Innovation under cap-and-trade programs

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Policies incentivizing the private sector to reach its innovative potential in "clean" technologies are likely to play a key role in achieving climate stabilization. This article explores the relationship between innovation and cap-and-trade programs (CTPs)—the world's most prominent climate policy instrument—through empirical evidence drawn from successful CTPs for sulfur dioxide and nitrogen oxide control. The article shows that before trading began for these CTPs, analysts overestimated the value of allowances in a pattern suggestive of the frequent a priori overestimation of the compliance costs of regulation. When lower-than-expected allowance prices were observed, in part because of the unexpected range of abatement approaches used in the lead-up to trading, emissions sources chose to bank allowances in significant numbers and reassess abatement approaches going forward. In addition, commercially oriented inventive activity declined for emissions-reducing technologies with a wide range of costs and technical characteristics, dropping from peaks before the establishment of CTPs to nadirs a few years into trading. This finding is consistent with innovators deciding during trading that their research and development investments should be reduced, based on assessments of future market conditions under the relevant CTPs. The article concludes with a discussion of the results and their implications for innovation and climate policy.

climate change | emissions trading | technological change | invention | clean technology

Facilitating innovation in "clean" technologies may be the key to achieving climate change stabilization without dampening economic productivity. Theory and experience indicate, however, that the private sector—apt to be the most significant source of this innovation—will not reach its full innovative potential without well-considered public policies. The pollution market failure involved in greenhouse gas (GHG) emissions implies that the development of emissions-reducing technologies will have less private value than the societal optimum. The market failure associated with innovators' difficulty in fully appropriating returns to research and development (R&D) investments—because of imitation and spillover, for example—implies that private incentives to innovate in clean technologies will be suboptimal. Another drag on private sector innovation stems from the trouble that capital markets and firms regularly have in predicting the risks and rewards of R&D investments, which can have uncertain outcomes and lengthy payback periods. Finally, there are significant challenges involved in displacing existing "dirty" technologies, which benefit from cost and performance advantages that accrue through the use of a technology over time, as well as from network externalities and the human reluctance to abandon sunk costs.

Addressing the pollution market failure should spur demand for clean technology and related private sector innovation (see ref. 1 for an introduction to policies exerting a "demand-pull" on clean technology innovation). Emissions standards, taxes, and trading are relevant climate policy instruments that are currently in place or under consideration for use somewhere in the world.

Cap-and-trade programs (CTPs, a form of emissions trading) are the demand-pull climate policy instrument with the largest economic scope in the world today, primarily because of current implementation in the European Union Emissions Trading Scheme (EU-ETS) and the Regional Greenhouse Gas Initiative (RGGI) in the northeast and mid-Atlantic region of the United States. In addition, a number of significant economic areas (e.g., California, Australia, etc.) are also in the process of initiating CTPs. In the most basic form of CTP, policy-makers set a cap on the quantity of permissible emissions and distribute "allowances" to emissions sources that collectively sum to the cap. If sources can reduce emissions cheaply on a relative basis against sources with different marginal abatement costs, they can sell excess allowances at whatever price the market will bear. CTPs can vary significantly in operation, however, based on policy design approaches to: cap stringency, predictability, and adaptiveness; source coverage; enforcement and market oversight; allowance allocation; allowance price restrictions; intertemporal allowance transfer (e.g., the "banking" of excess allowances for future use by current polluters and the "borrowing" of allowances from the future for current compliance); and so forth. Additional complications arise from CTP interactions with existing energy and environmental policies and from the permeability of the boundaries of capped regions (e.g., reductions in a capped region can "leak" emissions into uncapped regions if polluting activities shift there, or policy-makers may decide to count emissions reductions in uncapped areas or economic sectors as "offsets" for unrealized emissions reductions within a capped region or sector). Although it is not yet clear how successful current CTPs for GHGs will be, past CTPs for the control of sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions from the heavily emitting electric power sector appear to have fulfilled the fundamental promise of the instrument, which is quantifiable pollution reductions achieved through a flexible approach to compliance that is politically acceptable and keeps societal costs low.

