockley, 2017). In any case, CDR effect does not completely offset the warming induced by emissions – potentially for years to decades. As a consequence of this, CDR forward contracts cannot be regarded as fungible with respect to underlying technologies used by licensees. CDR futures and options markets can address this limitation, but their operation needs to be heavily regulated (Coffman and Lockley, 2017; Lockley and Coffman, 2018). The purpose of such a futures market would not be to delay the necessary economic activity for CDR in anticipation of future price falls, but rather to delay granting of the carbon credits resulting until full drawdown had occurred.

In summary, we suggest a pragmatic model for the CDR/SRM combination, based on Long and Shepherd’s bridge, where the SRM contractual bridge is either

- short-term, while waiting for CDR deployment
- medium term, if necessary, pending CDR effect (e.g. for enhanced weathering, and other biogeochemically rate-limited processes).

3.2 Advantages to the blockchain

The blockchain offers major advantages for implementing the kind of system we discuss, but also poses a range of significant challenges. From our introduction, it can be seen that the SRM service component is financially rather trivial – being both temporary in deployment requirement, and orders of magnitude cheaper than CDR. Accordingly, the major financial component is CDR. At any point, one would expect a range of CDR providers to offer services into the marketplace. These will vary in both price and time-to-effect. The automated nature of the blockchain allows a pollution monitoring and control system to purchase best-priced (verified) CDR credits in real time, validating the purchase on the blockchain. In practice, the market will clear the cheapest credits first – leading to economically-efficient CDR. The validation component of the blockchain, in turn, solves the key ‘market micro-structure’ design problem of the VCO market by providing both an automated mechanism for price formation and discovery, and some implicit expectation of reliable contractual performance (Garman, 1976).

Subsequent to the acquisition of CDR carbon credits, the SRM bridge can then be purchased – again on the blockchain. As noted above, we can see that tiny fragments of a whole currency unit can be effectively transacted. Accordingly, emissions can be precisely offset – using a process that adds little frictional and transaction cost to the overall process. The result is an offset process that works as closely to an economically and physically perfect set of conditions as is practical. Economically, contracting is inexpensive, automated and effectively instant. Physically, it offers a temperature-controlling bridge, followed by a verified removal of the carbon pollution.

Nevertheless, transaction frequency is potentially problematic, and is a necessary consideration for market design. Fossil fuels markets are characterized by relatively-large producers (e.g. oil rigs) and relatively-small consumers (e.g. cars). Mandating settlement by consumers would create overwhelming transaction volumes; it might additionally create overwhelming compliance and monitoring issues. By contrast, mandating fossils producers (or potentially processors and logistics firms) to create the point of account keeps transaction volumes modest. This is particularly the case if credits settlement is periodic – such as monthly in advance.

Current carbon emissions are around 10GtC/year. Assuming 10 transactions per second (tps), this sets a practical minimum transaction size at around 320t per transaction, on average. This is well outside the practical scale for domestic consumers and is approaching the scale of smaller CDR operations – e.g. small plantations. Accordingly, our proposal envisages supply-side settlement by miners, drillers or refiners – not by end-user consumers. One advantage of larger average transaction sizes, and markets with fewer participants, is that the carbon and economic costs of operating the IT infrastructure becomes relatively less burdensome.

3.2.1 Before blockchain implementation

Presently, there is no availability of commercial SRM, and CDR commercialisation is limited (e.g. to afforestation schemes). Nevertheless, we can take the current market for VCOs as being equivalent to the availability of similar geoengineering schemes. Commercial sales are typically relatively high-volume purchases, transacted manually. This limits supply chain transparency and makes rapid price changes impossible to communicate in an efficient manner. Any buyer (or supplier) who attempted to link an SRM 'bridge' to a slow-acting CDR approach would have a labor-intensive process to find and buy an appropriate package of interventions (assuming SRM 'credits' become available). For example, a relatively-rapid Direct Air Capture (DAC) process may require little or no SRM bridge – but a slow-acting Enhanced Weathering process would require a significant SRM bridge, while mineralisation was awaited. Matching these contracts, and pricing the result, would be laborious. Furthermore, the entire manual process is vulnerable to a range of fraudulent activities – reducing overall confidence in the market.

