A Climate Insidium with a Price on Warming

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Note: This work is not a RAND output. I have done this on my own time.

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Declaration of Interest: Grandchildren.

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Policy insights

- Existing emissions trading systems and carbon taxes do not constrain warming to any specific level, have poor incentives to join, and fail to produce useful future price information.
- This paper proposes a centralized market, cleared with optimization, for contracts explicitly tied to temperature change.
- The proposed design would explicitly constrain warming for many (e.g., 150) years into the future, and every auction would provide price information for this time range.
- Unlike existing emissions trading systems, the market structure and rules incentivize firms to participate even if their jurisdiction does not, potentially resulting in a rush-to-join behavior.

Abstract

In this paper, I introduce a new emissions trading system (ETS) design to address the problems with existing ETSs and carbon taxes.

First, existing ETS designs inhibit emissions but do not constrain warming to any set level. Existing ETSs have the indirect objective of reducing emissions instead of directly reducing warming. Even a global mechanism using an existing ETS cannot guarantee a particular warming path. Part 1: A Price on Warming addresses this. My proposed market trades contracts tied to temperature in a double-sided auction of emissions permits and sequestration contracts. Unlike existing ETSs, the mechanism has a consistent timescale and metric tied to warming, with explicit limits on global temperature in every period into the far future. Every auction finds prices for emissions into the far future.

Second, if a jurisdiction does not require firms to manage their emissions, the firms have little incentive to do so. Part 2: A Climate Insidium addresses this. My design incentivizes firms to participate even if their jurisdictions do not join. With sanctions from member jurisdictions and participating firms, the design has bottom-up incentives for joining, and the incentives rise over time under realistic conditions, potentially resulting in a rush to join.

Third, existing designs have high transaction costs for implementation, requiring international treaties to begin. Part 3: A Faster Path Forward addresses this. I propose a path without national or international action to begin. A coalition can implement these rules, creating political force to accelerate participation. Full implementation still requires national agreements.

This design appears to be closer to “first best”, with a lower cost of climate mitigation, than any in the literature, while increasing the certainty of avoiding catastrophic global warming. It might also provide a faster pathway to implementation.
Part 1: A Price on Warming: SMDAMAGE

1 The Flaw in Existing Market Designs for Emissions

Despite the urgent need to reduce greenhouse gas (GHG) emissions, we all have no certainty emissions will follow any particular pathway. We lack pathway certainty because emissions have no contractual adherence to any fixed global limits. Worse still, we all have no certainty of any particular pathway of warming.

In this paper, I propose a centralized global market for permits to emit greenhouse gases (GHG) and for contracts to sequester carbon dioxide (CO₂). The proposed market explicitly constrains warming in degrees Centigrade by time period far into the future. The market sets prices, which result in planned emissions to follow a specified warming pathway. Unlike other designs for emissions trading, this market appears to have bottom-up incentives for joining, and these incentives increase over time under realistic conditions.

Part 1 (chapters 1 and 2) describes the smart market approach generally, the specific market mechanism, and the nature of the contracts.

Part 2 (chapters 3 and 4) describes market governance, incentives, enforcement and potential problems.

Part 3 (chapters 5 and 6) proposes a roadmap of implementation with recommended future research, with a list of benefits and potential problems.

An Appendix describes a numerical simulation.

The scientific community knows the flaws in the various ETS. Sadly, jurisdictions have applied formal pricing mechanisms to less than 20% of the world’s emissions (World Bank 1, 2019). Where emissions markets exist, they do not always guarantee any particular limit (e.g., Australia’s “Safeguard” mechanism). Where they do attempt to reach a particular limit, the limit can be subverted (e.g., California, Haya 2019), and the limit does not apply to certain sectors (such as agriculture in New Zealand). ETS reveal allowance prices, but policymakers and researchers can only estimate impacts on emissions (Haites, 2018). Emissions markets can end on political whims (e.g., Ontario and Australia). Credit banking allows companies to purchase the right to emit now, but actually emit later, lowering pathway certainty. Inconsistent metrics (“global warming potential” in particular) ignore the different warming effects for emission of a given chemical over time (Farquharson et al 2016, Edwards and Trancik 2014). Some market rules incentivize cheating; for example, paying to destroy stocks of chemicals incentivizes covert production of those chemicals. See World Bank 2 (2019) for an up-to-date report on carbon pricing, and Stavins (2019) for a careful analysis of the full landscape of pricing policy.

Policymakers and researchers believe carbon taxes are easier politically, especially when combined with “dividends” to consumers. See, in particular, Shultz and Halstead (2020) who focus on political expediency, and Weisbach and Metcalf (2009) who thoughtfully and optimistically discuss the difficulties of tax design in good detail. Carbon taxes (as in Argentina) do not reduce emissions to any specific limit. Even a uniform global tax or a uniform price floor (e.g., Cramton et al 2017) could not guarantee the correct pathway of emissions, much less warming, because no policymaker can find the correct price for enforcing the required pathways of either emissions or warming. If the tax undercharges, we make insufficient progress. If the tax overcharges, we inhibit growth needlessly. Tvinnereim and Mehling (2018) make these points at length. For emitting firms, transaction costs with carbon taxes are lower than with cap and trade (Weisbach and Metcalf, 2009). But consumers are not the selfish players obstructing change; rather, we have to get past a few well-heeled fossil fuel insiders. Thus, carbon taxes seem to have a transaction cost of implementation almost as large as any other instrument. Finally, carbon taxes have no inherent mechanism for the vast sequestration required to remove the excess CO₂. Rather than establishing a robust procurement mechanism for sequestration, the money would go to bribing voters (increasing consumption), or subsidizing technologies (likely misguided, as “carbon capture and sequestration”), or building infrastructure (increasing consumption), or some other government priority (likely misguided). I would feel a little better about carbon taxes if policymakers used the money exclusively to procure sequestration.
Thus, no existing emissions market design constrains warming to any particular managed path when constraining warming is the whole point. The result is management uncertainty about emissions on top of the scientific uncertainty of the warming those emissions will bring. To quote Stiglitz (2019):

In the context of climate change, there is considerable uncertainty, e.g., about the magnitude of the links between greenhouse gases and climate change and that of the links between any instrument and greenhouse gas emissions. The latter uncertainty has led some environmentalists to argue for quantitative restrictions on emissions… One way of understanding this is to note that while the standard result argues for a single price of carbon in all places, for all uses, at all dates, the (appropriate shadow) price differ depending on the state of the world. There is much we don’t know: the effects of any policy on emissions or the effects of emissions and carbon concentrations on climate change, and the full effects of climate change on well-being. Thus, as we learn more about the state of the world the carbon price adjusts. In fact, the best we can do is to announce a carbon price today and a limited state-dependent sequence of prices going forward.

The proposal here aims to do better than this. At every auction, the market proposed here would announce state-dependent prices for every time period far into the future, while still allowing updates for learning. The proposal creates market forces to help agents anticipate changes in learning and technology, which policymakers cannot foresee.

Aggravating these uncertainties is the profound unwillingness, as is widely known (see, for example, Cramton et al 2017), of many firms and jurisdictions to engage with ETS mechanisms. Individual countries are unwilling to start their own ETSs and a global ETS appears too hard to organize.

The solutions proposed here is for a credible group of jurisdictions and firms to begin a global ETS as a type of climate club. Market rules specify sanctions against non-participating firms from both member jurisdictions and participating firms, including those in non-member jurisdictions. Whether a country joins or not, it can avoid a politically risky commitment to emission targets. Centralization allows firms to participate though the jurisdiction has not formally joined. This feature could result in de facto membership of a jurisdiction, lowering the political barrier for the jurisdiction to join. The result is bottom-up incentives for joining, and these incentives increase over time under plausible conditions, potentially resulting in a broad rush to join while inhibiting dropouts.

A caveat: I write this is an introductory paper with a few new ideas. I have not been able to address everything here. Much remains for researchers to study. I welcome comments and suggestions.

2 The Mechanism for a Price on Warming

2.1 The smart market approach

A smart market is a centralized auction cleared by optimization. The optimization enables trading of contracts in which the traded commodities have complex physics and shared constraints which otherwise hinder trading. A smart market enables the type of central control instrument, which Weitzman (1974) called “ideal” but also “infeasible,” because transmitting “an entire schedule of ideal prices or quantities” contingent on the state of the world requires “a complicated, specialized contract which is expensive to draw up and hard to understand.” With roots in operations research going back to George Dantzig in the 1940s, the smart market concept was developed in the late 1970s and 1980s by Smith and others (see McCabe, Rassenti and Smith 1991).