CTPs have several attributes that support clean technology innovation. CTPs define the potential payoffs for R&D investments by innovators through their allowance clearing prices, which set the bar for clean technology adoption by emissions sources (note that for many clean technologies, the main innovators are not the major emissions sources; see *SI Text, Technical Details*). CTPs also provide the policy stringency and timing predictability that case study research consistently points to as key to the support of innovation (2) through their typical design, which involves targets of increasing stringency implemented over multiyear phases. These attributes can manifest in other demand-pull instruments in different forms, however, and no emissions-reducing policy instrument is unambiguously superior in its incentives for innovation (3).

A unique aspect of CTPs is the variability of the price signal they provide, and it is not well understood what the effect of this

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is on the inherently uncertain innovation process. Allowance prices are unknown before trading begins and change as CTPs operate (the initial phases of Australia's CTP will be an exception). In addition, studies have noted that allowance prices are likely to drop when marginal abatement costs fall with technology adoption by a subset of early-mover emissions sources (e.g., refs. 3–5); as a result, later-moving emissions sources may face reduced incentives to adopt similar new technologies. The corollary for innovators is that early clean technology sales have the potential to cannibalize the later market, thereby reducing incentives for sustained R&D investments. This effect will presumably be either tempered or strengthened by the degree of credibility and relative stringency of future caps, as determined both directly by statute and indirectly through such details of trading operations as allowance banking and the use of offsets to meet compliance obligations (for more on innovation and long-term targets, see ref. 6).

This article employs empirical evidence to clarify our understanding of the relationship between CTPs and the innovation process. The next section discusses the rationale behind selecting certain CTPs, clean technologies, and aspects of the innovation process for study. The following section presents the results of a synthesis of new data and what reviews (e.g., refs. 7–10) have characterized as the small literature that assesses, ex post, the innovation response to CTPs. The article concludes with a discussion of the results and their implications for climate policy and innovation.

Background

Two CTPs were selected for this study. First was Title IV, the two-phase national CTP for SO_2 emissions in the United States that was initiated in the Clean Air Act Amendments (CAA) of 1990, with its second phase concluding at the end of 2010. Second was the Ozone Transport Commission NO_x Budget Program (the OTC CTP) and its virtually seamless replacement and expansion, the NO_x Budget Trading Program under the Environmental Protection Agency (EPA) NO_x State Implementation Plan (SIP) Call (the NBP CTP; the paired CTPs are collectively titled here the OTC/NBP). The OTC/NBP was a seasonal and regional CTP for NO_x emissions in the United States that was established in 1995, with trading beginning in 1999, the cross-program transition occurring in 2003, and the program effectively concluding in 2008. The *SI Text, Policy Context* contains a detailed treatment of the design and implementation of Title IV and the OTC/NBP, including a discussion of the legal and regulatory context that preceded and followed them, while the *SI Text, SO_2 and NO_x Emissions* details relevant reductions over time. Note that Title IV and the OTC/NBP are considered two of the world's most successful examples of the implementation of the CTP instrument, which makes understanding their connection to innovation of particular interest.

Studying Title IV and the OTC/NBP in this context has methodological advantages. Both CTPs have sufficiently long operations for empirical appraisal regarding the long-term, unpredictable phenomenon of innovation. The two CTPs control very different pollutants, which alleviates some of the concern about case overspecificity that can arise in empirical policy research. In addition, the two CTPs are generally comparable in terms of design to most GHG CTPs that are currently operating or preparing for trading (e.g., EU-ETS, RGGI, California), or have received serious legislative consideration, such as the CTP that passed one United States legislative chamber in June 2009. Their geographic scope is similar, for example, with the OTC/NBP affecting the same states as RGGI, as well as several others, and Title IV affecting the full United States, an economic area akin to that covered by the EU-ETS. Their primary sectoral scope is the same (coal-fired electric power plants). For allowance price uncertainty management, like most GHG CTPs, both CTPs rely on allowance banking (albeit with more restrictions under the OTC/NBP than Title IV) rather than *de jure* price ceilings and floors (Australia's first 3 y of flexible carbon pricing will be an exception). The two CTPs are not perfectly comparable with GHG CTPs, however. For example, they do not include a role for borrowing allowances from future years, nor do they have a role for offsets because of the nature of the pollutants they control. Furthermore, although GHG CTPs generally include at least a limited role for the auctioning of allowances—providing a price discovery mechanism, among other benefits—this was true of Title IV but not the OTC/NBP.

