Title Page

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Title: Induced Technical Innovation under Cap-and-Trade Abatement Programs

Author Affiliation:
Richard and Rhoda Goldman School of Public Policy
University of California, Berkeley
2607 Hearst Avenue
Berkeley, CA USA 94720-7320

Corresponding Author:
Margaret Taylor
Richard and Rhoda Goldman School of Public Policy
University of California, Berkeley
2607 Hearst Avenue
Berkeley, CA USA 94720-7320
tel: 011-510-642-1048
fax: 011-510-643-9657
mataylor@berkeley.edu

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Abstract

Considerable technological innovation will be required if the world is going to achieve a 50 to 80% reduction in greenhouse gas (GHG) emissions at an affordable cost. Cap-and-trade programs (CTPs) for GHG reductions are being widely promoted as the key policy instrument for achieving such reductions and stimulating the needed innovation. This paper provides a critical review of the innovation effects of CTPs in the U.S. for SO_2 and NO_x that have been in operation long enough to allow serious evaluation of the amount of innovation they have stimulated. Three definitions of innovation are used. The first involves increased diffusion of existing technologies to meet SO_2 and NO_x caps. The presence of significant innovation is not supported by market data in the case of three of four dominant existing environmental technologies. A second definition involves increased inventive activity in existing technologies. In this case, patent data suggest little or no major innovation. A third definition, involving the diffusion of new technologies, is not supported by the "just enough" mix of older compliance approaches that was used in these CTPs. Both successful and over-allocated CTPs are characterized by lower-than-expected allowance prices compounding the uncertainty inherent in R&D investment decisions, which often involve long-term commitments with uncertain technical and financial outcomes. While CTPs that involve caps with clearly stated decreasing trajectories may be able to induce significant technical innovation in an economically efficient manner, data from the U.S. SO_2 and NO_x trading regimes do not provide empirical support for this outcome. It may be time to devote at lease some attention to a number of other, more direct policy options.

Introduction

Considerable technological invention and diffusion will be required if global emissions of greenhouse gases (GHGs) are to be reduced by as much as 80% so as to achieve climate stabilization. Large portions of global GHGs are emitted by key sectors of the economy; for example, electric power (24% of global emissions), transportation (14%), industry (14%), and agriculture (14%), when combined, contribute 66% of global emissions (1). Big reductions are ambitious, particularly when one considers the long operating life of many major individual emissions sources, such as power plants, and the rapid growth of new sources in the developing world, especially China.

Market failures related to both pollution and innovation decrease the likelihood that the private sector – a vital innovation source – will provide the necessary levels of "climate-safe" innovation without public intervention. A critical question, therefore, is how policy can best foster that innovation. Unfortunately, this question is largely unanswered by empirical scholarship on environmental innovation.

In the meantime, climate policy is rapidly evolving, and cap-and-trade programs (CTPs) are now widely cited by decision makers as the preferred policy tool for GHG mitigation. The European Union, Australia, over half of both the U.S. States and Canadian Provinces, and one Mexican State are either already operating CTPs for GHGs or are developing programs. In a CTP, policy-makers set a cap on emissions and then allocate (or auction) emission "allowances" to polluting sources that collectively sum to the cap. If sources can reduce emissions cheaply, they can then try to sell excess allowances at whatever price the market will bear. In a number of CTPs, they can also "bank" these allowances for later use. The primary economic case for the use of CTPs is one of static efficiency. Previous CTPs have demonstrated that the instrument is capable of facilitating pollution reductions to meet relatively short-run caps at low cost when technology or other strategies to control emissions exist. But there is another important factor driving the emerging dominance of CTPs in climate policy: the conventional wisdom that CTPs are better than other policy instruments in providing an "incentive for innovation" (e.g. 2).

In addition to being essential to meeting GHG reduction targets, innovation is attractive to political leaders because of the promise of low cost emissions reductions and ancillary economic benefits through new jobs in "clean technology" industries. Not all innovations fulfill both these promises, however. Incremental changes to existing systems may allow low cost emissions reductions, at least in the short run, but may not be the sort of innovation that Schumpeter described in his vision of capitalism, a creative and destructive force necessary for long-term economic growth (3).

