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LETTER

Carbon dioxide removal and tradeable put options at scale

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Abstract

Options are derivative contracts that give the purchaser the right to buy (call options) or sell (put options) a given underlying asset at a particular price at a future date. The purchaser of a put option may exercise the right to sell the asset to the issuer at any point in the future before the expiration of the contract. These rights may be contracted directly between two parties (i.e. over-the-counter), or may be sold publicly on formal exchanges, such as the Chicago Board Options Exchange. If the latter, they are called tradeable put options (TPOs) because they can be bought and sold by third-parties via a secondary market. The World Bank has a Pilot Auction Facility for methane and carbon mediation which uses TPOs in carbon-relevant markets, giving producers (of e.g. forest restoration) a floor price for their product [1]. This enables long-term producer planning.

We discuss the potentially broader use of these options contracts in carbon dioxide removal (CDR) markets generally and at scale. We conclude that they can, if priced correctly, encourage rapid investment both in CDR technology and in operational capacity. TPOs could do this without creating the same type of systemic risk associated with other instruments (e.g. long-dated futures). Nevertheless, the widespread use of such instruments potentially creates novel risks. These include the political risk of premature closure [2] (conventionally rendered as 'counting your chickens before they are hatched'); and the economic risk of overpaying for carbon removal services. These instruments require careful structuring, and do not inoculate the CDR market against regulatory disruption, or political pressure. Accordingly, we note the potential for the development of TPO markets in CDR, but we urge caution in respect of identified risks.

1. Introduction

Greenhouse gases (GHGs), principally carbon dioxide (CO_2) and methane (CH_4), increase global temperatures through a process of radiative forcing. Sources of greenhouse gases can be natural or anthropogenic, i.e. caused by human agents. Anthropogenic GHGs therefore cause anthropogenic global warming; since atmospheric CO_2 is persistent on millennial timescales [3], CO_2 pollution is principally a problem of stock rather than flow. Any remediation efforts that reduce the stock of CO_2 (representing previous carbon emissions) are thus beneficial whether or not they are accompanied by reductions in current emissions through behavioural change.

Carbon dioxide removal (CDR) is functionally a subset of greenhouse gas removal (GGR), the latter of which includes methane, nitrous oxide and a number of fluorinated gases [4]. Assigned amount units (AAUs) are defined by the Kyoto Agreement, but are not particular to CO_2—instead including other GHGs, according to their Global Warming Potential (GWP) [5]. Distinguishing CDR from GGR is relevant, due to effect equivalence in the face of potential cost differences. Methane, corrected for GWP, may, for example, be a cheaper gas to remove than CO_2 and, on a small scale, methane gas removal already forms part of the World Bank's development policy toolkit [6]. Our discussion focusses primarily on CDR, which represents the lion's share of feasible GGR at scale, except where an explicit distinction is needed for clarity.

Various techniques have been proposed for CDR, and these vary widely in terms of technological sophistication, current readiness, cost, environmental impact, and storage stability. Examples include bio-energy with carbon capture and storage (BECCS); afforestation; and ocean iron fertilisation (OIF) [7]. The economic efficiency of global warming interventions can be optimised by delaying CDR, pending anticipated cost reductions, due to experience curve effects [8]. As the Paris Agreement anticipates, novel technologies ordinarily fall in price. Examples abound: cell phones, jet travel, wristwatches; all went from being luxury items to mass-market consumer goods within a generation [9]. Survivor bias confounds analysis: technologies that fail to demonstrate a steep experience curve typically falter in the face of competition. There is a consensus that technology-based CDR prices can be expected to fall with elapsed time and increasing scale [10]. Thus the Paris Accord posits delayed roll-out of negative emissions technologies, addressing near-future CO_2 releases, to run alongside concurrent abatement efforts [11].

At present, tradeable put options (TPOs) have been used by the World Bank to facilitate financing of projects with the potential to reduce GHG emissions (primarily CH_4 and some CO_2), but the capitalisation target remains relatively modest with just a handful of market participants [12]. We consider instead the application of TPOs for CDR/GGR use at a global scale. This has two key benefits: it offers subsidy support for infant industries (potentially as part of a broader industrial policy), and provides stable, long-term price planning to the CDR industry as it matures. TPOs allow investment of relatively modest sums to secure a price, but allows flexibility to sell at a higher price should the market permit.

Assuming ongoing demand, a reasonable investor may seek to fix a price for CDR services today, to offset risk of investing in the development of necessary technologies. The question is whether TPOs are the most appropriate instrument by which to arrange this risk transfer.

In section 2 we consider the design and operation of options markets generally, with particular regard to nascent industries. Section 3 discusses in depth how TPOs could be structured, with examples of instruments and markets. Section 4 examines potential market failures and appropriate safeguards. Section 5 consists of conclusions and clear recommendations for adoption of TPOs for CDR at scale.

