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## Carbon dioxide removal and the futures market

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## LETTER

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## Abstract

Futures contracts are exchange-traded financial instruments that enable parties to fix a price in advance, for later performance on a contract. Forward contracts also entail future settlement, but they are traded directly between two parties. Futures and forwards are used in commodities trading, as producers seek financial security when planning production. We discuss the potential use of futures contracts in Carbon Dioxide Removal (CDR) markets; concluding that they have one principal advantage (near-term price security to current polluters), and one principal disadvantage (a combination of high price volatility and high trade volume means contracts issued by the private sector may cause systemic economic risk). Accordingly, we note the potential for the development of futures markets in CDR, but urge caution about the prospects for market failure. In particular, we consider the use of regulated markets: to ensure contracts are more reliable, and that moral hazard is minimised. While regulation offers increased assurances, we identify major insufficiencies with this approach—finding it generally inadequate. In conclusion, we suggest that only governments can realistically support long-term CDR futures markets. We note existing long-term CDR plans by governments, and suggest the use of state-backed futures for supporting these assurances.

## 1. Introduction

Anthropogenic Greenhouse Gases (GHGs—principally CO<sub>2</sub>) increase global temperatures. Atmospheric CO<sub>2</sub> persists for millennia [1]; it is principally a stock problem, not a flow problem.

Carbon Dioxide Removal (CDR) has been widely discussed, and can be considered a subset of greenhouse gas removal (GGR) [2]. GGR additionally includes e.g. methane (CH<sub>4</sub>). The Kyoto Agreement defines Assigned Amount Units (AAUs) [3]. These are not defined for CO<sub>2</sub> alone—and include other GHGs, in amounts rendered equivalent by their Global Warming Potential (GWP). The CDR/GGR distinction is relevant, for reasons of effect equivalence—despite potentially significant cost differentials. For example, it may be cheaper to remove methane than CO<sub>2</sub> (taking into account their differing Global Warming Potential [4]). Hence, it is necessary to consider both GGR and CDR. As CDR is more the widely used term, and is by far the largest component

of feasible GGR, we use CDR as our primary term in this discussion<sup>1</sup>.

The economic performance of solutions to global warming may be optimised by time-shifting CDR in the medium term—to take advantage of anticipated cost reductions. Thus, the recent Paris accord relies heavily on Negative Emissions Technologies (NETs) to deal with near-term emissions of CO<sub>2</sub> in decadal timescales, even as it envisions concurrent abatement efforts [6].

We consider possibilities for the development of futures markets for CDR/GGR, as novel technologies tend to fall in price [7]. Many technologies (e.g. cell

<sup>1</sup> In our discussions of market design, we do not specifically consider GGR as distinct from CDR, but include this definition for completeness only as a CDR futures market could also provide a platform for trading other GGR contracts on a far smaller scale in the manner that the Chicago Board of Trade had, by the late nineteenth century, developed as the most important exchange for wheat futures trading, but also traded maize corn, oats, rye, or barley in far smaller volumes. See [5].

phones, computers, cars, telephones) went from being the preserve of the rich to mass-market staples within decades [8]. A survival bias exists: only successful technologies fall sufficiently in price to promote widespread adoption. Nevertheless, it is reasonable to expect a technology-driven CDR price fall [9]. Given an expectation of ongoing demand, a reasonable investor may seek to sell CDR obligations today, and assume the risk of delivering the technology at a lower price tomorrow. The question is whether or not a market for CDR futures is the most realistic way to organise risk transfer, and, if not, what other options exist.

Section 2 considers the operation of forward and futures markets generally, with particular reference to long-dated contracts. Section 3 discusses how a market for CDR futures could be organised, offering contract examples. Section 4 considers scenarios for market failure and possible regulatory responses. Section 5 offers some conclusions and possibilities for future research.

## 2. Forward markets versus futures markets

Forward and futures contracts are two kinds of financial instruments that fix a price now for performance in future, and provide convenient vehicles for borrowing and lending within commodities markets [10]. Options contracts, contracts-for-difference, and swap agreements also involve future settlement, and represent alternative tradeable instruments, involving many of the same caveats, as well as some additional risks discussed below. Carbon debt contracts offer another possible solution, which we consider in section 3 [11]. Our discussion in section 4 also applies to these alternative market designs.

The paradigmatic contract is for the forward-sale of a commodity product. Faced with uncertain market prices, a farmer may seek to forward-sell agricultural produce prior to production. This enables confident calculation of margins—at least to the extent that output can be predicted.

Risk transfer in both forward and futures markets depends on participants' beliefs about future market prices during the life of the contract. In general, sellers of a commodity use futures markets (in theory at least) to transfer risk: reduce financing costs; increase ability to assuredly perform on business obligations; etc. Simultaneously, these contracts offer wholesale manufacturers a realistic hedging strategy against short-term fluctuations in raw materials prices. The farmer is able to control the risk of lower grain prices in the future, and the baker is able to control the risks associated with rising prices. Both parties are able to hedge their exposure to price movements. Alfred Marshall summarised the social utility of such markets

with the pronouncement: 'the hedger does not speculate: he insures' [12].

In practice, commodity futures do not always adequately forecast prices, instead following a random walk [13]. Therefore there is considerable empirical disagreement about the value of futures contracts in risk management. There is better evidence that commercial firms use futures contracts as tools of arbitrage and to reduce transaction costs [14].