A more pedestrian understanding of innovation is used in the theoretical economics literature that underpins the claim about the superiority of CTPs. In this usage, innovation is limited to a binary choice facing polluting firms between either retaining their existing technology or developing and using a new technology. Entrepreneurial firms that are not polluters themselves but may specialize (and generate jobs) in clean technology are not explicitly included in this schema. In work that dates back to 1970 (4), the economics literature compares and ranks instruments such as taxes, subsidies, CTPs, and traditional environmental regulation (TER) in terms of the incentives they provide to polluting firms. Following (5), these include: (1) savings in the direct cost of pollution abatement (examples are equipment expenses and operating costs); (2) savings related to transfer losses associated with abatement (i.e., payments made by the firm, such as emission taxes); and (3) gains related to payments made to the firm (examples include emission subsidies and patent royalties). Innovator costs are defined as the funds necessary to develop and implement the technology. A number of authors have pointed out several critical assumptions that underlie these models, including: innovator equivalence with the polluter; complete diffusion of the new technology across all the firms in the industry; perfect appropriability of innovator rewards; perfect competition; perfect information; and the characterization of TER as limits on total firm emissions, rather than the more frequently used limits on emissions per unit output or input. A consensus is now emerging from theoretical economic studies that if these assumptions are relaxed, CTPs may *not* be unambiguously superior to other policy instruments in incentivizing innovation (e.g., 6, 7-12).

Theoretical debates aside, climate policy stakeholders would benefit from better knowing the extent of empirical evidence in support of the claim that CTPs are superior in inducing technical innovation. This paper begins to fill an identified weakness in the literature (see 13, 14) by doing this.

We examine two U.S. CTPs that: (1) have operated since the 1990s, a long-enough period for evaluation on the innovation dimension; (2) either substituted for or supplemented a well-known base policy of TERs that helped to establish baseline technology trends; (3) share important elements with such climate CTPs as the European Union Emissions Trading Scheme (EU-ETS) and the U.S. Northeastern States' Regional Greenhouse Gas Initiative (RGGI), including a phased approach to cap implementation and the regulation of similar emissions sources; yet (4) vary by pollutant and by governance level so they are not necessarily tied to one set of technological, political, and economic circumstances. Table 1 summarizes the designs and pollution context of these two CTPs and provides some observations regarding their respective allowance markets (for more detail on these CTPs, see Supporting Information and 15, 16, and for more information on the TERs preceding these CTPs, see Supporting Information and 17, 18-20).

Table 1: Overview of CTP Pollution Context, Design, and Market Behavior

	Title IV	**OTC/NBP**
Scope	National	Regional
Pollutant	SO_2	NO_x
Largest Emissions Source Subject to CTP	Coal-fired power plants	Coal-fired power plants
Cap Implementation	Two phases	Multi-phase
Treatment of Banking	Unlimited	Restricted
Allowance Price Behavior	Lower than expected, with one large price spike	Lower than expected, with two large price spikes
Market Depth	Initially autarkic, now liquid	Initially autarkic, now liquid

"Title IV" is a national CTP for sulfur dioxide (SO_2) emissions that was initiated by the Clean Air Act Amendments (CAA) of 1990. Title IV has two phases, 1995-1999 (Phase I) and 2000-2010 (Phase II). Under Title IV, banking is unlimited. Seventy five percent of the allowances generated in Phase I were not traded but were banked for use in future compliance (21). The bank generated in Phase I was so large that sources have been able to emit more than the aggregate allocated annual allowances throughout Phase II (22), as predicted in the late 1990s (23).

The second CTP examined is the Ozone Transport Commission/NO_x Budget Program (OTC/NBP), a seasonal and regional CTP for nitrogen oxide (NO_x) emissions. OTC/NBP began with a Phase I on May 1, 1995, during which year-round, region-wide emissions limits based on "reasonably available control technology" (RACT) standards applied to large stationary sources in non-attainment areas in several Northeastern and Mid-Atlantic States that formed the Ozone Transport Commission (OTC). These RACT standards, which were established under the 1990 CAA, amounted to roughly a 40% NO_x reduction from 1990 levels (24). Phase II, which began May 1, 1999, and Phase III, which was supposed to begin on May 1, 2003, established a nine-state CTP during the "ozone season" of May through September, with trading allowed year-long. Coincidental with the start of Phase III, the EPA established another ozone season CTP, the "NO_x Budget Trading Program" (NBP), which superseded the OTC Phase III but also involved additional non-OTC states; this CTP allowed the affected states to meet the mandatory "NO_x SIP Call" reductions that EPA issued in 1998. Litigation, however, delayed its implementation for non-OTC states. Note that banking is restricted in the OTC/NBP in order to minimize the potential for banked allowances to be used to exceed budgeted emissions in a given ozone season. Emissions in the OTC did not exceed allowances (although the allowance bank was large, accounting for 20% of allowances after the first year). To date, emissions in the NBP have only exceeded allowances in 2003 and 2005 (25, 26).