Like most CTPs, both Title IV and the OTC/NBP had relatively modest initial caps, established in advance of trading, which increased in stringency at set intervals over time, with applicability to a larger set of sources in later time periods. Title IV's trading phases were announced in 1990: Phase I, which operated in 1995–1999, applied a modest cap to 263 existing electric generating units; Phase II, which operated in 2000–2010, applied a cap equivalent to an emissions rate established in 1971 to about 2,500 existing units. The OTC/NBP's trading phases were more uncertain, however. As originally established in 1994, the OTC CTP had three phases. Phase I, which began on May 1, 1995, did not involve trading, but instead applied year-round, region-wide, "reasonably-available control technology" (RACT) emissions standards—first established for ozone nonattainment areas—to large stationary sources in the OTC region of the northeast and mid-Atlantic states. Phase II, which began on May 1, 1999, established a nine-state CTP in the OTC states during the summer ozone season of May to September, with trading allowed year-round. Phase III, which was supposed to begin on May 1, 2003, tightened earlier caps. Coincidental with the start of Phase III, however, the EPA established the NBP CTP, which superseded Phase III and expanded its scope to include non-OTC states (for which litigation delayed implementation).

Emissions sources could meet caps under Title IV, the OTC/NBP, and GHG CTPs using several approaches, including the purchase of allowances and the following abatement strategies:

Fuel modification: This strategy involves retaining the existing generation process, but switching to lower-emitting fuels. For SO_2 control, combusting coals that are either naturally lower-sulfur or "cleaned" of sulfur at preparation plants is a low-cost, effective way to achieve modest levels of abatement. For NO_x control, however, combusting lower-nitrogen coals has less benefit because it only impacts the oxidation of nitrogen in the fuel, rather than the reaction of molecular nitrogen and oxygen in the combustion air.

Combustion modification: This strategy involves altering the combustion process to achieve lower emissions. A prominent NO_x example is modifying combustion heat and oxygen to achieve modest levels of control at relatively low cost [e.g., low-NO_x burners (LNBs)]. For SO_2, sorbent injection, which operates on different principles, could be considered a similarly inexpensive, modestly effective, but less prominent control technology. Note that modification options that increase power plant efficiency may have abatement advantages that cut across carbon dioxide (CO_2), SO_2, and NO_x control.

Postcombustion control: This strategy involves controlling emissions after combustion, often with large, complex, expensive systems that provide high-performance emissions reduction. Postcombustion control technologies for SO_2, NO_x, and CO_2 include flue gas desulfurization (FGD), selective catalytic reduction (SCR), and carbon capture and storage, respectively. Note that carbon capture and storage is relatively immature and involves a more complex, uncertain system for managing captured pollutants than the other technologies.

Demand reduction: This strategy involves reducing utilization of high-emitting generation facilities, typically in exchange for increased adoption of other abatement strategies or energy-efficient technologies and practices. Relevant technologies are generally the same across all three pollutants.

Generation replacement: This strategy involves utilizing alternatives to coal combustion, including generation based on natural gas, renewables, and nuclear energy. Relevant technologies are generally the same across all three pollutants.

Four clean technologies that indicate the wide range of costs and performance encompassed by these abatement strategies were selected as the focus of this study: for SO_2 control, precombustion coal cleaning (*fuel modification*) and FGD (*postcombustion control*); and for NO_x control, LNBs (*combustion modification*) and SCR (*postcombustion control*). For each pollutant, the former "indicator technology" is comparatively low-cost and low-performance regarding abatement, and the latter is high-cost and high-performance (see *SI Text, Technical Details* for more context, including market, cost, and performance information). Each technology has specific application either to SO_2 or NO_x control, rather than to multiple pollutants, limiting independent policy variables that could have a discernible impact on innovation patterns. Note that indicator technologies were chosen for their relevance to abatement rather than to the support of CTP operations, unlike such technologies as continuous emissions monitors and databases that ease the administrative burden of CTPs on regulators (11, 12).