Smart markets are in active use for wholesale electricity and natural gas, transportation, and radio spectrum. Similar mechanisms are in use for medical internships, organ transplants, and specialized procurement. Those applications require allocations to adhere to complicated shared constraints, which impose high transaction costs in a normal market; some applications require combinatorial algorithms. The smart market drastically reduces these transaction costs by incorporating the shared constraints in an optimization used to clear the market. In the case of wholesale electricity, for example, generation must match demand within various system capacities, which the electricity system operator incorporates into a linear program to clear the market.
Figure 1 shows a high-level view of the smart market process. In my proposed design here, the shared constraints ensure effect of the agreed upper limit of warming for each time period far into the future.

![Figure 1. Process for a commercial smart market](image)

I call this market design and the associated optimization model SMDAMAGE, for Smart Market Design Addressing Management of Global Emissions. Like existing ETSs, the market would sell contracts for permits to produce GHG chemicals and buy contracts for CO2-sequestering activities. Agents could sell back unused permits and buy back inactive sequestration contracts. Participants trade through a central market manager: buyers buy from the market manager, and sellers sell to the market manager. The market manager is responsible for registering agents to trade, for enforcing market rules, and for proper functioning of market operations.

The main principle underlying this market is respect for the global warming limits. A second principle is adherence to rigorous economic principles. Critically, the market finds efficient permits for permits over time. My proposal has a consistent timescale and a consistent metric directly tied to warming. The institutional design enables equity to be addressed through a governance committee.

Since this mechanism does not impose the quantity component in a regulatory way, and since the price mechanism is not a fixed tax, the smart market seems to be what economists are calling a hybrid system, though it is simpler than those described in the literature (e.g., Abrell and Rauch 2016).

### 2.2 Nature of the commodity traded

The proposed market trades two types of contracts. The first type specifies the right to produce a quantity of GHG chemical during a certain time. The second type specifies the obligation to sequester carbon dioxide during a certain time. Trading multiple types of contracts within an ETS is not unusual; Gurfinkel Marques de Godey and Macchione Saes (2015) observe ETSs typically trade multiple commodities.

A contract to produce specifies a chemical, a quantity (e.g., in kilotons), and specific start and end times, e.g., one month. For simplicity of explanation, assume the agent emits the chemical as soon the agent produces it, recognizing each contract in reality would have to specify the expected timing of emission. Payment for production moves the transaction cost upstream from the consumer, increasing economies of scale (Heindl, 2017).

Buyers obtain the permission, but not the obligation, to produce the quantity of pollutant for the scheduled interval of the contract. Agents can buy permits for future periods, as far as the final bid period $T_B$ in the market schedule. The term length of the typical contract for production would be short, e.g., a month. Buyers cannot apply the contract to a different schedule than the one listed. They can use the contract to produce...
only for the schedule listed on the contract. If the buyer does not produce during the specified time, the permit expires with no value.

Agents might need to buy more than one kind of right at a time. For example, consider an agent operating a natural gas combined cycle plant for power generation with carbon capture and storage. The agent should buy permits for uncaptured carbon dioxide production and also permits for methane leakage.

Agents who purchase future production permits may offer to sell them back to the market. For example, consider a generator holding methane permits for five years into the future. The generator could reduce methane leakage early and then sell the remaining methane permits back to the market manager. The generator has no guarantee the selling price would be the same as the original buying price. The generator could also sell the contract privately, but would have to register the trade with the local jurisdiction and the market manager; sale through the central auction should have a lower transaction cost.

A contract to sequester specifies an activity, start and end times, and kilograms quantity in each period following a specified schedule. These contracts might be complicated. Sellers accept the obligation to sequester from the atmosphere the quantity of carbon dioxide over the agreed time. The term length of the typical contract for sequestration can vary depending on the activity, and agents can sell sequestration services for future periods, as far as the final bid period $T_h$ in the market schedule. For example, a contract to grow a hectare of pine trees might have a term of 30 years, absorbing different amounts of carbon dioxide each year. Such contracts are subject to adverse selection and moral hazard (Bushnell 2011, Burke 2016); this mechanism should have no more adverse selection than any other ETS. The market manager may agree to make partial payments over time; this mechanism helps solve the difficulty of the delay between the trade and implementation (Cacho, 2008). The market manager may wish to standardize the contracts in tons of CO$_2$ sequestered for each period of the contract schedule. Table 1 shows example contracts for a fictional 2020 auction.

| Type            | Term                  | Quantity         | Price          |
|-----------------|-----------------------|------------------|----------------|
| CO$_2$ emission | 2040-06-01 to 08-31   | +100 ktons CO$_2$| $15.50/ton     |
| SF$_6$ emission | 2024-01-01 to 03-31   | + 0.5 ktons SF$_6$| $212/ton      |
| Agriculture, biochar | 2025-04-01 to 2030-03-31 | -15 ktons CO$_2$ | -$12.50/ton   |
| Forestry, Loblolly pine | 2023-06-01 to 2053-05-31 | Varying amounts over 30 years | -$1,340/hectare |

Agents who sell future sequestration contracts to the market manager might offer to buy them back from the market manager. For example, suppose an agent has sold a 30-year contract to grow a hectare of forest, but fifteen years into the contract, wants to change the forest to some other crop, which sequesters less carbon dioxide. This agent could offer to buy the remaining 15 years of the contract back from the market manager.

The final period of constraint must be far in the future, e.g., 150 years, depending on the residence time of the different chemicals in the atmosphere. For various reasons, especially moral hazard and adverse selection, contracts for sequestration probably should not extend more than a few decades. The 150-year period corresponds to constraints on warming from near-term contracts. These contracts would result in increasing or decreasing warming over time depending on the dates of activity, and the chemical emitted or the sequestration activity. To account for these varying warming trajectories, I propose the market manager choose bids with an optimization model.

2.3 Market Clearing Model SMDAMAGE

SMDAMAGE — smart market design addressing management of global emissions — is a linear program. Computers can solve it easily and the solution algorithm automatically produces price information (Dantzig, 1998). I assume the warming effects of different chemicals combine in linear and deterministic fashion. I allow for the possibility a chemical could change to a different compound, with a different effect on global warming. Other researchers might be able to find a model with better accounting for chemical interactions...
and feedback loops. This research should be ongoing, but implementation should not wait for more research. Instead, market rules should allow for improving the science.

2.3.1 Indices

\( a \) = agent, \( a = 1, \ldots, A \).

\( p \) = activity (pollutant or contract), \( p = 1, \ldots, P \). I will also use this subscript for pollutants. I will also use it for sequestration contracts, in which case \( p \) is \( \text{CO}_2 \) though the market manager may specify the contract in other units, such as hectares of forest.

\( t, u \) = period, where \( t, u = 1, \ldots, T \), where \( T \approx 7,500 \) weeks. Generally, I will use \( u \) to indicate the period of emission and \( t \) to indicate the period of warming. I address the auction calendar in more detail below.

2.3.2 Parameters

\( \text{Cap}_p \) = allowed increase in thousandths of degrees Celsius in period \( t \), relative to some baseline temperature. Critical values for the auction include the start date of the first auction and the first period \( Y \) of constrained warming. The trajectory of this crucial parameter could follow scientific recommendations, but the managing committee might wish to change \( \text{Cap}_p \) as future impacts become clear. \( \text{Cap}_p > 0 \) allows a global temperature above the baseline in period \( t \). \( \text{Cap}_p = 0 \) requires the global temperature in period \( t \) to equal the global baseline temperature (e.g., from 1920). \( \text{Cap}_p < 0 \) requires a fall in the global temperature in period \( t \), in which case the market manager likely has a net buying position to get sufficient sequestration to reduce the global temperature.

\( B_{a,p,u} \) = bid price by agent \( a \) to produce 1 unit of activity \( p \) in period \( u \), e.g., a kiloton of \( \text{SF}_6 \) released or a hectare of forest to sequester \( \text{CO}_2 \). The market manager could mark up this bid price by the cost to enforce the contract. The market manager can ignore discount rates, because agents would be responsible for discounting their own bid prices, whether for interest rate or risk.

\( I_t \) = the initial atmospheric burden of pollutant \( p \), in units (e.g., megatons or kilotons) consistent with \( W_{p,a,u} \) above a base value, such as the difference between 2020 quantities and 1920 quantities.