Finance academics and practitioners also draw an important distinction between primary and secondary markets: primary markets are where buyers (or investors) purchase financial instruments from the companies which issue them, whereas secondary markets offer a way for buyers and sellers to trade amongst themselves. Secondary markets consist of diverse market participants with a range of motivations, including investors, speculators, hedgers and arbitrageurs. They provide liquidity to purchasers of the original instrument who may need or want to realise the value of the contract immediately [15]. It is a well-known belief in finance that the health of the primary market depends on a robust secondary market [16].

Unlike bilateral forwards, futures are generally exchange-traded. Exchanges impose margin requirements, and other rules and regulations. They usually require maintenance of a deposit (typically 2% to 10%), to guard against the risk of non-performance. Modern futures markets adjust deposits daily, to maintain 'mark-to-market' requirements for re-valuation as prices change. Large secondary markets exist for many commodity futures. Grain contract futures markets have been used extensively in the US since the mid-19th century. Although futures contracts continue to be traded on regional exchanges even today, the Chicago Board of Trade (CBOT) has conducted the lion's share of futures trading in corn and wheat from the early 20th century onwards [17].

The role of exchanges as central clearing authorities is an important feature of futures markets. The seller of a service assumes their counterparty is able to perform, but may face a situation where they have no control of who that eventual counterparty actually is. Accordingly, either the structure of the contract (by way of a large and potentially extensible deposit) or regulation of the market (by ensuring the financial capacity of trading parties) is required—to ensure that there is indeed a valid counterparty in existence at the time the contract falls due. The need to provide these guarantees (i.e. a central clearing counterparty with deep pockets), alongside the advent of electronic trading, has driven the acquisition of exchanges by large players such as the CME Group or Eurex [18].

The distinction between futures and forwards turns on whether the contract is exchange-tradable and whether or not it is cash-settled. A forward contract fixes the price and performance between two parties, and generally involves physical delivery of the

underlying asset, at least in commodity markets (as distinct from formal commodity exchanges). A futures contract is similar, but is traded on an exchange, and may pass through many hands before falling due. Modern commodities futures are solely financial instruments—they are only ever ‘cash settled’, not delivered. This makes them less subject to market abuse, e.g. price manipulation [19]. A futures settlement is designed to restore the counterparty to the same financial position as would have been the case had physical performance taken place.

Futures and forwards are designed to be functionally equivalent from the originator’s point of view, but operate very differently on secondary markets. Easy trading of futures, to allow economically-efficient outcomes, makes them an appealing instrument. However, forward contracts can be privately traded, often via large dealer networks. This achieves a similar result—albeit in a riskier fashion, and with higher transaction costs. Additional derivative products, including options, contracts-for-difference, and swap agreements, historically developed alongside well-established futures markets; over time, options dealing moved from curb-trading (literally on the curb outside the exchange) onto exchanges, while swap agreements and contracts-for-difference have, until very recently, been traded almost entirely over-the-counter (OTC) in bilateral agreements, in a manner similar to forward contracts [20].

Because of the mechanics of settlement, exchange-based trading in options contracts generally depends upon a well-functioning futures market [21]. Options create the right, not the obligation, to buy (a *call* option) or to sell (a *put* option) an underlying asset at a given strike price before a given expiration date. These are cash-settled through the same mechanism by which the clearinghouse settles futures contracts. When a buyer exercises an exchange-tradeable call option, the clearinghouse creates for her a ‘long’ futures position at the option strike price (i.e. causes her to buy a futures contract); the exchange’s clearinghouse, in turn, assigns a ‘short’ futures position to the seller of an identical call option (i.e. causes him to sell a futures contract). By contrast, when a buyer exercises a put, he receives a ‘short’ futures position at the strike price, and the ‘long’ futures position is assigned to the seller of an identical put [22]<sup>2</sup>. This mechanism ensures orderly settlement and minimises counterparty risk. We fully expect that options trading of this variety would develop as an integral part of an exchange-traded CDR futures market.

As the Financial Crisis of 2007–8 made clear, over-the-counter trading in options and other derivatives is especially sensitive to liquidity risks and to counter-

party default. Although the networks in which OTC trading of financial derivatives are conducted is enormous, spanning the entire globe, these normally deep liquidity pools are prone to both endogenous and exogenous shocks that can halt trading or reduce it to a minimum, as happened with credit default swaps on mortgage-backed securities during the recent crisis [23]. Because regulatory requirements require financial assets to be ‘marked-to-market’, the resulting fire sales caused catastrophic market failure [24]. In a more localised way, the absence of transparency about the financial positions of market participants makes it difficult to discern possible incentives for default in individual cases [25]. The empirical finance literature shows that moving such derivatives onto exchanges reduces both kinds of risks [26]. This is why there is a regulatory consensus in favour of doing so.

Generally, futures are short-term contracts, by the time frame of climate science. Agricultural examples with periods over a year are unknown [27]. Long-dated forwards were historically used in foreign currency markets (now largely superseded by swap agreements [28]); and in petroleum markets where they are considered very risky [29].

In our CDR example, the purpose of the contract would be to allow parties to take advantage of the shift in price expected on long timescales (decadal)—leading to an increased risk profile.

Longer term financial debt instruments exist (e.g. mortgages, leases, government bonds). Mortgages and leases are inherently backed by a tie to an underlying asset. In the last financial crisis, mortgages were transformed into tradable securities (securitisation). Absent such financial engineering, mortgages are difficult to trade on secondary markets. They are not fungible (neither the property, nor the borrower, is exactly like any other); and liquidation costs are significant (via foreclosure). For government bonds, the counterparty is the state—typically seen as one of the most dependable financial counterparties in the developed world, which is why short-dated government securities are considered to be the risk-free rate.