Empirical research on innovation focuses on activities that sometimes overlap, including: invention; commercial adoption and diffusion; and improvements that stem from experience with a technology, such as manufacture or operations (13, 14). The allowance prices observed during the trading phases of a CTP, which reflect the aggregate effect of abatement approaches to date, shape emissions source decisions to adopt clean technologies, as well as signal innovators about potential long-term payoffs to invention. Note that before allowance prices can be observed, however, emissions sources and innovators make early investments in clean technology adoption and invention, which can be crucial for long-term success, given the relevant lead times. In the build-up to CTP operations, these early investments are shaped by *expected* allowance prices, which analysts predict based on the price and pollution-reduction potential of available abatement strategies and the challenges anticipated in emissions cap compliance.

The following section of the article presents, for both Title IV and the OTC/NBP: (*i*) the revealed difference between expected and observed allowance prices; (*ii*) the mix of abatement strategies that allowed emissions reductions to occur at observed allowance prices, including the adoption of indicator technologies; and (*iii*) commercially-oriented inventive activity in the indicator technologies, as observed in patenting activity, which is the most prominent metric of inventive output in the literature. Note that policy eras are defined here as "traditional environmental regulation" (the period before the public decision to operate a CTP), "trading preparation" (the period between the decision to operate a CTP and the onset of trading), and "trading" (the period of trading operations).

Results

Expected vs. Observed Allowance Prices. Fig. 1 shows that expected allowance prices for Title IV and the OTC/NBP generally overestimated prices observed during trading. Fig. 1 is reminiscent of the findings in other studies that a priori overestimates of the compliance costs of environmental, health, safety, and energy efficiency regulation occur frequently (15, 16). Note that Fig. 1 ends just before legal uncertainty began to surround the initially designated successor program to both Title IV and the OTC/NBP, the Clean Air Interstate Rule (CAIR), in 2008 (see the *SI Text, Policy Context* for more information).

For Title IV, even the lowest bound of expected prices overestimated observed prices for 100% of Phase I and 85% of Phase II (prices entered and surpassed the expected price range only in 2005 and 2006, with the finalization of CAIR and early unease regarding the challenges of CAIR compliance; see *SI Text, Policy Context*). By the first year of trading in 1995, it was clear that allowance prices under Title IV would be lower than expected, but the benefits of tightening the cap on SO_2 emissions would be higher because of newly recognized health risks posed by fine particles linked to SO_2 and NO_x emissions (17, 20). The program did not change to reflect this, however. Note that allowance markets were initially autarkic under both Title IV and the OTC/NBP, but became liquid over time.

When allowance prices are lower than the present value of the expected future marginal cost of compliance with a CTP, emissions sources have an incentive to bank allowances or buy additional allowances. Of the allowances generated in Title IV's Phase I, 75% were banked for future use rather than traded (Title IV allowed unlimited banking) (17). The bank generated in Phase I was so large that it was predicted in the late 1990s (21) that emissions would be able to exceed the annual allowance allocation throughout Phase II (22). These predictions proved accurate for many years. The exception occurred when trading preparation for the successor to Title IV (CAIR) began to overlap with Title IV trading, and emissions sources began early compliance actions for CAIR, encouraged by its treatment of banked Title IV allowances. [In 2005–2009, Title IV banked allowances could enter CAIR on a 1:1 basis; this ratio was set to decline to 2:1 during CAIR's Phase 1 (to begin in 2010 for SO_2) and then 2.86:1 during Phase 2 (to begin in 2015 for both SO_2 and NO_x)] (23). The EPA expected sources to reduce emissions and bank excess allowances in 2005–2009 to such an extent that during CAIR trading, emissions would exceed caps through at least 2015.