2. Options: instruments and market design

Options are financial instruments to fix current minimum or maximum prices for future trades, conducted within a given time period. They provide a convenient means for attracting capital investment into markets. Futures contracts, [13] contracts-for-difference, swap agreements, and debt contracts [14] also involve future settlement, and have been treated separately by the authors in previous work in this journal [15].

We briefly introduce definitions, for readers unfamiliar with the subject:

- Expiration date: date by which option must be exercised, or becomes void
- Holder: the party benefitting from the rights of an option
- Writer: the party under obligation to buy (or sell)
- Strike: the price at which the option is executed, i.e. ultimately sold
- Premium: the price charged by the writer for the option
- Call: option contract conferring the right to buy at a strike price
- Put: option contract conferring the right to sell at a strike price
- Tradeable: option that may be sold on without amendment
- Market: any environment in which options are traded
- Exchange: formalised market for trading instruments, including options
- Intrinsic value: difference between strike price and market price
- Time value: premium over intrinsic value, due to potential price fluctuation
- Break-even: strike plus (or minus) premium for a call (or put)
- American option: option with no fixed exercise date (can be exercised until expiration)
- European option: option with a single fixed exercise date (the expiration date)
- Physical-settled: option contract requiring physical delivery of underlying
- Cash-settled: option contract settled for the cash value of option at expiration
- Bespoke contract: involving a very specific underlying asset (e.g. a plot of land)
- Common contract: involving a fungible underlying asset (i.e. a 100 bushels of wheat)
- Primary market: the initial market (e.g. auction) where these contracts are first sold
- Secondary market: an exchange or other market where contracts can be traded by third-parties

An example of a bespoke option contract is the purchase of land. A developer may acquire a call option over farmer's field, in order to seek permissions or finance relevant to his planned development. He is free of obligation to purchase, should market conditions change, or his planning process go awry. For example, he may pay $15 000 to secure an option to buy a field for $300 000—on which he might plan to develop a house worth $1 m.

The reverse of this is a put option—the subject of our study. A put obligates the counterparty to purchase, at a pre-agreed price—but does not compel the owner to sell. The effect of a put option is to set a guaranteed minimum price for a future sale. The seller is then free to seek a better price, prior to exercising such an option. As the guaranteed future price benefits the seller, he would ordinarily pay a premium to acquire such an option [17].

In previous work, we discussed the use of long-dated futures for CDR purposes, finding them generally unsuitable at scale [18]. In the previous contribution, we were concerned with exploring the viability of CDR futures (and their alternatives) for ensuring supplier performance. Here we want to explore TPOs as a mechanism for attracting capital investment in CDR technology by ensuring suppliers a minimum unit price for their product and by potentially pre-selling their services. Having purchased such a put option (which guarantees sale at a particular price), suppliers should be able to raise debt finance more easily to develop and deploy their technology. The buyer of the option has to pay the premium upon purchase, which rewards the seller, whether a state actor or private party, for bearing the technological risk that prices will fall much faster than expected. Once such a market was well-established, it is also theoretically possible that sellers of CDR services would also want to write tradeable call options (TCOs) permitting polluters to buy their services at a specified strike price by a given expiration date. That scenario is beyond the scope of this letter as it violates the assumption behind this proposal that prices of technological CDR can generally be expected to fall (a call option is a hedge against the price rising) and entails the same degree of counterparty risk (that the writer of the call option cannot perform if required) that we identified with respect to a CDR futures contract. The decision to allow TCOs is a regulatory one, but it is not recommended as a way of attracting capital investment in CDR technology.

In a general sense, all options contracts are prone to counterparty risk. A buyer of a call option may find that a bad faith counterparty refuses to sell at the price specified, or, alternatively, has sold the underlying elsewhere during the option period or never possessed it in the first place. Whilst absconding is a real risk, it requires malfeasance or recklessness arising from moral hazard (that someone will write and sell a call option either out of excessive optimism or without regard for their own ability or expected ability to perform). With a put option, the counterparty risk is qualitatively different, in that the issue here is the financial capability of the writer of the option to purchase the underlying at the price specified in the contract.

In order to counter the risk of non-performance, a margin requirement may be set by an organised exchange. This requires the writer of the option to place monies on account, sufficient to cover expected losses from their position. However, our discussion focusses on the state as option writer. For our purposes, we assume the state to have liquidity sufficient to dwarf any open options positions—rendering margin requirements unnecessary in primary markets, though they may be desirable in secondary markets (such as exchanges) where these instruments are sold on to private parties. Tradable options allow holders to transfer their rights. In the above example of a bespoke option, the developer may acquire the necessary permissions to develop the land, and then sell his option, without ever purchasing the land. He may similarly seek to do so without seeking the permissions—and profit simply from wider market conditions. Formal exchange markets exist for many options. Although futures contracts continue to be traded on other exchanges even today, the Chicago Board Options Exchange has developed as the dominant global market for formalised options trading from the early 1970s.