3.2.2 After blockchain implementation

Should CDR and SRM products be made available, and tradable on a blockchain, it is relatively simple for an automated buying process to assemble the necessary offsets and apply them to a transaction. Instant settlement is not necessarily available, but that depends on the precise system design. Nevertheless, blockchain transactions can reliably be propagated in minutes or hours. This leads to a situation where an automatic price discovery and contractual execution process can be employed. The effect of this is that the polluter (assumedly the miner, refiner, etc. – due to previously-discussed limitations of scale) pays at point-of-purchase. Depending on the contractual regime employed (which we expand later), the offsets will either have been generated in advance, or will be deployed after orders have been taken (with the former being an inherently more robust system). Automated buying, using a standardised blockchain system, will allow rapid comparison of prices. This can be conducted efficiently, across different technologies. For example, the price for fast-acting DAC can be compared to slow-acting EW, including the requirement for an SRM bridge for the latter technique. Due to the low transaction costs of a blockchain system, the resulting offsets can be seamlessly and efficiently purchased – even at modest volumes.

3.3 Feasibility

We do not provide a detailed technical appraisal of the design of appropriate blockchain systems in this paper – not least because the technology is rapidly-evolving. Despite this, we note that deployment of blockchain-based technologies continues apace – and similar requirements for robust, accurate transactions exist in financial markets, as in carbon markets. Nevertheless, the requirement to make a transparent ledger of purchases available for a large global market poses challenges in storing and exchanging data – as we have detailed earlier.

To allow such a system to scale effectively, and for it to contribute to the global carbon budget in a meaningful way, data volumes will require management. Various strategies exist, which we will not analyze in detail. These may involve some or all of the following strategies: deployment only for high-value wellhead-type contracts (~300 tC avg., as previously discussed); pruning historic transactions from public record; aggregation and consequential data compression of smaller transactions, before settling back to the main blockchain. The viability, appropriateness, and requirement for such strategies will vary widely, according to the style of implementation pursued, and the development of blockchain technologies. We therefore simply note the potential technical limitations – leaving this for future study.

3.4 Verification & regulation

3.4.1 Regulation of geoengineering activities

Critical to the robustness of the system we propose is the issue of verification. While a comprehensive treatment of this issue is beyond the scope of this paper, we nevertheless note the requirement to achieve two principal goals:

1) Ensuring SRM is safely and correctly executed.

2) Ensuring that any CDR credit offered maps properly to permanent geological sequestration. As per the introduction, we do not consider biological (living) storage of carbon to be sufficiently stable to offer a bona-fide CDR VCO – and any discussion of such techniques is for the convenience of offering clear examples.

Building on the work of Lockley (2016), we suggest that it is practicable to assume the development of an appropriate regulatory framework – and thus we view an in-depth discussion of how SRM credits can be validated from a regulatory point of view, and deployed responsibly from a scientific point of view, to be outside the scope of this paper. We suggest use of a similarly-sufficient regulatory system for CDR, and we draw readers' attention to the burgeoning literature on this subject (Gerrard and Hester, 2018).

3.4.2 Contractual regulation

The purchase of a CDR instrument on the forward or futures market at the point of fossil fuel extraction (or refining) mandates consideration of an additional issue – that of contractual performance. As per the introduction, need for *financial* market regulation exists in the futures market. Coffman and Lockley (2017) discuss in depth the issues of risk and regulation in the CDR futures markets. Their treatment of the issue is qualitatively different to ours: we do not suggest deferring performance to take advantage of anticipated cost reductions, but rather to ensure accurate timing of the delivery of the offset. Accordingly, long-term market underwriting is not necessary for our purposes. The role of a regulator in our system exceeds the exercise of purely financial controls. Its role is partly to ensure that economic activity performed to produce CDR offsets is not delayed to the point that delivery becomes unreliable. In practical terms, post-work granting of credits is typically advantageous – ensuring that performance risk is eliminated. Nevertheless, longer-term deferment of credits to promote resource stewardship may be needed. For example, enhanced weathering deposits could be rendered useless if smothered by other materials. Deferral of credits for maintenance would help reduce or even eliminate such risks.