For the OTC/NBP, even the lowest bound of expected prices established during trading preparation for the OTC CTP overestimated observed prices for 70% of the OTC CTP Phase II and 82% of the NBP CTP (prices entered and surpassed the expected price range primarily during spikes in 1999 and 2003, which have

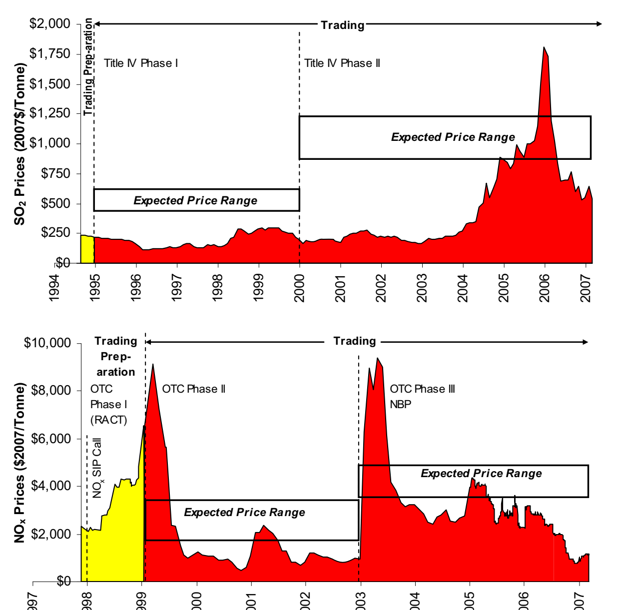

Fig. 1. The range of expected allowance prices compiled in refs. 17–19 versus observed allowance prices [see Cantor Fitzgerald (Various) Market Price Index, NY (www.cantorco2e.com)] for (*A*) Title IV and (*B*) the OTC/NBP. All prices are converted to 2007 dollars using Consumer Price Index monthly data in ref. 47.

been attributed to uncertainty regarding the advent of trading under Phase II and the transition to the NBP CTP, respectively). It is reasonable to believe that expected prices from 2003 onward would have further overestimated observed prices if analysts had known in advance of the OTC CTP that its Phase III would be superseded by the NBP CTP, and would therefore include an expanded set of states that did not start with as advanced a baseline level of NO_x control as the OTC states.

Meanwhile, allowance banking played a nontrivial role in the OTC/NBP, despite restrictions designed to minimize the chance that banked allowances might be used en masse in a given ozone season (e.g., during a hot summer) such that emissions would exceed budgeted levels. In the OTC CTP Phase II, banked allowances accounted for 20% of allowances after the first year, while in the NBP CTP they accounted for more than 10% in 2000–2003 and 2005–2007. Note that emissions never exceeded allowances during Phase II, and only did so during the NBP CTP in 2003 and 2005 (24, 25).

Adopted Abatement Strategies. For both Title IV and the OTC/NBP, an unanticipated mix of the abatement strategies of *fuel modification*, *combustion modification*, *postcombustion control*, *demand reduction*, and *generation replacement* facilitated successful compliance. This section reviews the role of these abatement strategies and highlights the contribution of the indicator technologies of precombustion control (which results in cleaned coals), LNB, FGD, and SCR. Note that the relevant technological changes reflect incremental improvements rather than radical breakthroughs, in accordance with theory (26).

Title IV. Two abatement strategies were particularly significant for SO_2 control during trading under Title IV. First, *fuel modification* accounted for about half of the emissions reductions achieved in Phase I (11, 27), largely because many emissions sources switched to naturally lower-sulfur coals (this low-capital and often cost-saving option had been important to SO_2 control in the early 1970s, before revised regulation made it impracticable; it became competitive again because of improvements in fuel blending and rail technologies that facilitated coal transport). Cleaned coals from precombustion control also played a role, with the number of operating coal preparation plants in the United States stabilizing in 1993–1997 during trading preparation and the early years of Phase I (*SI Text, Technical Details*), thereby interrupting a decline from 1982 peak levels.