\( Q_{a,p,u} \) = upper bid quantity by agent \( a \), units of activity \( p \) (e.g., kilotons \( \text{CO}_2 \) or hectares forest) in period \( u \).

\( T_B \) = final year that \( \text{Cap}_p \) is constrained, e.g., the year 2301. This is the end of the auction horizon specified by the market manager.

\( T_B \) = final year of denomination for contracts in the current year, specified by the market manager. For example, an auction held in 2020 would allow trading of contracts through \( T_B = 2050 \), but not thereafter. To partially address adverse selection, the auction manager could buy sequestration contracts for only the near term (implying one \( T_B \) for emissions and a shorter \( T_B \) for sequestration).

\( Y \) = first year in which \( \text{Cap}_p \) is constrained: \( \text{Cap}_p = \infty \) for \( t < Y \) and \( \text{Cap}_p = 0 \) for \( t \geq Y \). The market manager specifies this parameter. For example, an auction held in 2020 could have no constraints for temperature up to \( Y=2040 \), and then constrain temperature from \( Y=2040 \) through \( T = 2301 \). Because of storage in the atmosphere, prices in 2020 will immediately drive both emission reduction and sequestration.

\( W_{p,a,u} \) = absolute global temperature change in period \( t \) for one kilogram of pollutant \( p \) released or \( \text{CO}_2 \) sequestered from activity \( p \) in period \( u \), where \( u \leq t \) (see for example Shine et al, 2005, and Farquharson et al, 2016). \( W_{p,a,u} \) is negative for a sequestering activity.

Figure 2 shows \( W_{p,a,u} \) schematically for a generic pollutant. \( W_{p,a,u} \) might be positive in early years and negative in later years, or vice versa, depending on activity \( p \). The factor can account for chemical changes, such as methane changing to \( \text{CO}_2 \). These effects are somewhat uncertain, so this value should be set conservatively, e.g., at the 99th percentile of certainty. We can define more complicated contracts. For example, for a hectare of pine trees planted in period \( u \), denote the schedule of tons \( \text{CO}_2 \) sequestered as \( N_u, N_{u+1}, N_{u+2}, N_{u+3}, \ldots, N_T \). Then a period \( u \) contract for one hectare will warm period \( t \) by \( W_{\text{pine},a,u} = -\sum_{v=u}^{T} N_v W_{\text{CO}_2,v,p} \). This formula can account for specific types of trees and for seasonal effects. Thus, the formulation below is general.
Figure 2. Schematic of $W_{u,t}$, the future warming effects of a generic pollutant emitted in period $u$

Figure 3 shows a sketch of the bidding webpage, as a fictional bidder $a = \text{Emisor DeGas, Ltd.}$ might fill it out. First the bidder selects the activity, in this case $p = \text{nitrogen dioxide}$. Second, the bidder selects the start date of emission $u = 2020-08-02$. Third, the bidder selects the bid price $B_{a,p,t}$ and the maximum quantity $Q_{a,p,t}$. Finally, the bidder clicks the submit button.

2.3.3 Decision variables

$q_{a,p,t} =$ kilograms allocated to agent $a$ to produce activity (e.g., pollutant or sequestration contract) $p$ in period $t$.

$v_{p,t} =$ total activity $p$ in period $t$. We can interpret this variable as the total emissions or sequestration by sector $p$.

$\pi_{p,t} =$ market price, $\$ \text{ per unit (e.g., kilotons or hectares)}$ of activity $p$ in period $t$. This is the dual price (also called shadow price, marginal price, Lagrangean value) on constraint 3 below.

$\omega_{t} =$ marginal cost for a change in $Cap_{t}$. This is the dual price on constraint 4 below. We can interpret $\omega_{t}$ as the improvement to the market manager’s net revenue for an increase in the cap on warming in period $t$.

2.3.4 Model SMDAMAGE

Maximize $\sum_{agent=a=1}^{A} \sum_{activity=p=1}^{P} \sum_{period=t=1}^{T_{B}} B_{a,p,t} q_{a,p,t}$ \hspace{1cm} (1)

$q_{a,p,t} \leq Q_{a,p,t}$ for agent $a=1, \ldots, A$, activity $p=1, \ldots, P$, and period $t=1, \ldots, T_{B}$, \hspace{1cm} (2)

$\sum_{agent=a=1}^{A} q_{a,p,t} = v_{p,t}$ for agent $a=1, \ldots, A$, activity $p=1, \ldots, P$, and period $T = 1, \ldots, T_{B}$ dual price $\pi_{p,t}$ \hspace{1cm} (3)

$\sum_{activity=p=1}^{P} W_{p,u,t} I_{p} + \sum_{activity=p=1}^{P} \sum_{emission \ periods \ a=0}^{a} W_{p,a,t} v_{p,a} \leq Cap_{t}$ for $t = Y, Y+1, Y+2, \ldots, T$, dual price $\omega_{t}$ \hspace{1cm} (4)

$q_{a,p,t} \geq 0$ for all agents $a$, activities $p$, and periods $t$. \hspace{1cm} (5)

2.3.5 Explanation

(1) Maximize the value of the traded contracts to market participants. If the market manager based prices on bids rather than the marginal, the objective would maximize the market manager’s profit. This accepts the highest bidders for permits and the lowest offers for sequestration, subject to the constraints.
(2) Respect agents’ upper bid limits, as specified in their bids.

(3) Calculate the total quantity of activity \( p \) each period as the sum of the agents’ allocated quantities. The dual price \( \pi_{p,t} \) on constraint 3 serves as the global price for activity \( p \) in period \( t \). This price accounts for participants’ bids for the activity, the residence time of the pollutant activity, and the warming cap in each period.

(4) The market model caps the cumulative warming effects of emissions for period \( Y \) and thereafter in the auction calendar, ideally far into the future. Therefore, the first auction will calculate prices for every future period in the auction calendar. Those prices could change at the next auction.

(5) Variables \( q_{a,p,t} \) are nonnegative. The model does not need non-negativity constraints for \( v_{p,t} \) because equations 3 and 5 together ensure the nonnegativity of \( v_{p,t} \).

### 2.3.6 Market Clearing

Before bidding, agents wishing to trade must register with the market manager, verifying a range of fiduciary attributes. The market manager has the right to reject an agent for misbehavior, lack of credit worthiness, etc.

At the beginning of a market cycle, the market manager would open a bidding page like Figure 3. While the bidding page is open, perhaps up to a few hours before each auction, registered agents would enter their bids as price and quantity pairs. The price for a buy bid is the highest price the agent would be willing to pay for the given quantity. A buyer might get none, some, or all of the bid quantity. The price for a sell bid is the lowest price the agent would be willing to sell the given quantity. The market manager might accept none, some, or all of the seller’s quantity. To protect proprietary data, bids are private to the agents and the market manager. The market manager does not need to guess a discount rate, because participants use their own.

At the preannounced time, the market manager would close the bidding page. The market manager would construct the linear program SMDAMAGE and solve it. The market manager accepts bids specified by the decision variables \( q_{a,p,t} \) and announces the prices \( \pi_{p,t} \) for each activity \( p \) and each period \( t \). Thus, the market follows marginal cost pricing. All prices \( \pi_{p,t} \) are public. The market manager authorizes payment from buyers and authorizes payment to sellers. Figure 4 shows a sketch of the bid results.

### Figure 4. Sketch of bidding web page results for fictional agent Emisor DeGas, Ltd.

The following formula gives the market manager’s revenue:

\[
\text{Revenue in the current auction} = \sum_{\text{agent } a=1}^{A} \sum_{\text{activity } p=1}^{P} \sum_{\text{period } t=1}^{T_B} q_{a,p,t} \pi_{p,t} \text{sgn}(B_{a,p})
\]

(6)

where \( \text{sgn}(B_{a,p}) = -1 \) if \( B_{a,p} < 0 \) when agent \( a \) sells a sequestration contract, else \( \text{sgn}(B_{a,p}) = 1 \) when agent \( a \) buys emissions permits.

After the first auction, global markets would observe posted prices for each warming activity for each period for decades into the future. This price information would provide important signals to business and governments. The warming effects \( W_{p,u,t} \) of each activity \( p \) into the future drive the market prices \( \pi_{p,u} \) as seen from the mathematical dual constraint associated with the primal decision variable \( v_{p,u} \).

\[
\sum_{\text{periods } t=u} W_{p,u,t} \omega_t - \pi_{p,u} \geq 0, \text{ activity } p = 1, \ldots, P, \text{ and emission period } u = 1, \ldots, T_B, \text{ primal variable } v_{p,u}
\]

(7)
Thus, the market price in any period for emitting each activity depends on the activity’s future warming effects and the desired management pathway for warming. Such advance prices would better incentivize long-term planning of technologies (Vogt-Schilb and Hallegatte 2014).