Alternatively, to ensure full execution of credits granted in advance of biogeophysical performance, regulators may seek to rely largely on financial regulations – placing resource stipulations on the parties to the transaction, or at least to the underwriters of these parties. Suitable candidate firms for this underwriting opportunity are the larger financial institutions, and reinsurers. Similarly, regulators may seek to concern themselves not only with the fact of a contract, but on the business models behind it. Such potential financial measures are not unlike restrictions that exist in the banking sector (e.g. setting 'reserve asset ratios', thus reducing the possibility of a bank run). Detailed, forward-looking analyses of cost models, delivery plans, etc. may be valuable approaches for regulators to take – and may complement or even reduce the need to establish a framework of retrospective performance verification. Broadly speaking, however, grant of credits after economic performance is a more robust system – preventing the economy becoming awash with what may be colloquially regarded as carbon IOUs.

To be clear: grant of credits after delivery would not obligate the biogeophysical CDR to have taken place – but simply that the economic precursors had been completed. Put colloquially, the tree may not have grown – but it should have been planted. For certain types of CDR, process equipment could automatically validate performance (e.g. DAC). For others, inspection and sign-off inherently involves at least some manual or observational step (e.g. forestry inspections), which may be carried out by humans, or by equivalent monitoring systems (e.g. drones).

Pertaining to SRM, a similar strategy could be used for generation in advance of sales. SRM could be accelerated dramatically, thus enabling long contracts to be equivalently-completed very early. For example, we might assume that a ton of carbon is fully offset in 10000 days after completion of the relevant CDR economic activity – which we (artificially) assume occurs instantaneously, at this point. An SRM firm could either contract to deliver 10000 days of 1-ton-equivalent cooling. Alternatively, it could instead contract to deliver 1000 days of 10 tons-equivalent cooling. Of course, practical constraints on the minimum duration of SRM interventions apply, and such methods also risk termination shock if scaled. However, the principle of time-compression remains credible for smaller total interventions. By this method, the SRM firm could build a stock of "day-ton" credits, on the blockchain, ready for sale (N.B. our suggested 300 tC block limit). Such a system essentially eliminates the risks inherent in contracting for future performance for SRM. A (largely-theoretical) risk exists of overcooling, or of erratic cooling – particularly if large stocks of credits were built up prior to the emissions they purported to offset.

3.4.3 Fraud risks and prevention

When considering the robustness of blockchain-based CDR to fraud (and fraud attempts) consideration of the Interpol list, given earlier, is merited. By way of background, Interpol (2013) provides the following list of fraud types applicable to carbon credits:

i. Fraudulent manipulation of measurements to claim more carbon credits from a project than were obtained;

ii. Sale of carbon credits that either do not exist or belong to someone else;

iii. False or misleading claims with respect to the environmental or financial benefits of carbon market investments;

iv. Exploitation of weak regulations in the carbon market to commit financial crimes, such as money laundering, securities fraud or tax fraud;

v. Computer hacking/ phishing to steal carbon credits and theft of personal information.

Blockchain technology can contribute significantly to the reduction of fraud, in carbon markets. To address the specific fraud types individually:

i. Obtaining credits fraudulently is dependent on the underlying security of the verification methodologies. If operators are relied upon to log their own credits generation, abuse potential exists. However, if machinery is logged then credits can be confirmed by a physical analog to "proof of work," as in the bitcoin blockchain;

ii. Sale of non-existent credits is essentially impossible. The sale of credits belonging to someone else would require unauthorised access to their computer systems, which can be resisted using standard cybersecurity practices;

iii. The inherent transparency of the blockchain system tends to obviate the risk of false investment claims;

iv. Generally reduced by a transparent and secure clearing system – whether blockchain-based, or otherwise;

v. The ability of hacking to obtain credits unlawfully is greatly restricted. The widespread, and seemingly dependable, use of cryptocurrencies by criminals shows that the blockchain technology underpinning this currency is inherently robust to such fraud.