### 3. Possibilities for a CDR futures market

The investment challenge in CDR is not to predict price direction (almost inevitably downwards), but to determine the scale of the fall. In a competitive market, too high a predicted price results in lost sales. In all markets, too low a predicted price will result in financial losses fulfilling the contract.

For a buyer, such a transaction is beneficial. A seller of goods or services with a carbon impact could fully mitigate resulting CO<sub>2</sub> pollution with CDR credits, bought on the futures market at the time of sale or manufacture. These markets may generally resemble the market for Voluntary Carbon Offsets (VCOs) [30]. An alternative model for adoption, and

<sup>2</sup> Here ‘long’ and ‘short’ refer to buying (‘going long’) and selling (‘selling short’), and do not refer to the term (long-dated or short-dated) of the contract. *This terminology is conventional*, but may confuse those who are not familiar with the language of financial markets.

source of market demand, could be state-mandated Emissions Trading Schemes (ETS), such as those which have developed in the state of California, the European Union and in China [31].

If there is a plan to rely on CDR as a least-cost solution to the CO<sub>2</sub> problem, it makes significant economic sense to defer consumption, in anticipation of price falls. Reliable CDR futures offer a convenient package to the buyer, allowing them to walk away with clean hands from an otherwise dirty transaction.

We define our ideal transaction:

- A buyer seeks CDR, equivalent to pollution that he has caused (or is economically responsible for)—we take 1 tonne. Accordingly, he sets out to purchase a commitment to remove 1 AAU from the atmosphere by any satisfactory date—we take 30 years max. Finding that price for immediate or near-term removal of CO<sub>2</sub> are unacceptably high, he instead looks to buy a contract for delivery at a forward date, or to enter a cash-settled future contract with equivalent financial performance. Provided that such a ‘satisfactory date’ contract can be obtained at a lower price than the economic benefit from the emission of CO<sub>2</sub> in the present, it makes sense for a rational actor to emit now and contract for future removal.
- A seller believes he can sell the services of 1 tonne CDR to the buyer’s timescale, at a lower-than-spot price. The seller will then seek to cash-settle the future contract, on the assumption that technological progress will have made CDR cheaper by the due date. The seller of the future will profit from any anticipated price fall below the contract price, whilst assuming the risk inherent in that judgement.
- A producer is a firm which has, or that proposes to build, CDR/GGR technology. Whilst such technology remains substantially speculative or experimental, they would not be able to sell credits on the futures market. However, when the technology became ‘bankable’ (i.e. the technology risk is assumed to be minimal), then they could start selling contracts.

There is a benefit to the producer in selling their capacity in advance, but the main economically-active party in the market is the seller—who takes a position on the future price, and provides near-term economic certainty by assuming the risks of such a price judgement.

We do not consider the issue of verification of performance generally—instead assuming agreed standards. We concern ourselves only with issues of pricing, contracting, and risk—as regards performance on these accepted obligations at future dates. Notwithstanding the above, we suggest that reliable contracts of this type would not be linked to biosphere

storage activities—such carbon storage is likely to be too short-term to be a comprehensive solution to the buyer’s CO<sub>2</sub> emissions.<sup>3</sup> In contrast to the issues we discuss, biomass carbon storage has a different range of issues (e.g. growing time). These matters have been extensively discussed in other literature, e.g. those that deal with carbon banking and carbon debts [32].

Carbon debt markets are arguably better suited to the needs of small-scale foresters, whose chief concerns are smoothing cash flows and minimising transaction costs [33]. There is much lower technology risk in biological storage methods (e.g. afforestation) than in the more high-technology CDR approaches for which future prices can be expected to fall more rapidly. For those engaged in biological storage, the risks are primarily regulatory and political, as climate policy depends both on international agreements and domestic politics, such as the recent American presidential election, which could lead to abrogation of the Paris Agreements altogether by the United States, and, in any case, will result in diminished political will to support mitigation efforts [34]<sup>4</sup>. Policy and regulatory risks could easily bankrupt small-scale agricultural enterprises.

Encouraging afforestation projects and other biological storage methods in the developing world has been a priority of the World Bank, whose Pilot Auction Facility for Methane and Climate Change Mitigation (PAF), which held came on-stream in July 2015 [35]. The PAF functions as a primary market for tradeable put options, which are allocated via auctions [36]. They have a target market capitalisation of \$100 million U.S. dollars and offer an important model for international cooperation in the design of global CDR markets [37].

The scale and volume of CDR markets envisioned by the terms of the Paris Agreements, which anticipate the near-term development of Negative Emissions Technologies, and the presence of agents, with heterogeneous expectations about the rate of price decline, suggest that futures markets (which would, in all likelihood, also allow options trading) will be the market design preferred by large-scale polluters and financial intermediaries. Financial firms and investment managers (including institutional investors like pension funds, insurance companies, and endowments) in particular would value secondary CDR markets which provide vehicles for hedging risk associated with possible equity investments in Negative Emissions Technologies [38]. This is particularly true given the current tendency toward institutionalisation and financialisation in global capital markets and the need for exchange-tradeable, standardised contracts [39].