2.4 Numerical results

In the Appendix, I describe a numerical simulation of SMDAMAGE. While it is essentially a cartoon, the simulation conveys the possible behavior of the market.

The auction outcome will surprise. In many scenarios and years, emissions of CO₂, C2F6, CF4, HFC125, HFC134a, HFC143a and SF₆ were above 90% of their current emissions. However, the timing is critical. These same greenhouse gases had low fractions of their maximum bids early in the auction horizon, before the first constraining year. In these early years, the auction manager buys a great many contracts for sequestration by agriculture and forestry, and accepts few bids for greenhouse gases. The sequestration contracts take time to have enough effect. Once enough sequestration has been planted, global emissions could rise again later.

The global temperature would rise and then likely fall. After the year of first constrained warming, as agriculture and forestry sequester CO₂, the global temperature could fall and even overshoot the Cap, limit, drawing down the initial excess CO₂. The global temperature is unlikely to reach some kind of stasis in the next hundred years, but SMDAMAGE provides the tool to manage the global temperature.

The numerical simulation allowed me to characterize how the global temperature could change as a function of the first constrained year Y. Figure 5 shows these trajectories. Each curve corresponds to an auction run in 2020, with the first constrained year Y varying from 2029 to 2100. The graph shows the year Y where the series crosses the axis. Delaying the first constrained year results in a larger temperature increase, but lower cost to the auction manager.

These curves look optimistic, which might be due to my assumptions about the data. The model ignores the ocean inventory of CO₂ and probably many other important physical features. Nevertheless, consider the objective compared to other ETSs: this mechanism uses market forces to target warming directly.

Figure 5. Temperature trajectories over time by first constrained year Y (where the series first crosses the axis)

Static quantities and prices are wrong. Getting to zero (i.e., returning the global average temperature to some previous number, such as the average temperature in 1920) by a particular year will require a significant immediate ramp-up. Prices change considerably over time. Indeed, the only year in which the warming
constraint $C_t$ is binding is in the first year it is constrained; warming is above zero before that year, and below zero after that year. This result shows the misguidance of static limits in carbon tax and cap-and-trade mechanisms. Table 2 shows selected example prices from a hypothetical SMDAMAGE auction run in 2020, with the first constrained year $Y = 2050$. The table shows high prices in the early years, declining quickly in just a few decades. They are not static nor monotonic.

Table 2. Auction prices (constant $US_{2020}$, no discounting) by period and type of contract, for an auction held in 2020, with first constraint period $Y = 2050$. The table omits intermediate periods for brevity.

| Auction period | Agric walnut $/mt$ | Lob pine $/mhec$ | Pond pine $/mhec$ | C2F6 $/kt$ | CF4 $/kt$ | CH4 $/mmt$ | CO2 $/mmt$ | HFC125 $/mmt$ | HFC134a $/mmt$ | HFC143a $/mmt$ | N2O $/mmt$ | SF6 $/mmt$ |
|----------------|-------------------|----------------|-----------------|------------|----------|-----------|-----------|--------------|---------------|---------------|-------------|-----------|
| 2020           | 32                | 3930          | 6470            | 4736       | -138     | -61       | -275      | -32          | -42           | -52           | -31          | -49        |
| 2030           | 32                | 3950          | 4755            | 3670       | -129     | -61       | -420      | -32          | -48           | -52           | -31          | -49        |
| 2040           | 31                | 1936          | 2269            | 2794       | -129     | -57       | -620      | -31          | -52           | -31           | -49          | -492       |
| 2050           | 4                 | 1285          | 1328            | 2201       | -18      | -8        | -246      | -4           | -15           | -11           | -12         | -1408      |
| 2060           | 4                 | 1235          | 1326            | 2081       | -18      | -8        | -9        | -4           | -2            | -1            | -4         | -587       |
| 2070           | 4                 | 1178          | 1324            | 1925       | -18      | -8        | -10       | -4           | -2            | -1            | -4         | -601       |
| 2080           | 4                 | 1116          | 1324            | 1737       | -18      | -12       | -11       | -4           | -3            | -1            | -5         | -628       |
| 2090           | 4                 | 1043          | 1322            | 1527       | -18      | -8        | -12       | -4           | -3            | -1            | -5         | -648       |
| 2100           | 4                 | 957           | 1319            | 1305       | -18      | -8        | -14       | -4           | -3            | -1            | -5         | -668       |
| 2110           | 4                 | 851           | 1292            | 1064       | -9       | -8        | -17       | -4           | -4            | -1            | -5         | -682       |
| 2120           | 4                 | 733           | 1205            | 838        | -18      | -8        | -21       | -4           | -4            | -1            | -6         | -702       |
| 2130           | 4                 | 598           | 1072            | 621        | -18      | -8        | -29       | -4           | -6            | -2            | -7         | -709       |
| 2140           | 5                 | 460           | 912             | 432        | -9       | -4        | -41       | -5           | -6            | -2            | -7         | -709       |
| 2150           | 5                 | 305           | 665             | 257        | -18      | -8        | -63       | -5           | -8            | -4            | -8         | -689       |
| 2160           | 5                 | 141           | 245             | 116        | -9       | -4        | -96       | -5           | -8            | -5            | -8         | -621       |

Auction revenue depends on the first constraint year. In the numerical example (see Appendix), I could characterize how the auction manager’s net revenue in 2020 would vary with the date of the first “net zero” year. Figure 6 demonstrates this for an auction held in 2020, where $C_{t} = \infty$ for $t < Y$ and $C_{t} = 0$ for $t \geq Y$, for $Y$ varying from 2029 to 2100. Cost is high in the early years, but would quickly decline. This suggests a net zero goal of 2040 to 2050 if we implement SMDAMAGE soon. Continuing to increase the greenhouse gas burden raises the cost of solving the problem; every kilogram we emit now we must sequester later. To reiterate, this calculation shows the cost of the current excess inventory and the folly of continuing to increase that inventory. It seems implausible that we can blister the earth and come out revenue positive.

Figure 6. Auction revenue in 2020 by “net zero” year $Y$, 10$^{12}$ US$2020$, not discounted

To be clear, the costs recorded in the graph are not the total cost to the global economy, but rather the net cost to the auction manager.
Part 2. A Climate Insidium\textsuperscript{1}

3 Basic Rules and Incentives of the Market

3.1 Basic rules: universal participation and multilevel enforcement

Ideally, the international community would come together to make this happen. Jurisdictions would agree to firm uniform rules, selection of the warming pathway, how to improve the science over time, enforcement of the rules, and supervision of the market manager.

In this proposal, all jurisdictions (countries, states, provinces, etc.) require participation of all emitters of GHGs within their jurisdictions. All production anywhere of the listed GHGs requires purchase of a contract through this market. Jurisdictions would consolidate other emissions markets into this one. Initial permits would be available only for rights already obtained through existing emissions markets. Otherwise, market rules would prohibit grandfathering. Responsibilities for enforcement should be multilevel:

Rule 1. The governing committee chooses the global limits \( \text{Cap}_t \) on warming.

Rule 2. Participating commercial agents have responsibility to obtain permits for all production.

Rule 3. Everyone has responsibilities to avoid trade with non-participating agents, even if the participating agent’s jurisdiction is a non-member.

Rule 4. The governing committee has responsibility for promoting individual concern worldwide for everyone to support participating companies and to boycott companies that do not.

Rule 5. The market manager has responsibility to maintain a public list of non-member jurisdictions, and a public list of commercial agents who do not participate or who violate the rules.

Rule 6. The market manager has responsibility for paying whistle-blowers who expose violations.

Rule 7. Each member jurisdiction has responsibility for requiring agents within its jurisdiction to produce no more than permitted.

Rule 8. Member jurisdictions have the right to serve on the governing committee. Member jurisdictions found to have lax enforcement could lose committee voting rights.

Rule 9. Each member jurisdiction has responsibility to impose trade sanctions such as 2% tariffs against non-member jurisdictions, following the suggestions by Nordhaus (2015).

Rule 10. Each member jurisdiction has responsibility to sanction trade specifically against non-participating agents wherever they produce. This includes preventing or taxing trade with non-participating agents, and waiving tariffs on participating agents who produce in nonmember jurisdictions.