Our study considers particularly the issuance of TPOs by state-backed financial institutions, and international financial institutions, such as: the World Bank, European Investment Bank, African Development Bank, etc. Such institutions are at the upper end of the range of dependability as counterparties. Accordingly, counterparty risk does not feature heavily in our discussions. Before TPOs trade freely in a secondary market (usually an exchange), TPOs are usually auctioned by the original seller in a primary market in order to find a market-clearing price. There are two ways in which this may be done: by fixing the settlement price, or by fixing the option fee. In the first example, the option is set at a level that guarantees appetite. To pick a mundane example—a TPO may obligate the seller to purchase a sandwich for $100. Buyers then compete to acquire the option—until a market-clearing price is reached. In our example, they may bid $99 to get the right to sell that sandwich (although capital tie-up would be problematic, meaning an effective discount rate would have to be built-in to the transaction, were time a factor). The alternative approach would be to fix the option fee—such as at 10 cents. Assuming the market-clearing price for sandwiches was $1, the price would be bid to $1.10—to cover the market price, plus the option fee. Capital tie-up is less problematic, as the option fee is more realistically set.

Risk transfer in options markets hinges on market participants' expectations of future market prices over the life of the contract. Sellers of a given commodity buy put options (theoretically) to transfer risk: by establishing a floor price for their goods, they lower financing costs, increase their ability to perform on other obligations; etc Buyers of call options want to establish a maximum price to be paid, thereby protecting themselves against future price increases. Alfred Marshall discussed the social benefit of derivatives markets (including futures markets, options and swaps) as follows: 'the hedger does not speculate: he insures [19].'

In contrast with futures or forward contracts, TPOs do not confer any direct benefit to the writer. Indeed, they expose the writer to significant (but not unlimited) risk—as the price of a commodity may theoretically fall to zero. The only commercial benefit to this approach from the writer's point of view, is that it allows the collection of a premium. State actors, however, gain a relatively cost-effective way to subsidise the development of a particular industry or technology.

Holders of tradable options assume their counterparty is willing and able to perform, but they may very well lack knowledge or control of who the eventual counterparty is. Thus, regulation is warranted, including the vetting or qualification of buyers and sellers by the primary auction market and by the secondary market. With the latter, such regulation could include the establishment of a creditworthy central clearing authority and the introduction of 'mark-to-market' accounting by exchanges to adjust margin requirements on a regular basis (daily, weekly, monthly, annually depending on price volatility). Exchanges can act as central clearing authorities (CCAs), and can clear classes of derivatives via a central mechanism, which can be shown to reduce risks. The establishment of CCAs in most financial exchanges today has produced a wave of consolidation of smaller exchanges, and the development of dominant international players, including Eurex and the CME Group, both of which would be candidates for Climate Finance Options Exchange [20].

An option contract fixes the price and performance between two parties, and in the case of vanilla options involves physical delivery of the underlying asset. However, modern options contracts are often used as purely financial instruments—frequently being cash-settled for the value of the option at expiration, i.e. are not delivered, at least on secondary markets. In order to prevent market abuse, many exchanges maintain position limits (mandating maximum size of an open position) for cash-settled options [21]. Such a provision should not be necessary in the TPO markets we are envisioning, but position limits would be advisable if TCOs were permitted by regulators.

Ordinarily, options are short-term contracts, by the time frame of climate science. Long-term equity anticipation securities are exchange-traded options contracts, with a lifespan of over one year [22]. They are available in put or call variants, and they provide a relatively close analogue for the instruments we propose and discuss in this paper.

In our CDR example, the purpose of the contract would be to allow TPO holders to achieve price certainty on medium-term timescales (perhaps 3–20 years, depending on purpose)—leading to a reduced risk profile.

Longer-term debt instruments exist, such as mortgages, leases, and long-dated government bonds (e.g. a 30 year treasury bond). Mortgages and leases are backed by their tie to an underlying asset. Prior to the 2008 financial crisis, mortgages obligations were converted into tradable securities (a process known as securitisation). Prior to the widespread adoption of this process, mortgages were difficult to trade on secondary markets. They are not strictly a commodity—as properties and borrowers are non-homogeneous. Furthermore, liquidation (foreclosure) costs are onerous. By contrast, government bonds are genuinely homogenous, and are underwritten by the state, which is ordinarily one of the most dependable counterparties in the developed world. Accordingly, the rate on short-dated government debt (e.g. a three-month US Treasury bill) is considered to represent the risk-free rate.