<sup>3</sup> A properly designed and engineered geological CO<sub>2</sub> reservoir is assumed to be stable without maintenance on centennial timescales, but changes in land use may occur and are difficult to prevent.

<sup>4</sup> At bare minimum, Trump’s election is expected to delay any potential federal support for biological storage projects by an election cycle.

We do not consider in this paper how such contracts may be obligated or used in practice. Those are political questions not economic ones. These contracts may be made on a voluntary basis—as are modern VOC contracts, with varying motivations. They may be made by obligation: by legal mandate, or by supply-chain obligations (e.g. purchase of construction concrete may oblige an offset of CO<sub>2</sub> arising from manufacture).

#### 4. Market failures and regulatory responses

The superficially appealing nature of CDR futures disguises various complexities and significant limitations. They differ substantially from ordinary futures: the role of buyers and sellers is reversed as regards risk.

In the classic farming example (save for insurable crop failure) the assets covered by the contract will certainly exist. The farmer has little opportunity to renege on the contract, save for abandoning the farm or selling the crops elsewhere—triggering sanctions. In the CDR equivalent, there exists significant technology risk. Sellers may anticipate technology that is not delivered. It may be late, fail to work as expected, or may simply be far more expensive than predicted. This technology risk adds to conventional counterparty risks. A CDR futures market would suffer significant (uninsurable) external risks, greater than those typical in conventional commodity markets. By contrast, the corn prices are unaffected by technology change, within a growing season.

Additionally, there exists a regulatory dimension to technology risk. CDR producers may be willing to provide at the price agreed, but may be prevented from so doing. For example, the inexpensive strategy of Ocean Iron Fertilisation (OIF) [40] is controversial [41], and may be prohibited. Likely, Direct Air Capture (DAC) [42] will be significantly more expensive than changes in land use. It may therefore be possible for a provider to perform technologically and economically, but impossible from a regulatory viewpoint. The resulting (assumedly unexpected) price shift may render the seller entirely incapable of meeting their contractual obligations.

We can compare the futures market for CDR services with other markets in which such contracts could conceivably be used. Moore's law [43] suggests reliable increases in compute capability over time. A reasonable investor may determine that he can reliably contract to provide compute capability at any price above that predicted by Moore's well-tested law. Accordingly, the level of risk would be modest.

By contrast, the capacity of skilled investors to predict future prices of CDR is limited by the early development state of the technology. Historical data on which to base any assumptions of future price falls is sparse.

Two factors are likely to have an overwhelming influence on technology costs in CDR (as distinct from

regulatory costs). These are firstly time, and secondly deployment scale.

Considering time: a varied suite of CDR-enabling technologies is expected (e.g. surplus solar energy for DAC, improved seismic surveying for CO<sub>2</sub> storage). The development of these technologies is likely to be largely decoupled from CDR itself, and thus 'sitting and waiting' may result in large price falls. We acknowledge the varying stage of development for differing technologies, but note that none have been decisively tested at scale as a complete system. Noting the use of CO<sub>2</sub> burial, such as in enhanced oil recovery, the production component for a pure CO<sub>2</sub> stream remains challenging. For example, in Bio-Energy with Carbon Capture and Storage (BECCS), difficulties remain in sustainability supplying a suitable feed stock, without excessive supply chain emissions, ecosystems impacts, food crop competition, or GHG production arising from land use change [44].

Deployment scale is a more mercurial factor. Steady increases in production volume are one of the surest indications of forthcoming cost falls, as internal and external economies of scale take hold in an industry (an 'experience curve' or 'learning curve') [45]. However, futures contracts are ordinarily subject to performance at an agreed time, not an agreed market volume. Accordingly, it is challenging to predict the complex interplay between time, scale and price. If a futures provider assumes rapid deployment, he may be forced to perform at a far higher price than predicted. By contrast, an unduly cautious seller may overprice CDR futures, assuming slack demand keeping prices high. He would make a large margin—but on a low volume of sales. In a competitive market, he may simply be outbid.

Total market profits are scale-linked. Low-cost abatement implies almost no demand for high-priced CDR. Accordingly, there is little or no value in CDR markets at small scale, as no significant scarcity premium is available. A strong investment case requires an assumption of scale. Buyers will inevitably select providers with the most optimistic models of future scaling. Furthermore, investors may be attracted to firms whose projections are similarly-optimistic. There exists a potential risk of Darwinian selection for delusion and denial among service providers. Firms making hubristic predictions may be the only ones able to attract buyers or investors. This poses extreme risks: not only for the sector; but also to the wider economy, due to the potential size of the market.

The issue of performance risk is fundamental to the success or failure of the CDR futures concept. Were CDR futures to be a small financial market, market risks could be contained—but they would have failed as a political instrument. Only a large market is capable of exerting any meaningful influence on the climate problem. Accordingly, market risk appraisal must include an assumption of scale.

At scale, the challenge becomes one of reliable performance. In conventional futures, a deposit guarantees performance. Assuming a pumpkin is \$1 +/- 20c, a deposit of 40c guarantees performance. Even a contract which assumes the highest price, but finds the lowest, does not incentivise a buyer to renege.

CDR futures may face dramatically higher price uncertainty. Favoured technologies may turn out to be late, over-priced, unsafe, or prohibited. With steep expected falls in price, and long timescales to performance, such uncertainty may result in a prohibitive deposit. With \$20–\$60 per ton CO<sub>2</sub>, risk assumed is \$40. This would require the seller deposit of \$40 on a contract that may be sold for as little as \$20. Not only is this cost-prohibitive; but in a primitive market (i.e. without escrow), a bad-faith buyer may purchase contracts, pocket the deposit, and walk away. This mandates a central clearinghouse, as found in modern futures markets.