Second, emissions sources balanced widespread *fuel modification* with the targeted use of *postcombustion control*, which provides high reductions at relatively high cost. Overall, however, less adoption of new FGD systems occurred during trading than had been expected during trading preparation, in part because emissions sources used FGD systems dating back to the 1970s to a greater extent than predicted (28, 29). This result disappointed the FGD industry, which had anticipated that the improved cost and performance of its systems (which emerged from technical advances made during traditional environmental regulation, particularly process chemistry developments that greatly increased system reliability; see refs. 30 and 31), would lead to higher demand for new systems under Title IV. Instead, demand for FGD systems grew during trading preparation, but declined during trading (*SI Text, Technical Details*). Furthermore, the lower-than-expected allowance prices observed during Phase I prompted cancellations of FGD orders on the order of 3,600 MW_e of planned capacity (32), which is equivalent to 19% of the FGD capacity brought online during Phase I; one cancellation even occurred after $35 million had been spent on construction (17). According to ref. 33, about one-third more FGD installations would have been adopted under a counterfactual traditional environmental regulation (i.e., a uniform emissions-rate standard) that was equivalent in its stringency to Title IV.

The other three abatement strategies played more limited roles in SO_2 control during trading under Title IV. *Generation replacement* occurred primarily because of an ongoing increase from the late 1980s in the proportion of natural gas-fired generation in the electric power sector, which had the effect of decreasing both SO_2 and NO_x emissions to some extent (*SI Text, Technical Details*). *Demand reduction* was facilitated primarily through reduced utilization of high-emitting generating facilities rather than the unsuccessful attempt to incentivize energy efficiency and renewable energy under Title IV (34). Finally, *combustion modification* occurred through the operation of sorbent injection systems by a few emissions sources.

OTC/NBP. Several abatement strategies made significant contributions to NO_x control during trading under the OTC/NBP. *Generation replacement/demand reduction* was unexpectedly important, with decreased utilization of high-emitting plants inside the capped region made possible via increased utilization of existing nuclear and natural gas-fired power plants, as well as the purchase of off-peak power from outside the capped region (25, 35).

Combustion modification also controlled NO_x emissions during trading, primarily via small-scale modifications (optimization) of existing equipment (ref. 36 estimates that this unexpectedly reduced power plant boiler emissions rates by 10–15%) and the utilization of LNBs, which performed better in the 1990s than had been expected (25, 35). Note that annual demand for new LNB installations in the United States actually declined during trading, however, in the continuation of a decline that began in 1994 (*SI Text, Technical Details*). The 1994 peak was the culmination of a demand surge that began just after the 1990 CAA addressed NO_x emissions by: (*i*) establishing a traditional environmental regulatory approach to NO_x emissions from existing sources for acid rain mitigation purposes (Phase 1 began in 1996, Phase 2 in 2000); (*ii*) requiring RACT standards (another traditional environmental regulatory approach) for nonattainment areas in State Implementation Plans and (*iii*) initiating the process that resulted in the 1994 agreement to establish the OTC CTP.

Meanwhile, demand for *postcombustion control* SCR units rose to previously unmatched heights during trading (*SI Text, Technical Details*), particularly in the non-OTC states preparing to participate in the NBP CTP in 2003. Three notes are pertinent to this rise in demand. First, the low pre-trading baseline SCR adoption rate reflects the fact that the United States did not claim that SCR was an acceptable technical basis for NO_x regulation of new sources until 1998, years after the technology had been adopted in Japan and Germany. Second, increased demand for SCR during trading did not require a corresponding decline in demand for LNBs because SCR and LNBs are not substitutes; rather, pairing the two can increase environmental effectiveness and lower costs (37). Third, the SCR demand observed during the OTC CTP Phase II was significantly lower than expected for the OTC states (17).

Finally, *fuel modification* was not a significant factor in NO_x control.