3.4.4 Policy and research implications

The infrastructure necessary to implement a blockchain-based transaction system could conceivably be devolved down to the device level. It is theoretically possible to mandate the use of internet-connected agent software on each device to monitor energy usage and obtain geoengineering contracts at the moment of use. However, this is largely pointless – as there is already a billing and transactional infrastructure associated with energy supply, and this can be easily built on – to create "wellhead" contracts, as discussed earlier. A wellhead approach also overcomes difficulties inherent in processing small transactions. Logically, the transaction need not be associated with the point of use, but rather the point of metering, or indeed taxing. Accordingly, should this methodology for handling emissions be used, it would be incumbent upon the legislator to ensure that appropriate billing and contracting infrastructure existed at the point of delivery – like the mandatory collection of sales taxes at point of sale. The existence of various forms of revenue share agreements for extractive industries means that there is an existing contractual infrastructure in place, which can be adapted to ensure this delivery.

Efficient systems for both selling credits, and for monitoring their production, may be envisaged. First, the blockchain may be used to effect rapid and cost-efficient carbon transactions. This would enable a polluter to purchase a CDR offset, with a necessary SRM bridge. The rapid, computerised nature of such transactions means that real-world carbon costs can be dynamically-added to a polluting purchase – either directly, or by adjusting input costs (e.g. the oil used to transport a toy). This allows real-time and reasonably-complete offsetting of purchases, such as fuels, flights, etc. – noting the minimum transaction sizes, discussed earlier.

Secondly, the blockchain may be used to verify the production of such credits to a much finer level of detail. A full consideration of such methodologies is beyond the scope of this paper, but we can offer a summary example: a miner operates machinery, grinding rock to remove a ton of atmospheric CO_2. Upon task completion, this blockchain-connected machine would issue a CDR credit (or a time-dependent series), based on mineralisation. Such a mineralisation process may take a century to fully complete (arguably beyond the lifespan of centralised regulatory institutions). A credit buyer would then have to purchase a complementary SRM bridge credit. As discussed prior (with commensurate limitations), this may, for convenience and reliability, be a contract for 100x over-performance, delivered for only 1 year (not 100 years). A firm with a marine-cloud brightening machine may operate that machine to generate such an offset. Upon completion, a certificated machine would then post the offset to the blockchain, allowing purchase by the polluter. In this manner, a properly-implemented and monitored blockchain solution could allow the verification of the trade in carbon credits, and potentially their verified generation, too.

3.5 Comparison with alternative approaches

The principal existing methodologies for addressing carbon pollution include a carbon tax, or cap-and-trade policy (Metcalf and Weisbach, 2009; Carl and Fedor, 2016; Ploeg and Withagen, 2014). The main advantage of our pollution-linked methodology is that it encapsulates and disposes of the climate effects of a given unit of pollution. By contrast, depending on a carbon tax has no direct economic link to disposal. While it is possible that such a tax could be used for similar geoengineering, there would not necessarily be an obligation on governments to deploy the money in this manner. Furthermore, without such a direct link, there is a risk of over- or under-charging. If the EU ETS scheme is any guide, under-charging is likely because of the historically weak responses of governments to climate change, in the face of lobbying (Green, 2017). In addition, any radical tax shift would be likely to be disruptive to the economy – and the lack of a defined geophysical link may crystallize opposition, which is a distinct disadvantage, when compared to our proposals.

An alternative comparator is cap-and-trade. In this case, the principle systemic weakness is the lack of economic flexibility. Below the cap, there is no aggregate incentive to reduce the level of pollution – nor to remedy the impacts. Above the cap, no pollution is permitted – even if flexibility will result in great economic benefits, above and beyond the cost of the carbon externalities, or of carbon removal. Nevertheless, a blockchain-based system could potentially mesh with cap-and-trade – potentially permitting cap-breaching if geoengineering was used to remedy the resultant pollution. We do not discuss the details of implementing such an 'overdrive' condition, in this paper.

4 Conclusions

We considered in this paper two fundamental approaches, one of which is a subset of the other. First, we reflected on whether it is reasonable to extend the 'polluter pays' principle to require that the 'polluter geoengineers'. Secondly and specifically, we considered the requirement of a like-for-like geoengineering intervention, reversing fully the effect of carbon emissions. Initially, this would be by using SRM to remove (as far as is possible, with an imperfect technique) the short-term radiative forcing effects of any carbon emissions. Eventually, there would be a requirement to physically remove an equivalent amount of carbon to that which is released in the polluting activity – placing this in permanent geological storage.