CDR (for disposal) is a commodity which confers only social benefit. The financial value to an individual is limited to its value-in-use to discharge an abatement obligation. Using the 'infant industries' argument, a state writer may wish to set an artificially-high CDR value. However, the 'true' value of CDR is only as set by society. Therefore, any short term, high-priced TPOs differ from the 'true' value only in as much as there is general social consensus on the 'true' value of reducing the stock of atmospheric carbon. However, the price of voluntary carbon offsets, or state-regulated carbon credits, offers a guide to any price premium.

3. Possibilities for a CDR TPO market

We make the assumption that a public body is motivated to see CDR occur—and has been resourced to enable this to occur. This may happen in one of two sets of circumstances. The public body may seek to nurture the infant industry, in order to build up human capital, capital equipment, and technical know-how. This would suggest a small investment, at a relatively high \$/ton. Alternatively, they may seek deployment of CDR at scale. This would suggest a large investment, at a relatively low \$/ton.

A CDR technology developer is paralleled by the property developer described in section 2. To develop CDR technology, he needs to know that the process developed will find a market. For example, he may believe a 'factory gate' price of \$100/ton is possible. Thus, the ability to sell his service at \$200/ton offers an opportunity for substantial profit. However, he must invest heavily in development to achieve this profit and may, in fact, need to borrow to do so.

Once the technology development has been done, the CDR developer has two choices. He may keep the TPOs, and to deploy the plant to create the capacity needed to exercise the option, thereby making the envisioned profit. Alternatively, he may decide to sell out. In that case, a new owner-operator will buy out his option as well as his technology, allowing him to recoup his development cost instantaneously. The market therefore tends to divide naturally into two different strands of economic activity: technology developers, having high risk, high skill, and high margins; and plant operators, with lower risk, lower skills, and lower margins.

The difficulty, in market design, is to enable the overall market to facilitate the bridge between development and deployment of CDR by subsidising the industry. The challenge from the option writer's point of view is to support the industry in a cost-effective manner. Setting too high a settlement price may obligate the writer of the option to pay too high a price for carbon dioxide removal at a future date. Setting too high a premium would deter potential developers. The auction facility developed by the World Bank is an elegant solution to this problem, with a potential caveat that it pits technological solutions against each other without any particular concern for potential scale. State actors may wish to subsidise some forms of CDR development more than others, in which case either specific auctions for TPOs to be settled by specific types of CDR would be necessary, or, alternatively, some additional direct subsidies to those industries would be necessary.

This is because some approaches to CDR are relatively light on development costs. For example, enhanced weathering chiefly needs basic scientific research, by means of observation [23]. Expected costs may be in the range of tens of millions. By contrast, BECCS is an extremely expensive technique to develop—potentially costing many billions in pilot plant development. The delay inherent in this process tends to ease the political burden of agreeing this commitment—politicians frequently being guided by 'not in my term of office' as a planning horizon.

Given the expectation that average CDR unit prices will decrease over time as the technology matures, it is desirable to sell options at as low a settlement price as possible. Increasing the option fee is not particularly desirable. Accordingly, one market approach is to fix the option fee, but let the settlement price float. The auction would quickly find the market price. However, when using this method, it is important to set a realistic block size. A TPO buyer will be very reluctant to risk acquiring a small number of options—as this would not give enough future security to be able to incentivise any kind of development process. Ensuring a balance of block sizes is helpful for ensuring that no single party corners the market and sits on the options, thereby creating barriers to entry.

The challenge on the supply-side CDR market prediction is not to predict the price direction for the underlying technology (dependably downwards due to the experience cure), but to judge speed and scale of price drops. From the demand side, the price the state is willing to pay is inherently artificial, as legally and socially obligated carbon abatement is primarily a political question resolved by political processes. In the short- and medium-term, CDR unit prices could rise before they fall, if abatement becomes legally mandated, or if there is widespread price inflation [28]. In a competitive market, suppliers waiting for too high a price will suffer lost sales opportunities. Settling for too low a predicted price will result in financial losses fulfilling the contract.

For a CDR innovator or operator, such a transaction is beneficial as the cost is limited to the premium paid for the option. Holding a TPO gives a guaranteed market for technology—either as an intellectual property play, or as a turnkey plant. In addition, should the technology fail technologically or commercially, the position can be readily liquidated by means of a sale of the TPOs to a stronger firm or investor. Alternatively, a prospective operator may buy TPOs in anticipation of being able to purchase a technology license or rights holder. Therefore, provided the premium is low enough, or the strike high enough, TPOs represent essentially a one-way bet in the market. Given a fixed allocation of permits into the market, the overall objective of price support can be achieved in the face of competition. Any premium obtained by the writer will likely be insufficient to withdraw price support from the market entirely. In the unlikely event that competition for options is so fierce as to bid up the premium (or bid down the strike, according to the preferred auction structure) it would be indicative of investor confidence in the market underpinned by future legal CDR obligations for usage-matched disposal.