Note the difference in rules to other market designs: participating commercial agents have responsibility to avoid trade with nonparticipating agents, without regard to jurisdiction membership. To my knowledge, no other ETS has such a rule. The insight here is that company-level incentives are key part of the problem, and companies’ incentives are heterogenous. Taking advantage of heterogeneity can create a path forward and strengthen enforcement. Vasconcelos et al (2019) make a theoretical case for this, if I understand their paper correctly.

\textsuperscript{1} I took this word from https://wiki.achaea.com/Insidium: “…the Insidium seeks to bolster internal advancement while eradicating heathen lies in their quest to spread the Truths. Those who seek this route understand that subtle, long-term strategies produce the greatest rewards, consciously choosing to take deliberate actions in the present with a view to bringing civilisation one step closer to achieving true Strength.” Accessed 5 March 2020. I know little of the associated game or firm. I use this word to mean a coalition that builds slowly at first but with increasing strength and increasing incentives to join.
3.2 Incentives to join for jurisdictions and to participate for commercial agents

The proposed centralized auction with decentralized enforcement appears to incentivize jurisdictions to join and commercial agents to participate. The key difference to other designs is the ability of firms to participate even if their jurisdictions are non-members, combined with members and participants fostering broad societal pressure on non-member jurisdictions and non-participating firms. Centralization enables this feature, unlike regional ETSs. Further, these incentives appear to increase over time. These characteristics could result in a cascading bottom-up “me too” rush to join, in sharp contrast to the “you first” incentives of other designs.

Assume a coalition of willing jurisdictions and firms starts the market. That is, a credible group of jurisdictions agree to require commercial agents within their jurisdictions to purchase the emissions permits and to follow the associated rules. Some firms might agree to participate even if their own jurisdictions do not join. Remaining jurisdictions are non-members and their commercial agents are non-participants. The market manager auctions all permits, holding nothing back.

Consider the incentives of a non-participating commercial agent within a non-member jurisdiction, such as the firm represented by the circle at bottom left in Figure 7. The market manager would record the agent as a scofflaw. First, the agent faces increasing trade sanctions by both member jurisdictions, and participating agents, especially if the agent has significant export operations. The agent may choose to participate in order to avoid sanctions. Second, the agent might expect their jurisdiction will eventually become a member, at which point the agent would need production permits. The agent has incentive to participate even before its jurisdiction joins to be ready for this contingency and to avoid possible price increases. Because the market manager puts all permits on sale, this availability might incentivize participants to join early in hopes of lower prices, which are likely to rise as more participants join. Third, the non-participating agent faces reputational risk with its customers, local and international stakeholders, and whistle-blowers. This risk would likely increase over time as news of the agent’s non-participation became more widely known. Thus, as more agents participate, a given non-participant in a non-member jurisdiction faces increasing business risk, increasing trade sanctions, increasing reputational risk, and increasing likelihood their own jurisdiction will join.

Figure 7. Schematic of membership and participation: some firms might participate though their jurisdiction is not a member

Consider the incentives of a non-member jurisdiction, such as the jurisdiction represented by the heavy box at the bottom right of Figure 7. First, participation of commercial agents within could result in de facto jurisdictional membership, though the jurisdiction is a non-member. Joining would become politically easier over time. Second, the non-member jurisdiction would have no right to auction revenue, if it were available, while an increasing amount of revenue comes from agents within its borders. A variety of stakeholders within the non-member jurisdiction would then advocate for the jurisdiction to join, perhaps to obtain access to revenue. Third, the jurisdiction could save money by eliminating subsidies and regulations made obsolete by the central market. Thus, as more agents anywhere participate, the non-member jurisdiction faces a
decreasing political risk to join, and an increasing political risk to stay out. When the non-member decides to join, all commercial agents within its jurisdiction would be required to participate, raising the incentives even further for other agents to participate and for other non-member jurisdictions to join.

Consider the incentives of commercial agents who cheat. Cheaters might produce more than permitted or produce at different times than permitted. Cheaters might trade with non-participating agents. The market manager would be primarily responsible for publicizing the identities of cheating agents. However, all member jurisdictions and participating agents would be responsible for detecting cheaters and imposing sanctions on them. Whistleblowers could expose the scofflaw. As an increasing number of agents participate and jurisdictions join, sanctions against cheaters would increase. The incentive for commercial agents to cheat appears to decrease over time. Producers of GHGs with the highest permit prices, such as sulfur hexafluoride or nitrous oxide, will have correspondingly high incentive to cheat.

Consider the incentives of member jurisdictions who cheat. They might allow commercial agents to exceed production limits, or they might allow non-participating agents to trade. Other participating agents would sanction the cheating agents, and other member jurisdictions would sanction both the cheating jurisdiction and its cheating agents. These intergovernmental sanctions can include loss of voting rights regarding use of the auction revenue. As more jurisdictions join, a cheating jurisdiction can be more easily sanctioned and with greater sanctions. The incentive for jurisdictions to participate appears to increase over time.

Consider a large country that does not participate as a whole, but has participating jurisdictions within. Sprinz et al (2018) point out the hindrance from lack of U.S. leadership in a climate club. This hindrance would be loosened by participation of states such as California, and loosened further through participation by American firms in non-participating states.

In addition to the incentives between jurisdictions and firms, and between firms, this design empowers individual consumers to harry non-participating firms directly by reduction in demand, or at least reputation (though reputational penalties are not enough, Karpoff et al, 2005), even if those firms are in nonmember jurisdictions. Citizen boycotts of non-participating firms would incentivize those firms to participate, picking them off one at a time, while inhibiting drop-out behavior. This strongly contrasts with the inability of consumers to influence fossil fuel emitters in the absence of a centralized mechanism where citizens see no specific activity that the firms should be doing.

These strong incentives to participate should go a long way toward eliminating free-riding behavior. While these behaviors need to be simulated to understand the effectiveness of the sanctions, the individual-to-business sanctions and business-to-business sanctions suggest that these incentives are a superset of and therefore at least as strong as those proposed by Nordhaus (2015).

The double-sided nature of the auction might incentivize emitters to vertically integrate with sequestration activities. The incentives come from economies of scope where emitting firms could convert their emitting technologies to sequestering technologies, and from economies of scale where emitting firms want to invest in any kind of sequestration to reduce permit price risk.

### 3.3 Governance and enforcement

The market should cover at least the GHGs listed in the Kyoto Protocol, including carbon dioxide, hydrofluorocarbons, methane, nitrogen trifluoride, nitrous oxide, perfluorocarbons, and sulfur hexafluoride. Market rules should allow the governing committee to add other GHG chemicals to the auction.

Governance should include improvement of the operation of the market, such as reducing transaction costs (Coria & Jaraitė, 2015, but see Crals & Vereeck, 2005, for a different view), especially for sequestration projects (Gledhill, Grant & Low, 2008, and Michaelow et al, 2003).

Because the first principle of this proposal is adherence to the warming pathway, the market manager and jurisdictions could use the first tranche of revenue for enforcement. The market manager could use revenue from fines to retire production permits. If the manager had a policy of retiring more permits than necessary
to offset the emissions from the infraction, the threat of lower supply might incentivize other emitters to report infractions.

The market manager should not be the sole enforcer. Jurisdictions must also be responsible for local enforcement. I propose a strong whistle-blower policy; whistle-blowers could be entitled to payments based on current market prices. The governing committee should promote a global attitude of individual support and personal responsibility for enforcement.

With the market rules allowing for improving science over time, I also propose improving enforcement over time. For example, jurisdictions and the market manager may demand blockchain corroboration of agents’ emissions sensors. Poor jurisdictions might need help with enforcement.

Market rules would prohibit the market manager from paying anyone to avoid emissions. The market manager can pay participants only for sequestration. The governing committee will have to establish rules for existing stocks.

Market rules would establish a process for improving the science over time, as well as how to adjust previously allocated permits when that science results in changes to parameters $W_p, \text{ or } Cap$. Other researchers might find an alternative formulation of SMDAMAGE with better modeling of the physics. The basic design of the smart market would remain the same.

4 Potential problems

What could go wrong?!

Implementation of an ETS is affected by many factors, such as constitutional provisions, international treaties, the ability to create competition, the influence of emitters, public opinion, and the government’s need to raise revenues (Haites, 2018). All of these and others will apply to my proposal, and I am not ready to address all of them. But here are a few.