Escrow does not solve the problem of the contract requiring a deposit far greater than expected margins—which must be lodged for decades. This is a wholly unrealistic contractual form.

Existing futures markets generally use frequent margin calls (e.g. daily), to ensure liquidity. This is a market structure that functions well for markets that have a range of characteristics typical of ordinary commodities markets:

- Fluctuating prices
- Modestly sized, compared to the global economy
- Short-dated contracts

By contrast, markets for CDR/GGR have different characteristics

- Expected falling spot prices, during the life of the contract
- Large compared to the global economy
- Long-dated contracts

An alternative strategy for controlling performance is market regulation. The insurance market closely parallels a potentially-attractive structure for the CDR futures market. In insurance, everyday risks (burglary, house fire) can be borne by a single firm. With a sufficient stock of policies, such risks become highly predictable. The insured essentially pays to convert an unpredictable cost (a burglary) into a predictable one (a premium). Large-scale or systemic risk (hurricanes, floods and earthquakes) place the insured and insurer in more similar positions—as major losses may occur across the portfolio. Accordingly, insurance firms need their own insurance. Such ‘catastrophic risk’ insurance is sold around the reinsurance market, to replicate the experience enjoyed by the householder in the first example—

risk reduction, for a reasonable price. Reinsurers carefully balance their portfolios; storms do not strike all possible cities in any given year.

By contrast: as a commodity, CDR creates identical risks across the whole market simultaneously. Many of these risks are regulatory, which in turn are difficult to hedge or insure against and could result in catastrophic market failure [46]. Furthermore, if one CDR future fails due to the unavailability of critical enabling technology, failure of many others is also possible. More likely, since CDR futures would be based on different technologies, the effects of technological failures would be reflected in pricing. This becomes a question of the scale of the effect. If sellers assumed a CDR cost of \$40 ton from producers, a price of \$41 may be catastrophic for some, but survivable for most. By contrast, a price of \$50 would likely cause a wave of corporate failures, sufficient to impact on the wider economy. A price of \$200/ton would be simply undeliverable.

Two factors combine to increase market risks: ‘selection pressure’, when only the most bullish firms attract investors and customers; and duplicitous behaviour from ‘bad actors’. Managers and shareholders of firms providing CDR services on a futures contract may be either take reckless risks (morale hazard), or may wilfully sign contracts that are actively fraudulent (moral hazard)—having no intention to ever deliver on them [47]. These potential issues present major risks to the development of a healthy and functional market in CDR futures.

With inherently precarious markets, regulators face a difficult balancing act: growth is vital, but encourages systemic risks (climate and economic) which cannot be easily mitigated.

The regulator may also verify CDR performance and standards. Briefly: CDR techniques vary widely in side-effects and risks:

- Environmental impact—Some are benign (e.g. DAC); others disrupt ecosystems (e.g. OIF).
- Long-term risk—Enhanced weathering [48] offers reliable storage; shallow storage of pressurized CO<sub>2</sub> (after DAC) risks leaks [49].
- Biological techniques (e.g. afforestation) typically result in temporary storage of CO<sub>2</sub> (e.g. a century) [50].

Beyond the strict confines of CDR, further complexities exist in the wider GGR field.

Accordingly, we note generally that CDR is far from being a homogenous market. For CDR were reduced to a commodity, effort would have to be invested to ensure the *bona fide* of credits. Further, use of GGR as a substitute for CDR would sensibly be the subject of additional regulation, both on equivalence and on environmental impact. This will further increase a demanding regulatory burden. Creating

separate regulators for verification and futures issues may be merited—although resulting interplay makes independence a major challenge to successfully implement—with ‘finger pointing’ a likely result of any market failures.

A range of possible interventions exist for a market-only regulator:

*Contract length*—Longer contracts are riskier. Long-term price predictions depend not only on foreseeable technology risks (over time, these become less ‘noisy’—but larger), but also on societal risks (which generally increase over time). In the absence of an established cost curve, the capacity of any firm to make predictions about society, politics, economics, etc. on a timescale of decades is highly questionable.

*Resource*—regulators may seek to place limitations on the parties eligible to transact, or at least to their underwriters. Obvious candidate underwriters are major financial institutions and reinsurers. However, the financial crisis of 2008 has shown clearly that blue-chip institutions are vulnerable to unexpected collapse. The instability resulting leads government to support institutions deemed ‘Too Big To Fail’—offering supposedly private markets *de facto* state underwriting protection (essentially a socialisation of risk, and a privatisation of profit—a classic market failure).

*Transparency*—regulators may concern themselves with business models, not just transactions. Similar restrictions exist in the banking sector (e.g. capital adequacy requirements) [51]. Detailed scrutiny of cost models and delivery plans may be merited.

A mosaic of the above approaches may be expected, and we have argued separately that there is a role for emerging blockchain technology in solving problems associated with contract lengths and transparency with respect to market participation [52].

A regulated market offers potential benefits. However, inherent risks exist in relying on a futures market for technologies which are: rapidly falling in price; and have the potential to destabilise the global economy.

Current futures contracts are typically shorter-term, and are used in markets with a much higher degree of price certainty. It is unclear whether a regulatory structure can be developed which allows the inherent disadvantages of a private-sector CDR futures market to be overcome.