Relevant comparator market concepts are the state-mandated Emissions Trading Schemes [29]. However, an alternative comparator is the functionally similar, but instrumentally different Feed-in Tariff (FiT) market. This is designed to provide infant industry support to the renewables industry—guaranteeing market access (typically by net metering for households). The objective for this is to support the installation of small-scale renewables, thus supporting the development of supply capacity, and consequent price falls. Schemes exist in Germany, Spain, UK and several US states. In the UK, the original price was 42 p kWh—many times the domestic rate for electricity. This premium has recently been cut, as the success of the scheme made it costly to operate.

The termination of the FiT scheme, detailed above, was intensely problematic for the industry—as investments planned on the basis of promised support were rendered non-viable at a stroke. The advantage of our proposed structure over other market incentives is that it relies on a legally-robust publically-traded instrument—default on which would profoundly damage states' financial credibility. This situation renders any kind of default unlikely, assuming the general viability of a state's finances. The policy plan envisioned by the Paris Agreements is to establish, as far as is possible, a stable market price for CDR services. This can best be done by ensuring that a ready and reliable market exists for the CDR services—and TPOs offer an appropriate and controllable means to achieve this.

We define our ideal transaction:

1. A government body seeks to encourage CDR—we take 1 tonne CO_2e (Kyoto: AAU). Accordingly, the body offers a TPO on removing 1 AAU from the atmosphere by any satisfactory date—we take 20 years max for a deployment-scale contract. Finding that technologies for immediate or near-term removal of CO_2 are under-developed, the body looks to write a TPO in the primary market via an auction facility. Provided that such a 'satisfactory date' contract can be obtained, to all development of the technology, it makes sense for a writer to offer such security.
2. A developer (potential holder) believes he can sell the services of 1 tonne CDR to the buyer's timescale, at a lower-than-strike price. The seller will then seek to pay a *de minimis* premium, on the assumption that technological progress will have made CDR cheaper by expiry. The developer will likely need many thousands (or even millions) of tonnes permitted, to make technology investment attractive, so a bundling approach is probably administratively efficient. Smaller volumes can be efficiently transacted on a blockchain [30]. An auction will ordinarily be used for setting either the premium or the strike price.
3. An investor notes that a developer has a technology proposal, and the TPOs to accompany its operation. Alternatively, the investor may seek to acquire the TPOs directly. Once the 'lock and key' combination has been acquired, the investor will be willing to back the developer to produce the technology.
4. After the development of the technology, an operator may seek to purchase the developers' interest in either the technology generally (e.g. by acquisition of intellectual property), or to acquire an individual plant. The operator will also seek to acquire TPOs, sufficient to make the operation of said technology/plant reasonably profitable over the life of this technology.
5. Traders would operate in the secondary market. These may be other developers and operators, or alternatively investors and speculators. They would buy and sell TPOs, with appropriate margin requirements, in response to market news and the attractiveness of unrelated investments.
6. Upon completion of the CDR activities, the writer first would verify delivery (a process likely to be executed by an appropriate body charged with performance verification), and after verification would then settle the contract. In ordinary circumstances, early settlement would be a more efficient market process—as it enables more amenable cash flow to operators (for return to investors).

We draw attention to the difference between pilot-plant development (pilot site in the case of e.g. enhanced weathering), and technology licensing. The use of TPOs to support single-plant development implies a small volume and a high strike price. By contrast, a technology licensing approach can be supported at a much lower strike—but far larger volumes would need to be provided. Furthermore, a pilot plant approach might reasonably specify a methodology in the option agreement—in order to better to diversify the range of technologies developed. 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). Additionally, biological storage has issues with permanence, which typically do not afflict properly-run DAC operations. Accordingly, the use of a differential strike is potentially attractive.

A TPO writer would ordinarily wish to establish a high-volume strike at the social cost of carbon. For tightly restricted volumes, a much higher strike is likely—perhaps up to an order of magnitude higher. This will support technology development, but at a manageable overall cost. Although unusual for options, a renewal premium could conceivably be built into the contract structure [31]. This would ensure that the writer had early notice of any loss of confidence in the market price at expiry during the life of the option. Options holders who had lost confidence in their ability to supply at, or below, the strike price, would ordinary default or sell the option.

We assume agreed-upon standards for settlement, including performance verification and methodological suitability. Carbon disposal must be sufficiently stable, and environmentally benign, to satisfy the writer. In the event of the writer being obligated (e.g. by treaty) to write TPOs, an appropriate overarching framework of regulation would be required. Otherwise, a 'race to the bottom' would ensue, with writers incentivised to accept storage that was unstable, impermanent, or environmentally damaging—to discharge their obligations at the lowest possible cost. The result could be 'disposal' in fire-prone forests, or in high-pressure underground chambers at risk of deadly leakage.