Commercially Oriented Inventive Activity. Investments in invention are bets that a given R&D direction will succeed economically in the future, when the time required for technical success has elapsed. The standard approach to empirical study of invention is to analyze technologies according to patenting activity, which is a gauge of inventive output directed toward sales in the nation issuing the patent; it is also a useful proxy for R&D expenditures, which are often difficult to obtain, particularly at a disaggregate level. The *SI Text, Technical Details* provides the particulars of constructing patent datasets for the four indicator technologies, including the approach to ensuring consistency, back-dating as close as possible to the moment of invention, and establishing the analytical frame (the patents selected were issued in the United States between January 1, 1975 and December 31, 2009, with original priority dates through December 31, 2004 and pendency periods of 20 quarters or less). The *SI Text, Technical Details* also addresses some of the potential limitations of patent analysis in this context, including issues of statistical power and appropriate counterfactuals.

Fig. 2 demonstrates that patenting activity in the four indicator technologies peaked during traditional environmental regulation and declined during trading to nadirs comparable to levels observed before the start of national SO_2 and NO_2 regulation in the United States in 1970 (38). This pattern holds across the indicator technologies, regardless of cost, performance, market trends, or unique history, and is consistent with innovators deciding during trading that their R&D investments are not worth sustaining or increasing, based on assessments of likely future market conditions under Title IV and the OTC/NBP. The *SI Text, Technical Details* upholds this pattern using different cuts of the data and considers—but dismisses—several alternative explanations, including: exogenous trends in United States patenting activity; changes in the underlying data with regard to patent classifications; a magnified influence of extranational policy events because of disproportionate representation of foreign innovators among the patent assignees; technological limits or maturity which might preclude future invention; and changes in the propensities of innovators to patent as a result of electricity sector deregulation. Note that the levels of patenting activity vary across technologies, with more complex technologies generally exhibiting higher levels of patenting. The precise timing of the observed patenting declines also varies somewhat (e.g., declines for FGD occurred throughout trading preparation and trading, declines for precombustion control and SCR occurred after a brief increase during trading preparation, and declines for LNBs occurred during trading, after increasing throughout trading preparation).

Discussion

Operating CTPs have prompted emissions sources to use a strategic mix of allowance purchases, allowance banking, and the abatement strategies of *fuel modification*, *combustion modification*, *postcombustion control*, *demand reduction*, and *generation replacement*. These CTPs have also generally had allowance prices that were lower than initially expected, according to the evidence presented here for Title IV and the OTC/NBP and elsewhere for the EU-ETS (39), RGGI (40), the United Kingdom's Emissions Trading Scheme for GHGs (41), and Southern California's REgional CLean Air Incentives Market (RECLAIM) for NO_x and SO_2 (42). Downward pressure on allowance prices is in keeping with the CTP instrument's strength in marshalling market dynamism in the service of emissions reductions. For example, it is the expected effect of encouraging a broad field of search for the adoption of abatement strategies that allow emissions sources to cost-effectively modify existing systems and practices (e.g., fuel blending advances for SO_2 control under Title IV, combustion optimization developments for NO_x control under the OTC/NBP, and so forth) Note, however, that for some CTPs, concerns have been raised about the relative role in lower-than-expected allowance prices of policy design factors such as cap stringency, allowance allocation, offsets, allowance banking, and leakage.

Regardless of the exact mix of contributory factors, the tendency to overestimate CTP allowance prices before trading—which is reminiscent of recurrent a priori overestimation of the compliance costs of traditional environmental, health, safety, and energy efficiency regulation (15, 16)—implies that early investments in clean technology adoption and invention will often turn out to be overvalued once trading begins. When this becomes clear to emissions sources and innovators, one logical effect should be reassessment of investment commitments. Supporting evidence for this has been documented in the case of SO_2 control under Title IV and for NO_x control under RECLAIM, when emissions sources chose to cancel significant in-progress clean technology installations (42, 43). Also consistent are the results above, that commercially oriented inventive