4.1 Fairness between countries, equity considerations

Determining whether a given country breaks even would require a numerical simulation of SMDAMAGE for each country. The large energy exporters are likely to have the greatest losses (Jacoby et al 2008) unless they can pivot to sequestration.

Regarding equity, Stiglitz (Stiglitz 2019 and Stiglitz et al 2017) is concerned that carbon taxes will hurt the poor more than the rich. His papers therefore recommend both carbon taxes and regulation, such as requiring a particular sector to change to a greener technology, nonlinear electricity tariffs, and subsidies for public transportation.

In my view, global warming will hurt — is already hurting — the poor far more than carbon pricing will hurt them. In addition, resolving the problem of inequity adds large transaction costs (getting to agreement about equity) to the primary problem of reducing warming. If we instead move forward risking the appearance of hard heartedness, we have a better chance of solving the common problem, and we are likely to reduce costs for the poor.

In any case, while the proposal here is a more stringent mechanism than any previous, it does not exclude subsidies or regulations. Because it limits quantities, jurisdictions could subsidize affected commodities (at high risk of creating shortages), public transportation, etc.

More generally, SMDAMAGE has nothing explicit about the social cost of carbon. These costs are uncertain but likely to be high. (For a sophisticated analysis, see Cai, Judd and Lontzek, 2017.) Implicitly, this proposal should lower the expected social cost of carbon and increase its certainty by increasing certainty about the warming pathway. Other researchers might figure out how to incorporate the social cost of carbon directly in the objective function of SMDAMAGE.
4.2 Legal impediments

Implementation of SMALMAGE will require consideration of international treaties, constitutional provisions, and local laws. These seem surmountable, but I will have to leave this discussion to others. Gardoqui and Ramirez (2015) discuss global trade rules in the context of a climate club. Weil (2018) discusses these rules at greater length and greater pessimism.

4.3 Initial allowances

To introduce allowances into an ETS, governments can auction them or give them away (Goulder and Schein, 2013). Giving away permits might lower the recipient’s incentive to reduce emissions, entrenches them in past behavior and technology, and can give recipients both windfall profits and a competitive advantage against new entrants; free permitting is subject to political manipulation (Huber 2013). Thurber and Wolak (2013) found higher carbon prices favored generators, and policymakers should minimize free allocations. Huber also points out that the regulatory cap can result in price increases that raise revenue for participants.

Besides those disadvantages, free allocation of permits reduces the market manager’s revenue, thus hindering purchase of sequestration contracts. So I do not propose free allocation here. I propose a pure polluter pays mechanism.

The initial allowances could also be negative. Following the start of the market, the governing committee could require permits for all emissions after a past year, say 2010. The committee could use SMALMAGE to calculate prices for those earlier emissions; those prices would likely be very high. Further delay simply raises these costs. A credible threat to charge for past emissions could incentivize agents to reduce their emissions before the market begins.

4.4 Liquidity

According to Holt and Shobe (2013), key measures of performance of the market include liquidity, price discovery, efficiency, and price volatility. SMALMAGE should have excellent price discovery and economic efficiency. I discuss volatility below. Liquidity is “a measure of how many units of the market asset...are available to come into the market as the price rises”, as they put it. Holding limits intended to prevent market power reduce liquidity. I would not propose market limits though I see the temptation. A liquidity shortage could occur in early years if bids for emission cannot be offset by sufficient offers to sequester. The corresponding high prices would serve to kickstart behavior change. The problem of liquidity might take more research for this market.

4.5 Volatility

Policymakers and researchers are concerned about an ETS’s ability to flex in response to economic shocks e.g., Kollenberg and Taschini 2016. Doda (2014) wrote, “A well-designed system can prevent prices from falling too low during a recession and so maintain the abatement incentive, or from overshooting in a boom and excessively constraining production by regulated firms precisely when they are at their most productive.” I am skeptical of the need for such flexibility in general. Markets should adjust on their own and governments are supposed to do little about it.

4.6 Competitiveness

ETSs can affect international competitiveness, but mitigating mechanisms can lower economic efficiency (Schmalensee and Stavins 2017a, 2017b; Goulder and Schein 2013; Fell and Maniloff 2018; Fowlie 2012). They can suffer from agents with market power (Godby, 2002) and can inhibit project development (Larson & Breustedt, 2009). Offsets can be ineffective (Wara and Victor, 2008), and regulators allow “self-protection” and sector-based targets inconsistent with price efficiency (Gledhill, Grant & Low, 2008). Some of these problems are likely associated with the different degrees of ETS implementation; apart from equity, the playing field is level if all countries face identical prices.
4.7 Revenue sufficiency

Since revenue increases public support for cap and trade (Mills, Rabe and Borick 2015; Klenert et al 2018), the potential lack of revenue neutrality, depending on the choice of $\text{Cap}_p$, could hinder its implementation. The governing committee should also accept donations from governments, foundations and individuals. Charitable institutions and individuals could donate funds to increase their prestige.

I hope the research community can lower the revenue gap by optimizing pathways for $\text{Cap}_p$ and finding clever trading mechanisms to raise revenue.

4.8 Moral hazard

Solutions to global warming are rife with adverse selection (hidden information affects the risk of transaction) and moral hazard (hidden behavior affects the risk of transaction).

Where to start? Inability to measure other countries’ emissions (Petrakis and Xepapadeas, 1996), fantasizing of carbon capture technology (Hamilton, 2013), fantasizing of geo-engineering (Fairbrother, 2016), fantasizing of fusion, fantasizing that technology can’t help at all (Wagner and Zizzamia, 2019), hoping everyone else will reduce emissions so we don’t have to (Anesi, 2009), hoping future generations will be richer and better able to solve the problem (Sachs, 2015) as in arguing about the discount rate (Nordhaus, 2006),2 producing a greenhouse chemical to get the credit for destroying it, threatening to clear the forest to get paid (Fearnside, 2011), clearing a forest to get a credit for planting, taking money to plant a forest that was going to be planted anyway (Burke 2016, Bushnell 2011), taking money to plant the forest but not following through.

One editor rejected an earlier version of paper on the basis that the paper did not solve the last moral hazard in the list above. Here’s my answer: I can call out what I think is nonsense, but I can’t solve all the problems of moral hazard. I hope that this paper avoids or solves some of them. At least this proposal should do no worse than existing ETSs.

Other people might be able to do better. The European ETS administrators have worked hard at this. I can imagine small sequestration contracts aggregated by third-parties with sufficient reputation to provide some guarantees. The member committee could choose to adjust SMDAMAGE coefficients $W'_{p,ct}$ for sequestration on the assumption that some contracts will fail. I would like to see some kind of mechanism for clawing back money if the market does not meet its temperature targets, but I can’t see how this would be designed. I have suggested a whistleblower mechanism. Drones can count trees now. The researchers in mechanism design should be able help. Petrakis and Xepapadeas (1996) address moral hazard in measuring emissions. MacKenzie, Ohndorf and Palmer (2011) have a hopeful proposal titled “Enforcement-proof contracts with moral hazard in precaution: Ensuring ‘permanence’ in carbon sequestration.”

But we can’t fold our hands because we’re afraid of the moral hazard. That moral hazard itself is the worst.

Part 3. A Faster Path Forward

5 Who’s on first?

5.1 Top-down or bottom-up?

This proposed market could be implemented in a top-down or bottom-up strategy. Monast (2017) discussed top-down and bottom-up strategies in detail. I think he would call my proposal a “coordinated design strategy.”

Sabel and Victor (2017) describe the top-down approach as centralized efforts to align the behavior of key decision makers. The top-down approach can lead to gridlock, and implementation of my proposal would almost certainly suffer this problem. Implementation of an ETS or carbon tax requires payment of an

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2 I think putting it on future generations is gutless and irresponsible. We made the mess so we should clean it up.
enormous transaction cost at jurisdictional level. Of course, we wish for an ETS or carbon tax at international level, which makes the transaction cost two orders of magnitude larger. Thus, we do not see many of these transactions, and neither should we expect them in the near future. Still, this is where we wish to go.

Here is a path for implementation of this proposal: the countries of the world join to implement SMDAMAGE as a single global market for warming. Based on how well the world has moved down similar paths, we need an alternative.

In a less-ambitious form of a top-down strategy, researchers have called for climate “clubs” with the muscle to develop top-down policies (e.g., Nordhaus 2015, Keohane et al 2017, Sable and Victor 2017, Paroussos et al 2019). A club of ETSS could provide a credible start for my proposed market. As Paroussos et al explain, establishing such a club requires identifying “excludable” benefits which the club can prevent non-members from enjoying. Paroussos et al give a list of such benefits, such as access to finance and border tariffs. For finance, the governing committee could loan auction revenue to jurisdictions and firms. While not as difficult as a worldwide treaty, the transaction cost to develop a climate club is also very large. Still, this might be a powerful intermediate step.