Worthy of brief mention is the fact that biomass carbon storage has a specific range of issues (e.g. growing time)—as addressed extensively in other literature, e.g. those exploring carbon banking and carbon debts [32]. In such markets, TPOs are potentially suited to the needs of small foresters, who may lack access to formal finance markets. Their chief economic concerns are smoothing cash flows and obtaining price predictability—without undue transaction costs [33]. In this regard, TPOs may function akin to agricultural futures [38].

The potential scale of these markets, and the presence of intermediaries and investors, with heterogeneous expectations about the rate of cost decline, suggests that tradeable options markets are an attractive means of organisation. This is particularly the case, considering current trends toward institutionalisation and financialisation in international capital markets [39].

4. Potential market failures and regulatory approach

The appealing nature of CDR options disguises various complexities, which differ substantially from those associated with ordinary options. In CDR, there exists significant technology risk. Holders may anticipate technology that is not delivered. This technology may be late, fail to work properly, or be prohibitively expensive. Accordingly, writers must at all times be mindful of the difference between options and obligations—recognising that the former has no inherent guarantee, and dependability is largely a function of counterparty history, which is difficult to ascertain in new markets such as these.

We discuss only public bodies as writers. This is for two reasons. Firstly, CDR is a public good, ordinarily provided only by the state. We accept, in the alternative, potential small-scale contributions from philanthropists, in a similar manner. However, counterparty risks with such philanthropic contributions are likely to be modest: with reputation the best guide to future performance; and little risk of any failure causing generalised economic destabilisation.

There exists a regulatory dimension to technology risk. CDR operators may able to meet the strike price but could be prevented from operating due to methodological unsuitability. For example: the CDR strategy of ocean iron fertilisation (OIF) [40] is controversial [41], and may conceivably be prohibited. An appropriate structure would be necessary to compensate the holders of any restricted-method options, should those options become undeliverable by dint of regulatory action from the state (functionally, the writer—notwithstanding bureaucratic divisions of responsibility). Even in the event of method-unrestricted TPOs being used, it is necessary to consider the impact of method prohibition. To continue the above example: an OIF ban may have industry-wide effects, if this is widely accepted as the preferred strategy. Accordingly, it may be necessary to either shield operators from legislative and regulatory changes during the option period, or alternatively to organise an adequate compensation scheme, perhaps through a buyback scheme. Any reasonable compensation scheme should consider not only the premium (which can be easily refunded), but also the perceived bait-and-switch experienced by investors. The UK FiT scheme, discussed above, is a prime example of this—with widespread dismay from investors at the UK government's *volte face* on support. This uproar would have been far worse had the market intervention been prohibition, as opposed to withdrawal of price support.

At larger scales, there is a general risk of market disruption in the event of state default. Accordingly, if and when such contracts become a significant part of the global economy, a bail-out scheme would be needed to guard against the risk of default. If, for example, Italy were treaty-mandated to support a CDR industry, it would be necessary to ensure that other countries (e.g. Germany) were able to step in, should the Italian state be generally unable to meet its obligations. The predictability of future CDR prices is constrained by the nascent state of the technology. Cost curves, relative to time or to deployment scale, have yet to be established. As a further complication, there is no clear front-runner, technologically. Whilst most attention has been paid to BECCS, environmental limits make this extremely challenging to implement at scale [42].

Two specific factors are expected to exert overwhelming influence on technology costs (as distinct from regulatory costs) in CDR: time and deployment scale. With respect to time scale, a mix of CDR-enabling technologies are expected to emerge, e.g. cheap renewable electricity for direct air capture (DAC). Development of these is distinct from CDR development. Accordingly, price falls for CDR are expected—even in the event of complete inaction. Deployment scale is an unpredictable factor, insofar as it is dependent on technological progress and stability in factor prices. Increases in production volume are strongly correlated with falling costs, as internal and external economies of scale arise (an 'experience curve' or 'learning curve') [43].

We can compare the options market for CDR with other markets in which such contracts could conceivably be used. Moore's law [44] suggests reliable increases in compute capability over time, while Swanson's law is a conversion of the above into solar photovoltaic prices. A reasonable investor may determine that he can reliably contract to provide computation at prices above such experience-curve predictions. Accordingly, the level of risk would be modest for an investor or developer buying TPO with a strike below-current-market, provided it was long-dated. Timed options are administratively easy to write; market-volume options would potentially be superior in their ability to track prices, but considerably more complex to draft and administer, [45] but have been deployed with some success in natural gas markets [46].