By contrast, we note recent international agreements mandating CDR in the long term. We also note the high levels of trust investors afford long-dated government bonds—even those that represent a significant fraction of Gross Domestic Product (GDP). We consequently suggest that government-

backed CDR futures would be a reasonable and credible instrument, attracting market confidence. Indeed, without such a contractual instrument in place, government commitments to CDR may lack assured delivery.

## 5. Conclusions

Futures represent an attractive and useful instrument for the circumstances of CDR: i.e. a nascent technology, with a long-term need for future deployment in a remedial capacity. Sellers of CDR futures would be able to benefit from price falls resulting from technological development. Buyers would gain near-term price certainty; and, in some circumstances, favourable pricing compared with mitigation. Significant microeconomic benefits result: large cost reductions; certainty increases; and consequential improvements to welfare.

However, the nature of CDR futures makes the creation of self-regulating contract forms inherently difficult. Long durations, and large price uncertainties, make unregulated CDR futures unenforceable. Therefore, a regulator is required: to ensure the capability of parties to futures contracts; and/or to ensure and control deposits.

Furthermore, CDR futures are a potentially very large market—necessarily so, to benefit the climate. Therefore, macroeconomic and systemic factors must be considered. Whilst the above microeconomic advantages offer potentially large macroeconomic benefits in aggregate (based on the large market size), there is an inherent risk that CDR futures may be under-priced by the private market—and indeed there is ‘selection pressure’ for such market failure to occur. A small under-price will simply result in the loss of expected profit by the sellers, or perhaps a net financial loss. By contrast, a large under-price may result in the bankruptcy of the firms obligated to deliver on the contract. In this scenario, the contracts may be ignored—resulting in a large loss of utility to society. Any attempts to enforce under-priced contracts may result in a series of major company collapses, and generalised financial crisis akin to the events of 2007–8. Controlling these market risks will properly be the concern of any legitimate regulator—but capacity to do so does not necessarily result from desire alone.

Accordingly, we identify a high risk of moral and morale hazard, and suggest the need for cautious market regulation. However, we note the inherent limitations of a regulatory approach to addressing market failure: price uncertainties, and large trading volumes, tend to impose systemic risks on society. We therefore find generally that encouraging long-term private-sector futures contracts is at best risky; and at worse reckless, or even malfeasant.

Accordingly, we suggest only the use of government-backed CDR futures to support any state

obligations under climate treaties. In practical terms, this would closely approximate to a carbon tax, with the state agreeing to fund matched CDR services at a future date.