Here is a second path for implementation of this proposal: willing jurisdictions and firms join to implement SMDAMAGE as a single global market for warming. The willing jurisdictions would likely include those already with ETSS. The overall incentive should be to solve the problem of global warming at the lowest cost to society. Jurisdictions will want to join for this reason while lowering outlays for subsidies and regulations, and to avoid implementing their own ETS. Based on how well the world has moved down similar paths, we might need an alternative.

According to Sabel and Victor (2017), the bottom-up strategy has decentralized policy design and implementation. The bottom-up strategy requires institutions to encourage public and private entities to explore policy options and scale up successes. In my view, the transaction costs for actions by individuals, companies, and small jurisdictions are small, and we already see many such transactions of this type. To be effective, though, the bottom-up strategy must evolve from decentralized scattered actions toward centralized coordinated actions. So, how can we shift from bottom-up to global scale?

5.2 The key role of the firm on the permit side

The basic market rules suggest the insidious path toward a global market.

A market maker takes the first step. This market maker could be any large firm, a powerful charitable foundation, or an appropriate international institution. It could be a large jurisdiction such as California, but I think a firm could start faster, so let’s call the market maker GreenTechCo. GreenTechCo would want others to help and should recruit a coalition. GreenTechCo’s coalition would establish the market institution as an independent nonprofit and hire the market manager. Let’s call the market manager Greta. Greta, with oversight from the governing committee of members, establishes Cap following Rule 1.

In step 2, the market maker lurches forward with demands that its suppliers, and the suppliers’ suppliers, purchase emissions permits from Greta as a condition of continued business with GreenTechCo. Let’s call the supplier Emisor DeGas. GreenTechCo has incentive to help Emisor DeGas clean up its emissions, and incentive to find a different supplier only if Emisor DeGas refuses to participate. GreenTechCo’s coalition invites, encourages, and pesters other companies to participate in the market.

As steps 1 and 2 move to a walk, Greta begins to sell permits, but also begins to buy sequestration contracts. Standing up this work will be a major undertaking, but she has funding for it. More on this in the next section.

To add muscle to these legs, I propose the customer-labeled emissions permit (CLEP), an instrument I have not seen elsewhere (perhaps Nori LLC, Seattle, WA, is doing this). The CLEP could be implemented many different ways, but think of a CLEP as a tag on the permit that Emisor DeGas buys from Greta. The tag shows the label “GreenTechCo,” the time period of production, the pollutant, and the quantity spewed by Emisor DeGas when it makes a specific batch of product for GreenTechCo. The contract registers the tag
with Greta, who can verify its authenticity. Thus, Emisor DeGas has proof of permit specifically for GreenTechCo’s materials, down to the shipment. (The International Organization for Standardization could turn the CLEP into an ISO standard. With blockchain technology, every can of soup could have proof of permit. A customer could scan a QR code; the app would ping Greta’s database.) GreenTechCo can then demand this proof for every shipment from Emisor DeGas. Thus, GreenTechCo can verify Emisor DeGas’ adherence to Rule 2: participating commercial agents must get permits for all production.

In step 3, consider Greta’s point of view, and recall Rule 3 above; everyone has responsibilities to avoid trade with non-participating agents, even if the participating agent’s jurisdiction is a non-member. This means Greta requires Emisor DeGas to get its own suppliers to buy permits. The residence jurisdiction for these other suppliers does not matter. Thus, the market has a widening network of participating companies.

GreenTechCo should then have an easy time (compared to making a global treaty) convincing its headquarters city to begin demanding participation of its own suppliers, even if the city cannot require local firms to participate generally.

In step 4, recall Rule 4: the governing committee has responsibility for promoting individual concern worldwide for everyone to support participating companies and to boycott companies that do not. Ordinary consumers can insist on participation by their retail firms, and those retail firms can insist on participation by their suppliers. Rules 5 and 6 begin to impel the market forward, with Greta listing scofflaws and paying whistleblowers. Consumers will know who is in and who is out.

With step 5, willing jurisdictions take the leap to join. By “joining,” I mean Rule 7: each member jurisdiction has responsibility for requiring agents within its jurisdiction to produce no more than permitted.

In step 6, other larger jurisdictions find a lower political cost of membership, because many companies within are participating and lobbying for their jurisdiction to get a seat on the governing committee with Rule 8.

In step 7, the market moves to a sprint with Rules 9 and 10: member jurisdictions impose trade sanctions against non-member jurisdictions and non-participating firms. Only the most odious jurisdictions will remain out.

The incentives in the path mapped above differ wildly to the stalled international agreement process. This could work because these rules enable a divide-and-conquer strategy at the level of the individual firm and because the transaction costs everywhere are so much lower.

- Responsible CEOs have assurance that they are participating in the strongest known economic mechanism for reducing global warming.
- Firms can participate one at a time without their jurisdictions joining.
- Firms can join as they become ready, and their business partners have incentive to help them.
- Transaction costs to firms of buying permits are lower with the central mechanism; an small unsophisticated company of goodwill can easily arrange for the permits it needs.
- Consumers can boycott one firm at a time whether or not their jurisdiction is a member. Early adopting firms win the race in marketing. Late adopting firms get mud on their face.
- Jurisdictions can join one at a time without need for international treaty. They avoid standing up their own ETS administration, so small countries can join immediately. Internally, the jurisdiction has a relatively low transaction cost to join, especially if firms within already participate.

5.3 The sequestration side

Greta’s business in selling permits will match her business in sequestration, but sequestration will take more administration. Standing up this work will be a major undertaking. Fortunately, she has funding for it and strong support from her member committee. Facing the moral hazards one at a time, she will have to help stand up supply chains of sequestration across the globe. Large agricultural and forestry players might sign up
quickly. Third parties may aggregate small sequestration contracts, selling them on behalf of small players. This will be messier than the permit side of the market, with higher costs for transactions and enforcement.

Plant biologists will have much work in developing the SMDAMAGE coefficients \( W_{\text{per}i} \) for the many types of sequestration, whether planting forest, planting grasses, planting mangroves, burying biochar, enhancing agricultural soil carbon, etc. Inspection firms will make hay in tracking sequestration. Greta will need lawyers and mechanism design scientists to sort out contract details.

6 Conclusion

In the short run, decision-makers are likely to want more research to understand a complete design of the market institution, the full role of the market manager, the auction schedule, the structure and nature of the bids, the bidding process, ways to simplify the bidding process for different types of economic agents, and automated bidding, and tools to mitigate adverse selection. Recognizing emissions as occurring at the same time as production could have unintended effects, where producers stock chemicals in advance of emission, anticipating higher later prices. The contract should at least specify a maximum time between production and emission. Other important issues for market design include the process of market clearing and the use of marginal cost pricing. The work is ripe for application of experimental economics, for gaming in the implementation process and in market operation.

I recognize the difficulty on the road to implementation. Perhaps the greatest argument against this proposal is hopeless pessimism. Visionary leaders have solved hard problems in the past. Business people who believe in markets and individual choice, and who dislike government regulation and subsidies, would support this proposal. It is easy to be cynical, but emissions are now widely traded and the problem has the world's attention. We all need certainty of the warming pathway, we need the lowest cost solution to this most expensive of problems, we need a robust mechanism that is implementable, and we need it soon. I have described a plausible path, for this world drunk on heat, as I wish it would go. We can easily imagine many ways people will break rules and cheat and stall and hinder and even write obstructive laws in bad faith. None of those is sufficient reason to stand still anymore.

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8 Numerical Appendix for A Price on Warming: Smart Market Design Addressing Management of Global Emissions

In this section, I describe a numerical simulation of SMDAMAGE. I consider the results speculative for a range of reasons. I had to speculate about global demand for emissions, global supply of sequestration, and a path of planned temperature. While much of this data is available publicly, my use of it might not have done justice to the authors’ intent. Further, pulling together so much disparate data proved technical and complicated and I might have made mistakes in it.
### 8.1 Activities simulated

I omitted all abatement activities with negative cost. This assumption is conservative, in the sense that agents would abate a great amount at very low cost simply when faced with a price.

Even with its display of future prices, the numerical simulation is static: it does not take into account how agents will react to prices once posted. As agents react to the first round of prices, we would expect a change in the revealed abatement curves during bidding in the next period.