In general, we build on the work of previous authors and conclude that this SRM-CDR Bridge approach is reasonable, from a physical science point of view. From an economic point of view, a ‘polluter geoengineers’ approach directly links clean-up costs to emissions. If such repair is conducted without undue delay, this approach directly responds to market prices – thus more closely matching the clean-up costs imposed on society than does a carbon tax set at an arbitrary level. Compared to a carbon tax, a polluter-geoengineers system (whether blockchain-based, or otherwise) offers a precise geophysical link to pollution, and a price that is consequently economically-robust and impervious to lobbying influence–except perhaps in the regulatory approval or permitting of unsatisfactory schemes, which is a concern in the governance of climate engineering more generally. It is also more flexible than a cap-and-trade system, with which it could potentially be meshed – creating a hybrid, where emissions over a cap have to be geoengineered. Compared to a naked cap-and-trade system, the blockchain offset system permits more flexibility – offering polluters the chance to under- or over-shoot the cap, as economic conditions dictate.

We then considered the contractual mechanisms to achieve the necessary sequence of trades. Specifically, we considered the use of blockchain-based ‘smart contracts’ in this market.

As our discussion has explored, there are a number of advantages and disadvantages to a blockchain-offset system – specific to the research questions we have posed.

i. The divisible and attributable nature of SRM and CDR geoengineering makes it practical to implement Long and Shepherd’s SRM bridge concept on a ‘polluter pays’ basis, given a sufficiently-developed market for both SRM and CDR. Such an approach, assuming properly-regulated geoengineering, inherently allows close matching of pollution charges with clean-up costs.

ii. The blockchain allows the automatic assembly of multi-part smart-contract transactions, involving CDR with an SRM bridge. Subject to system design, these transactions can be performed rapidly, and can handle very accurate transactions. Sale of contracts after completion of works is preferred, but escrow contracts for works ordered are conceivable.

iii. Blockchain is a fast-evolving technology. Implementation for small transactions on a global scale market is technically challenging. Accordingly, further research on the detail of implementation strategy remains a priority for future research. We propose the use of wellhead contracts, to address transaction volume limitations.

iv. Blockchain-based systems provide advantages to regulators, when compared to some alternative approaches. They offer an opportunity to incorporate proof-of-work methodologies (by embedding in process machinery) and to link these directly and rapidly to the market; they inherently provide a transparent and robust environment to conduct and record transactions. This enables regulators to focus on fitness-for-purpose rather than proof-of-work.

v. Regarding fraud, we note that the blockchain has the advantage of being highly-resistant to falsification, and reasonably cheap to transact – without requiring human intervention. Nevertheless, a fully-detailed proposal to establish how to verify the actual geoengineering activity is required.

vi. Blockchain-based systems render the system robust to a range of potential problems with central clearing authorities: fees creep, centralised corruption and fraud, institutional collapse, and catastrophic data loss – among other risks.

In conclusion, the implementation of an appropriately designed blockchain-based system of contracts for geoengineering is practical in all aspects considered: physical science, economic viability, and operational and contractual execution. Further exploration of this technique as a means of offering equitable and robust carbon accounting is thus recommended.

Notations

AGW	Anthropogenic Global Warming
CDR	Carbon Dioxide Removal
CBOT	Chicago Board of Trade
BECCS	Bio-Energy with Carbon Capture and Storage
DAC	Direct Air Capture
ETS	European Union Emissions Trading Scheme
EW	Enhanced Weathering
GGR	Greenhouse Gas Removal
GHG	Greenhouse Gas
IEAGHG	IEA Greenhouse Gas R&D Programme
IPCC	The Intergovernmental Panel on Climate Change
IT	Information Technology
ITCZ	Inter-Tropical Convergence Zone
MCB	Marine Cloud Brightening
MTF	Missing Trader Fraud
OIF	Ocean Ion Fertilisation
SAI	Stratospheric Aerosol Injection
SRM	Solar Radiation Management
TPO	Tradable Put Options
VAT	Value Added Tax
VCO	Voluntary Carbon Offset

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