## References

- [1] Archer D and Brovkin V 2016 The millennial atmospheric lifetime of anthropogenic CO<sub>2</sub> *Clim. Change* **90** 283–97
- [2] Lomax G *et al* 2016 Reframing the policy approach to greenhouse gas removal technologies *Energy Policy* 2015 **78** 125–36
- [3] IPCC 2001 *Appendix II Glossary. IPCC Third Assessment Report—Climate Change 2001 Working Group III: Mitigation* (Cambridge: Cambridge University Press)
- [4] IPCC 2013 *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ch 8 p 711–14 table 8.7.2013
- [5] Hoffman G W 1941 *Prices and the Futures Market: A 15–Year Survey, 1923–1938* No. 747, US Department of Agriculture, Washington, DC
- [6] Hulme M 2016 1.5 °C and climate research after the Paris agreement *Nat. Clim. Change* **6** 222–4
- [7] Milgrom P and Roberts J 1990 The economics of modern manufacturing: technology, strategy, and organization *Am. Econ. Rev.* **80** 511–28
- [8] Chandler A D *et al* 2009 *Inventing the Electronic Century: The Epic Story of the Consumer Electronics and Computer Industries*, with a New Preface vol 47 (Cambridge, MA: Harvard University Press) (10.4159/9780674029392)
- [9] For example, see Figueroa J D, Fout T, Plasynski S, McIlvried H and Srivastava R D 2008 Advances in CO<sub>2</sub> capture technology—the US Department of energy’s carbon sequestration program *Int. J. Greenhouse Gas Control* **2** 9–20
- [10] Williams J 1989 For the classic framing of these markets as a method of borrowing and lending commodities *The Economic Function of Futures Markets* (Cambridge: Cambridge University Press) (10.1017/CBO9780511571848)  
Williams J C 2001 Commodity futures and options *Handbook of Agricultural Economics* **1** 745–816
- [11] Coleman 2011 Financial Contracts and the Management of Carbon Emissions in Small Scale Plantation Forests, *Motu Economics and Public Policy Working Paper 11/04* p 18 (10.2139/ssrn.1829801) as above, argues for carbon lending in carbon sequestration markets in forestry, where the technology risk is low. We find his argument convincing for biological sequestration, but do not find it convincing for CDR markets more broadly where technological risk is the main consideration.
- [12] Marshall A 1919 *Industry and Trade* (London: Palgrave Macmillan) p 260
- [13] Working H 1958 A theory of anticipatory prices *Am. Econ. Rev.* **48** 188–99  
Working H 1960 Note on the correlation of first differences of averages in a random chain *Econometrica* **916–8**  
Williams J C 2001 Commodity futures and options *Handbook of Agricultural Economics* **1** 745–816  
Saleuddin R and Coffman D’M 2014 Can inflation expectations be measured using commodity futures prices? *Cambridge Working Papers in Economic and Social History*, No. 20, August
- [14] Williams J C 2001 Commodity futures and options *Handbook of Agricultural Economics* **1** 745–816
- [15] Williams J 1987 Futures markets: a consequence of risk aversion or transactions costs? *J. Polit. Econ.* **95** 1000–1023
- [16] For a classic treatment see Garbade K D and Silber W L 1979 Structural organization of secondary markets: clearing frequency, dealer activity and liquidity risk *J. Financ.* **34** 577–93
- [17] Ellul A and Pagano M 2006 IPO underpricing and after-market liquidity *Rev. Financ. Stud.* **19** 381–421
- [18] Hoffman G W 1941 Grain prices and the futures market: a 15-year survey, 1923–38 *USDA Technical Bulletin* **747** 17
- [19] Liebenberg L 2002 Strategic response of the traditional exchanges: the death of the open-outcry pit *The Electronic Financial Markets of the Future* (London: Palgrave Macmillan) pp 143–62  
Darrell Duffie and Haoxiang Z 2011 Does a central clearing counterparty reduce counterparty risk? *Rev. Asset Price Studies* **1** 74–95
- [20] Pirrong C 2001 Manipulation of cash-settled futures contracts *J. Business* **74** 221–44
- [21] See Rowsell L 1993 Commodity derivatives *OTC Markets in Derivative Instruments* ed N Cavalla (London: Palgrave Macmillan) pp 71–100  
Butler K C 2016 Currency options and options markets *Multinational Finance: Evaluating Opportunities, Costs, and Risks of Operations* pp 117–142
- [22] Carter C A 2007 *Futures and Options Markets: An Introduction* (Long Grove, IL: Waveland Press) pp 64–6
- [23] Deuskar P, Gupta A and Subrahmanyam M G 2011 Liquidity effect in OTC options markets: premium or discount? *J. Financ. Markets* **14** 127–60  
Baker M and Stein J C 2004 Market liquidity as a sentiment indicator *J. Financ. Markets* **7** 271–99  
Brunnermeier M K 2009 Deciphering the liquidity and credit crunch 2007–2008 *J. Econ. Perspect* **23** 77–100
- [24] Siriwardane E, Herskovic B and Eislefeldt A 2016 Risk Reallocation in OTC Derivatives Networks *2016 Meeting Papers* No. 538. *Society for Economic Dynamics*  
Murphy D 2013 *OTC Derivatives: Bilateral Trading and Central Clearing: An Introduction to Regulatory Policy, Market Impact and Systemic Risk* (Berlin: Springer) (10.1057/9781137293862)
- [25] Acharya V and Bisin A 2014 Counterparty risk externality: centralized versus over-the-counter markets *J. Econ. Theory* **149** 153–82
- [26] Loon Y C and Zhong Z K 2014 The impact of central clearing on counterparty risk, liquidity, and trading: evidence from the credit default swap market *J. Financ. Econ.* **112** 91–115
- [27] Brennan M J and N Crew 1997 Hedging long maturity commodity commitments with short-dated futures contracts *Mathematics of Derivatives Securities* ed M A H Dempster and S R Pliska (Cambridge: Cambridge University Press) pp 165–90
- [28] Takezawa N 1995 Currency swaps and long-term covered interest parity *Econ. Lett.* **49** 181–5  
Smith C W, Charles W Smithson and Macdonald Wakeman L 1986 *The Evolving Market for Swaps* Managerial Economics Research Center, Graduate School of Management, University of Rochester
- [29] Routledge B R, Seppi D J and Spatt C S 2000 Equilibrium forward curves for commodities *J. Financ.* **55** 1297–338
- [30] Bayon R, Hawn A and Hamilton K 2012 *Voluntary Carbon Markets: An International Business Guide to What They Are and How They Work* (Abingdon: Routledge)
- [31] Papageorgiou A *et al* 2015 Emissions trading scheme: evidence from the european union countries *Creativity in Intelligent, Technologies and Data Science* (Berlin: Springer) pp 204–15  
Liu L, Chen C, Zhao Y and Zhao E 2015 China’s carbon-emissions trading: overview, challenges and future *Renew. Sust. Energ. Rev.* **49** 254–66  
Jiang J, Xie D, Ye B, Shen B and Chen Z 2016 Research on China’s cap-and-trade carbon emission trading scheme: overview and outlook *Appl. Energ.* **178** 902–17  
Shobe W, Holt C and Huetteman T 2014 Elements of emission market design: an experimental analysis of California’s market for greenhouse gas allowances *J. Econ. Behav. Organ.* **107** 402–20