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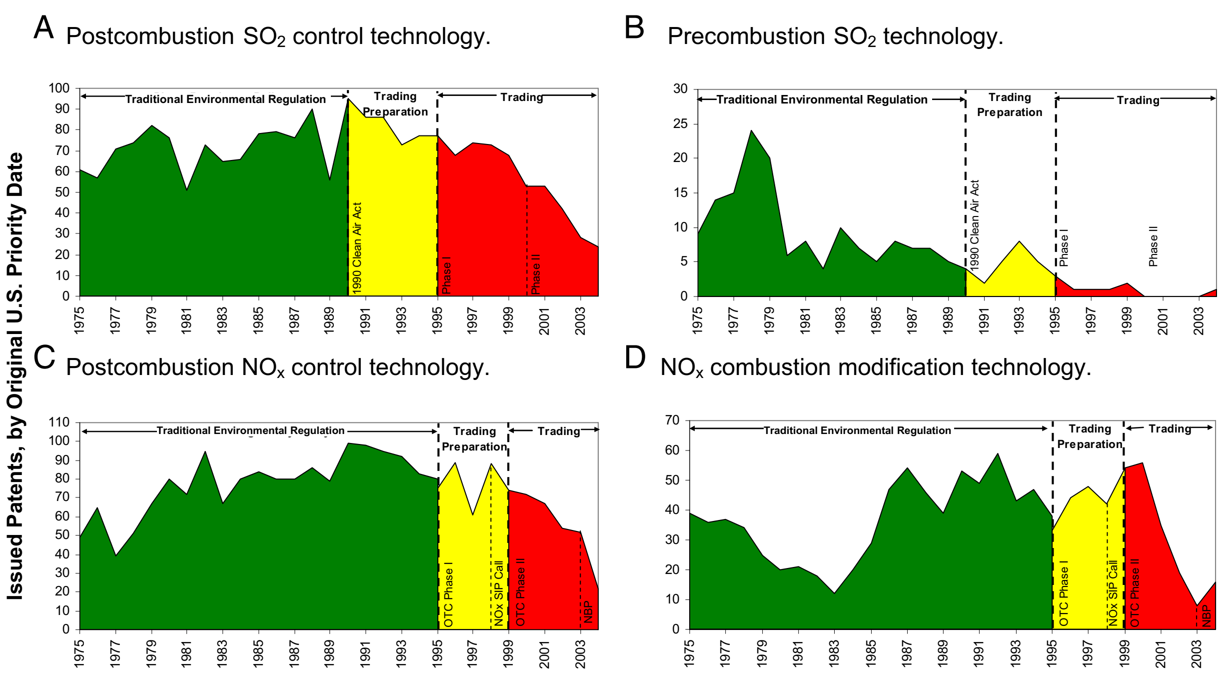

Fig. 2. (*A–D*) Patenting activity in the four indicator technologies in United States policy eras defined by traditional environmental regulation, trading preparation, and trading under Title IV and the OTC/NBP. The patents presented here were issued in the United States between January 1, 1975 and December 31, 2009, have pendency periods no greater than 20 quarters, and are depicted according to their original priority date.

activity declined during trading for SO_2 and NO_x indicator technologies of varying cost, performance, and market trends, dropping from peaks observed before the establishment of CTPs to depths a few years into trading. The implication is that CTPs do not inherently provide sustained incentives for private sector R&D investments in clean technologies, but may add to the uncertainty inherent in inventive activity. This effect is worth noting, given the likely importance for long-term climate stabilization of capturing the potential of R&D to create and improve clean technologies, as well as develop scientific personnel and organizational innovative capacity (44).

Allowance price-stabilization options (e.g., fixing prices in a predetermined range, per ref. 45, or modulating prices through an independent third-party market actor chartered to advance the public interest, and so forth) have been suggested as ways to limit the uncertainty of CTPs, including for innovators. These options are likely to pose trade-offs, however, particularly regarding the field of search for innovation, other elements of CTP design (e.g., the treatment of offsets and intertemporal allowance transfer), and complementary policy efforts with their own attributes of technology demand-pull and/or supply-push (e.g., emissions standards and public R&D support, respectively). The knowledge base necessary to characterize these trade-offs and inform climate policy efforts to incentivize the private sector to reach its innovative potential in clean technologies is still nascent, and is developing across a number of research traditions and methods (9). Synthesizing this knowledge and deepening its attention to strategic activities and behavioral issues within the "black box" of innovation (46) will aid global efforts to achieve the technological change necessary to avoid the worst impacts of climate change.

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