Total market profits are also scale-linked. The availability of low-cost abatement implies effectively zero demand for high-priced CDR linked to future emissions. This provides a significant barrier to entry for CDR providers, as carbon offsetting is more affordably available via abatement. Therefore, in contrast to other emergent markets, no significant scarcity premium is available. Except in the case of low-volume, high-strike TPOs, a strong investment case requires an assumption of scale. Such high-strike contracts are a reasonable bridge approach, pending technology proving and scaling. Only a large CDR market is capable of exerting any meaningful influence on the climate problem. Accordingly, market risk appraisal must include an assumption of scale. A falling strike price as new contracts are issued allows infant industry support in a manner that is appealing to investors at all stages—and can be made highly transparent from the origin, if needed.

CDR options may face high medium and long run price uncertainty. Chosen approaches may turn out to be impractical, expensive, unsafe, or may be banned. With rapid anticipated price falls, and potentially long timescales to performance, uncertainty may make price-setting very problematic. There remains a very real risk of a wholesale failure of a given scheme—with little or nothing being delivered on the execution date. Additionally, there may be political pressure for *post hoc* amendment of the strike price—most likely by allowing buyers to exchange TPOs for higher-priced or longer-dated alternatives, in effect designating them 'Too Green To Fail'.

The nature of CDR (at its current state of development) tends to create identical risks across the market. If a single option fails (e.g. due to lack of an essential enabling technology), subsequent failure of an array of others is possible. If holders assumed a factory-gate CDR cost of $40/ton, a price of $41 may be comparable to the investment premium—meaning non-delivery is unlikely. By contrast, a price of $50 would likely cause a wave of expirations, which would destroy or diminish confidence in the facility. This may result in political pressure to offer additional market support—such as a revised strike price (via a re-issue, as discussed above). A factory-gate price of $200/ton would be undeliverable; mispricing on that scale would require the scheme to be rebuilt.

Accordingly, the lowest risk-strategy from a writer's point of view is to issue TPOs with a very high strike price and allow the premium to be bid up at auction. This will ensure that, even in the event of cost overruns, the contracts will likely be honoured.

Assuming performance (not just fundraising) is a goal, then market risks are increased by 'selection pressure'. The most bullish firms are more likely to attract investors. This potential issue present major risks to the development of a healthy and functional market in CDR options, and again encourages the use of a high strike, high deposit strategy is used—which promises real investor pain, in the event of expiry.

Continuing on the subject of expiry, a brief mention of political pressure is again merited. In the operation phase, delayed delivery will result in the partial expiration of an option portfolio. A plant requiring 72 days run to deliver against an options portfolio may manage it in 90, due to late commissioning or unplanned downtime. From a developer's point of view, such delays could be catastrophic. Even if they might be able to sell the TPO onwards in a secondary market and even if the spot price for CDR is relatively close to the strike price, their creditors might exercise debt covenants that trigger insolvency, i.e. their financing arrangements might be dependent on the TPO remaining unexpired. A plant may take three years to develop and commission and still may be able to deliver all its CDR within 90 days. In the event of delays, there is likely to be severe political pressure to avoid a scheme failure—especially when jobs, and safety, are seen to be 'on the line'. Accordingly, we suggest a possible taper for high-strike, low-volume development TPOs. This will incentivise early performance, without creating a 'cliff edge' for technology developers.

Tapers are only likely to be necessary in early stages of the market's operation. The aim is to develop a highly-liquid market of TPOs with various expiry dates. A producer with a delay could release his stock into the market, buying later-dated (but lower-strike) TPOs in their place. However, in early trading, this is unlikely to be viable—as insufficient liquidity is likely to be available, considering the size of the current market.

The writer would also need to verify CDR performance and standards. CDR approaches vary widely—particularly as regards side-effects and risks:

- Environmental harms—Some, if properly conducted, are generally benign (DAC) [with mineralisation]; others may gravely disrupt ecosystems (BECCS).
- Maintenance requirement—Mineralisation [47] offers millennial-duration storage; afforestation is vulnerable to fire, if poorly managed [48].
- Biological storage (e.g. afforestation) typically achieves storage of CO_2 on centurial timescales [49]—generally insufficient for inter-generational climate protection.

Further complexities exist if GGR, not just CDR, is permissible under the options scheme—not least the timescale used for calculation of equivalence. Nonetheless, our working assumption is that the AAU system is adopted. This will reduce the regulatory burden.

CDR is thus far from being a homogenous market and cannot be reduced to a commodity unless effort is invested to ensure the *bona fide* of removal. Creating separate regulators for verification and futures issues is likely beneficial. However, interplay makes genuine independence elusive. Much 'finger pointing' is to be expected, in the event of market failures. In particular, the environmental regulator is likely to be accused of 'moving the goalposts' in the event that regulations need to be tightened. The market regulator is, likewise, liable to be accused of writing ineffective or inflexible contracts.

The following interventions are available to a market-only regulator:

Contract length—Longer-term options theoretically reduce performance risks (assuming a constant price) but pricing them is more difficult. Long-term price predictions depend on (reasonably) foreseeable technology risks, but also on societal/political risks (which are less foreseeable, and ordinarily increase over time). Absent an established CDR experience curve, widely differing opinions on price are likely to be found in the market.