For each activity, the simulation requires:

- **Bids.** I obtained values for bids from the literature on marginal abatement cost curves, as described below. Bid selection required assumptions about behaviors. For example, the available data on forestry provides a range of plantable total area, but little information about the rate at which foresters could plant. To convert from a static marginal cost curve to a set of bids over time, I assumed 20 years to plant the highest number of $H$ hectares, so foresters could plant this area at a maximum rate of $H/20$ hectares per year. Thus, the change in behavior requires a ramp-up time.

- **Warming effects,** ideally recorded as the degrees Celsius change in each period after the activity. I obtained these warming effects by using the climate simulation Hector (Hartin et al. 2015). To obtain the warming effects from Hector, I simulated a 50% increase in the base emission of each chemical, and then recorded the change in temperature for each future year in the simulation, to 281 years into the future. This simulation defined the warming effect $W_{p,u,t}$.

The simulation includes the following activities.

1. **Agriculture,** megatons $CO_2$ sequestered per period.

   I extracted bid data from Smith et al. (2014, their figure 11.17). Sorting and aggregating by price produced a three-point bid stack. I inflated from US$2005 to US$2020 and fitted a curve: megatonnes $CO_2$/year mitigated = $0.0587p^2 + 39.613p + 926.25$, where $p$ is US$2020$ price, then I produced 57 bids in $4$ increments from $0$ to $224$/ton $CO_2$, to a maximum of 6,854 megatons/year; I assumed zero megatons would be sequestered at a price of $0$. I further divided the bid quantity by the number of periods per year. The decision variables are in units of megatons, so an objective coefficient of $100$ implies a bid of $100$ million per megaton.

   I assume agriculture sequesters $CO_2$ only in the period of bidding. Warming effects are from Hector based on the agricultural $CO_2$ sequestered per period.

   I assume no initial stock of agriculture, although the initial burden of $CO_2$ calculated below implies an initial inventory of natural sequestration.

2. **Forestry,** million hectares planted per period, represented by three tree types labeled black walnut, loblolly pine, and Ponderosa pine.

   I extracted sequestration data Stavins and Richards (2005, their figure 2), which shows the annual carbon uptake by year for loblolly pine, Ponderosa pine, and black walnut, in different regions of the United States. Summing over the 155 years in the graph gave total short tons $CO_2$/acre for each representative tree type, which is the basis for creating bids based on sequestration. I then converted from short tons/acre to metric tons/hectare. Finally, I calculate $W_{p,ad}$ for $p =$ loblolly pine, Ponderosa pine, and black walnut. The decision variables are in units of a thousand hectares per period. For a hectare of pine trees planted in period $u$, denote the schedule of tons $CO_2$ sequestered as $N_u, N_{u+1}, N_{u+2}, N_{u+3}, \ldots, N_T$. Then a contract for planting a thousand hectares in period $u$ will result in warming of period $t$ by the following:

   $$W_{p,ad} = -1,000 h \sum_{v=u}^{t} (N_v \text{ mttons } CO_2)/(1,000 h)/\text{period} \times [W_{CO_2,p,10^{-3}C°}/(\text{mttons } CO_2)]$$

   To obtain bids for global forestry, I found Stavins and Richards (2005, their figure 6), which shows estimates for $1997$/ton costs for carbon sequestration per year. I fit a curve to match their graph to get
$/\text{ton}$ as a function of (US) megatons CO$_2$/year. I used the highest value on their chart as the global highest bid for forestry. I inflated from $1997$ to $2020$, converted from acres to hectares, and from short tons to metric tons. Finally, I multiplied the sequestration per hectare over the life of each tree type by the $/\text{ton}$ to get $2020$/hectare.

Extrapolating to the globe, de Coninck et al (2018, section 4.3.7.2) indicates the earth might have up to 500 million hectares available for forestry. I assumed the 500 million hectares had a maximum planting rate of 25 million hectares per year, equally divided among the 3 types of representative trees. Bids then ranged linearly in steps of 25,000 hectares per tree type per year, up to a maximum of 8,000,500 hectares/year, and from a low of $1,724$/hectare of loblolly pine to a maximum of $82,028$/hectare of ponderosa pine.

This estimate is speculative, in part because it builds up the bids based on a priori estimates of the value of carbon sequestration, not the cost of planting and operating a forest, and because the simulation uses only three representative tree types common to the U.S.

Further, the simulation does not model the total capacity of forestry. Bid quantities are small enough that ramp-up in the model takes at least 20 years, but does not limit the total forestry area. Fortunately, the solution never uses all the forestry area.

I assumed zero inventory of forestry, although the calculation for the initial burden of CO$_2$ implies an initial inventory of natural sequestration.

3. CO$_2$, megatons (GtC in Hector) emitted per period. Warming effects from Hector (as “ffi”).

I obtained bid data from Anger and Sathaye (2008), who give marginal abatement cost coefficients in €2005 by country for energy-intensive and non-energy-intensive sectors. I compiled the marginal abatement cost curves for both sectors and all countries into a single bid stack, as seen in Figure 8, in 10 megaton increments, with an upper bound of €1,000, and then I converted prices to $/US2020$ (at €1/$1.1$, and inflating from 2005 to 2020).

Figure 8. Selected global CO$_2$ marginal abatement cost, based on Anger and Sathaye (2008)

As the initial burden, I calculated the megatons CO$_2$ in the atmosphere at 410 ppm for 2020, and subtracted the calculated megatons CO$_2$ in the atmosphere at 303 ppm for 1920, resulting in a 2020 burden of 810,958 megatons of CO$_2$.  


4. CH$_4$ and N$_2$O, megatons emitted per period. Warming effects from Hector. For both of these, I obtained bid data from Harmsen et al (2019), and developed bids from a curve fitted to their year 2100 emissions curve.

For these chemicals and the remaining, I calculated an initial burden based on the current atmospheric concentrations, which I found from Ehhalt et al (2001); Ravishankara, Daniel, and Portmann (2009); Tonkovich (2019); and Prinn et al (2000).

5. C$_2$F$_6$, kilotons emitted per period. Warming effects from Hector.
6. CF$_4$, kilotons emitted per period. Warming effects from Hector.
7. HFC125, kilotons emitted per period. Warming effects from Hector.
8. HFC134a, kilotons emitted per period. Warming effects from Hector.
9. HFC143a, kilotons emitted per period. Warming effects from Hector.
10. SF$_6$, kilotons emitted per period. Warming effects from Hector.

8.2 Software

I wrote the model in Python with the open source modeling language PuLP and the COIN-OR CBC solver. The model typically solved in 3 or 4 minutes.

8.3 Running the simulation

Following assembly of the data and debugging of the model, I set the model to have its first auction in 2020, with bidding through $T_b = 2170$, and the last constrained period as $T = 2301$, with two bid periods per year.

I constrained the change in temperature to zero starting in $Y = 2020$, so $Cap_{2020} = 0.0$. This model was, not surprisingly, infeasible. I made a second run to minimize temperature. The solution accepted all bids for sequestration and none for any emissions. Temperature rose a half degree C through 2024, but lowered below zero by mid-year 2028. This implausibly optimistic scenario set the limits on the mathematical solution space.

I then ran 81 simulated auctions. In each auction, the market opened in 2020 with the first warming-constrained year ($Cap = 0.0$) in year $Y$, for $Y = 2020$ to 2100. The model was infeasible for $Y = 2020$ to 2028, but feasible for $Y = 2029-2100$.

8.4 Potential Improvements

Most likely, my numerical simulation is optimistic about temperature, but pessimistic about the cost. A simulation less optimistic about temperature and less pessimistic about cost would shift the Figure 6 graph rightwards and upwards.

For example, the warming effects for SF$_6$ (taken from Hector) seem too small; I expected higher prices for SF$_6$. Estimated emissions as calculated by SMDAMAGE could be put back into a climate simulator for validation.

On the other hand, I ignored learning effects in bidding; bids were static over the full bidding horizon, implying business will always want to emit the same amount of GHGs. I also ignored discounting for simplicity of exposition, though I have the function available in the code. Ignoring learning and discounting overestimates costs.

In SMDAMAGE, bids could be made more accurate by using marginal abatement curves by small region or city (Nadine and Kennedy 2016).

This smart market permit mechanism would extend to a range of other environmental applications. For example, jurisdictions could require manufacturers to pay for production of plastic, while using the revenue to procure services to clean up the oceans.
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