- Xiong L, Shen B, Qi S, Price L and Ye B 2016 The allowance mechanism of China's carbon trading pilots: a comparative analysis with schemes in EU and California *Appl. Energ.* **185** 1849–59
- [32] For an overview of these debates, see Bigs by H 2009 Carbon banking: creating flexibility for forest owners *For Ecol. Manage.* **257** 378–83  
Chomitz K and Lecocq F 2003 Temporary sequestration credits: an instrument for carbon bears *World Bank Policy Research WP 3181* (Washington, DC: World Bank)  
Coleman A 2011 Financial Contracts and the Management of Carbon Emissions in Small Scale Plantation Forests *Motu Economics and Public Policy Working Paper 11/04*  
Esuola A and Weersink A 2005 Carbon banks: an efficient means to exchange sequestered carbon *J. Environ. Qual.* **35** 1525–32  
Kling C and Rubin J 1997 Bankable permits for the control of environmental pollution *J. Public. Econ.* **64** 101–15  
Leiby P and Rubin J 2001 Intertemporal permit trading for the control of greenhouse gas emissions *Environmental and Resource Economics* **19** 229–56  
Marland G, Kirsty F and R Sedjo 2001 Accounting for sequestered carbon: the question of permanence *Environ. Sci. Policy* **4** 259–68  
Rubin J 1996 A model of intertemporal emission trading, banking, and borrowing *J. Environ. Econ. Manag.* **31** 269–86  
Sedjo R and Marland G 2003 Inter-trading permanent carbon credits and rented temporary carbon emissions offsets: some issues and alternatives *Clim. Policy* **3** 435–44  
Markowski-Lindsay M, Stevens T, Kittredge D B, Butler B J, Catanzaro P and Dickinson B J 2011 Barriers to Massachusetts forest landowner participation in carbon markets *Ecol. Econ.* **71** 180–90
- [33] Coleman A 2011 Financial Contracts and the Management of Carbon Emissions in Small Scale Plantation Forests *Motu Economics and Public Policy Working Paper 11/04*, p 18
- [34] Nisbet M 2016 Climate denial's Trump card *New Sci.* **230** 18–9  
Kemp L 2016 US-proofing the Paris climate agreement *Clim. Policy* **17** 86–101
- [35] Kim J Y 2015 Remarks at Plenary Session *Third International Conf. on Financing for Development (Addis Ababa, Ethiopia, 13 July 2015)*  
Ausubel L M, Cramton P, Aperjis C and Hauser D N 2014 *Pilot Auction Facility for Methane and Climate Change Mitigation: Relevant Environmental Auctions* ([www.pilotauctionfacility.org/sites/paf/files/Review%20of%20Environmental%20Auctions.pdf](http://www.pilotauctionfacility.org/sites/paf/files/Review%20of%20Environmental%20Auctions.pdf))
- [36] For a detailed discussion of market design, see World Bank 2016 About the PAF *Pilot Auction Facility* ([www.pilotauctionfacility.org/content/about-paf](http://www.pilotauctionfacility.org/content/about-paf))
- [37] Höhne N, Warnecke C, Day T and Röser F 2015 *Carbon market mechanisms in future international cooperation on climate change* (Cologne: New Climate Institute)
- [38] For the argument that technologies to fight climate change will most likely be financed by the state incentivising development, see Janeway W H 2012 *Doing Capitalism in the Innovation Economy: Markets, Speculation and the State* (Cambridge: Cambridge University Press) pp 276–7 As with the previous financial bubbles which Janeway describes, there is considerable potential for speculative bubbles both in climate change engineering firms and in CDR futures markets.
- [39] Frechette D L and Weaver R D 2001 Heterogeneous expectations of traders in speculative futures markets *J. Futures Markets* **21** 429–46  
see also Cheng I H and Xiong W 2013 *The financialization of commodity markets* No. w19642. National Bureau of Economic Research ([10.3386/w19642](https://doi.org/10.3386/w19642))
- [40] Buesseler K O *et al* 2008 Environment: ocean iron fertilization—moving forward in a sea of uncertainty *Science* **319** 162
- [41] Lukacs M 2012 World's biggest geoengineering experiment 'violates' UN rules *The Guardian* (Accessed: 7 March 2016)
- [42] Lackner K S 2013 The thermodynamics of direct air capture of carbon dioxide *Energy* **50** 38–46
- [43] Moore G E 1965 Cramming more components onto integrated circuits *Electronics Magazine* p 4
- [44] For a sense of the debate see Vergragt P J, Markusson N and Karlsson H 2011 Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in *Glob. Environ. Change* **21** 282–92  
Muratori M, Calvin K, Wise M, Kyle P and Edmonds J 2016 Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS) *Environ. Res. Lett.* **11** 095004
- [45] Day G S and Montgomery D B 1983 Diagnosing the experience curve *J. Marketing* **44**–58
- [46] For a good discussion of the difficulties in insuring or hedging against regulatory risks in this area, see Fan L, Hobbs B F and Norman C S 2010 Risk aversion and CO<sub>2</sub> regulatory uncertainty in power generation investment: policy and modeling implications *J. Environ. Econ. Manag.* **60** 193–208
- [47] Lockley A J and Coffman D D 2016 Distinguishing moral hazard from morale hazard in geo-engineering *Environ. Law Rev.* **18** 194–204
- [48] Kohler P, Hartmann J and Wolf-Gladrow D A 2010 Geoengineering potential of artificially enhanced silicate weathering of Olivine *Proc. Natl Acad. Sci. USA* **107** 20228–33
- [49] Celia M A *et al* 2009 Risk of leakage versus depth of injection in geological storage *Energy Procedia* **1** 2573–80
- [50] Locatelli B and Pedroni L 2004 Accounting methods for carbon credits: impacts on the minimum area of forestry projects under the clean development mechanism *Clim. Policy* **4** 193–204
- [51] Chortareas G E, Girardone C and Ventouri A 2012 Bank supervision, regulation, and efficiency: evidence from the European Union *J. Financ. Stabil.* **8** 292–302
- [52] Lockley A J and Coffman D D 2016 'Geoengineering and the blockchain: a near complete solution to emissions?' *Working Paper Presented at the Fall Meeting of the American Geophysical Union, San Francisco Negative Emissions: Staying Below 2°C I Posters* 14 December 2016, Paper ID GC33B-1239