Contract structure—As previously discussed, taper and maintenance fee structures are potentially advisable in early stages of the market.

Participation—regulators may concern themselves with the identity of market players, not just with the transactions. Comparable restrictions exist in banking (e.g. capital adequacy requirements) [50]. The regulator may seek to restrict participation in the market only to particular types of firms. For example, they may wish to allocate high-strike TPOs only to start-ups, which lack the financial support of a large parent company. Alternatively, they may prioritise a 'process test' approach, seeking instead to engage only with highly capable corporate players—for whom the initial TPOs would be regarded as relevant only in as much as they are indicative of an ongoing state commitment to the process, as opposed to being financially significant in and of themselves.

5. Conclusions

In our discussion of the viability of TPOs in the design of CDR markets, we note the existence of international agreements mandating long-term deployment of negative emissions technologies. We suggest that state actors are best suited to marshalling the financial resources and the investor confidence necessary to ensure safe and efficient market operation. Government-backed TPOs for CDR would be a reasonable and credible instrument, attracting market confidence. Indeed, without a comparable contractual instrument to ensure state performance, government commitments to CDR may lack financial commitments. The above is true at both large and small scales, much like the UK experience with the FiTs scheme. TPOs represent an appealing instrument for use with CDR: i.e. a nascent technology, facing an uncertain future demand curve. Buyers of TPOs would be able to develop and scale technologies, with the benefit of price certainty.

By contrast, sellers would not gain long-term price certainty, and would only obtain a current view of the market's view on the value of these instruments. While TPOs may be useful for guaranteeing future prices, their provision to the market does not guarantee potential CDR providers security during the development phase—as technology developers may be outbid, particularly for high-volume, low-strike TPOs. We conclude there is a case, especially in early stages of the market, to design TPOs targeted at specific delivery methods. These would not trade as widely, if at all, on the secondary market, which is their chief limitation.

TPOs potentially introduce systemic political risk. The assumption behind the current World Bank Pilot Auction Facility is that most buyers of TPOs will indeed exercise the option. This has been true in the current scheme with redemption rates as high as 95% [51]. With more speculative technologies, purchase of a TPO may represent nothing more than a pricing bet, with no accompanying plans to develop the technology. Secondary markets in TPOs provide liquidity by encouraging speculation. The alternative strategy, of using non-tradable options, will simply occlude markets: as corporations will be the only likely buyers, as creating special purpose vehicles to trade such options is trivially easy for corporate operators.

Nevertheless, in modest-volume trading of TPOs, buyers would gain price certainty. Significant microeconomic benefits result: reductions in pricing risk and attraction of capital. Whilst such an approach may work well in an 'infant industry' context, it is likely to require substantial modification as the technology scales—in particular, a rapidly-falling price. The FiT market offers useful comparisons: in the short run, a high-price technology support economic model; in the long term, a much lower price may assist with improving certainty in the medium term. In theory, multiple flavours of TPOs may be released simultaneously, subject to a single central clearing authority in secondary markets.

Providing high strike price contracts with a premium auction has important benefits in the early stages of establishing a market. It provides confidence for developers and investors, while modest volumes can control total cost impacts for state actors. In later use at scale, lower strike prices prevent inefficient use of capital. If used at scale, and in the medium to long term, TPOs may a potentially be a very large market. We identify a high risk of political interference and suggest the need for prudential market oversight. However, we note the inherent limitations of a regulatory approach to addressing market failure: political pressure tends to encourage slapdash scrutiny of operators. We therefore find generally that permitting political involvement in such markets is risky, finding instead that an independent, global, technocratic market regulator is an appealing form of governance.

Global governance has additional advantages. First, our discussion has not dealt with land-use planning policies, as we have been concerned only with market design; but a technocratic market regulator could encourage global cooperation on planning issues around the permitting of CDR plants. Second, a similar argument can be made for the coordination of industrial regulation and plant safety, which need addressing as the technology matures, and which require a separate regulatory mechanism.

For clarity, this paper does not argue for CDR technology development as an alternative to mitigation of carbon emissions; mitigation remains necessary, and global regulation of CDR markets would facilitate a more coherent policy response than that provided by national or private alternatives.

In summary, therefore, we find that a government body can usefully introduce TPOs to the market, with the following restrictions and provisos.

1. Apolitical, independent oversight of delivery
2. An intended inverse relationship between strike price and volume, providing diminishing support as the market scales
3. A clear declaration that TPOs cannot be regarded, politically or economically, as guarantees of the technological viability of specific CDR schemes
4. Potential tapering expiration of TPOs, particularly while waiting for market liquidity to develop.
5. Premium auctions: to support higher strike prices, while lowering risks of non-performance.

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