In Figure 1, allowance price data for Title IV and the OTC/NBP are matched with published reports of the price ranges anticipated by analysts when those CTPs were first legislated (note that there is usually a lag between CTP legislation and operations during which price expectations are the only guide available to innovative actors). As in other figures in this paper, the data is plotted according to eras in time defined by: (1) TER; (2) "trading preparation," or the period between the legislation of a CTP and its operation as a trading market; and (3) trading. Figure 1 shows that in both CTPs, trading operations revealed generally lower-than-expected allowance prices (for more information on allowance market behavior and possible explanations for that behavior, see Supporting Information). This condition was also seen for most of the Regional Clean Air Incentives Market ("RECLAIM") in southern California, which began in 1994 and applies to both SO_2 and NO_x emissions, as well as during the recently completed pilot phase of the EU-ETS.

(a) Title IV (b) OTC/NBP

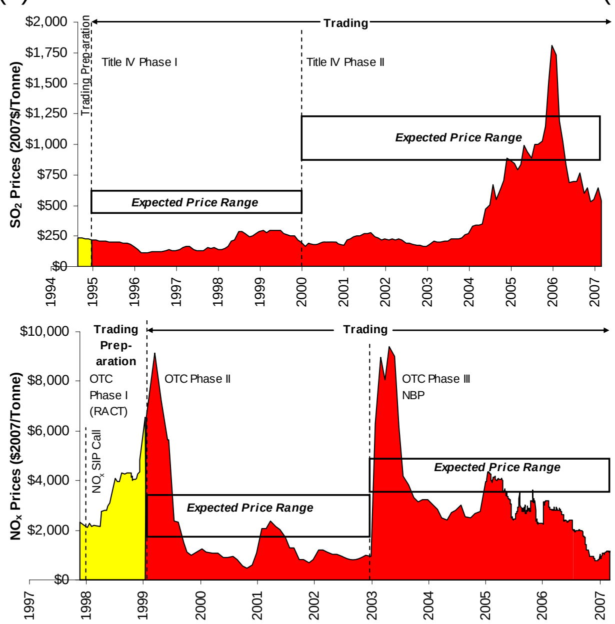

Figure 1: Actual allowance prices versus the range of expected allowance prices in August, 2007 dollars for (a) Title IV and (b) OTC/NBP. Actual prices are from (27), as compiled in (28) and (29), while expected prices are from (16, 21, 30). Conversion to August 2007 dollars used the Consumer Price Index (CPI) monthly data contained in (31). In cases in which only annual price estimates were available, conversion was done using the CPI from June of the relevant year.

The low allowance prices seen in RECLAIM and the EU-ETS have been explained by "over-allocation" of emissions allowances. For RECLAIM, allowance allocation was so much greater than actual emissions that most sources did not have to change operations in order to comply with the cap (32, 33). In fact, many polluters under RECLAIM cancelled initial control equipment orders in favor of purchasing cheap allowances (32, 33). The situation changed in May 2001 when regulators responded to a very large allowance price spike, attributed to the California electricity crisis, by removing power generators larger than 50 MW_e from the CTP and requiring them to install the control technology they would have been required to install about a decade earlier under TER. For the EU-ETS, unexpectedly low carbon dioxide (CO_2) allowance prices have resulted in delays in low-carbon investment decisions because of the risk of lower future prices (34).

In contrast, Title IV and the OTC/NBP are considered successful CTPs, with caps met at low cost. For example, Title IV is estimated to have achieved its first phase environmental goal at a 50% cost-savings for polluting sources, relative to traditional environmental regulation (35). But this static efficiency success is not necessarily an indicator of success in driving innovation. Operationally, innovation in this context could mean one or more of the following: (1) increased diffusion of existing technologies to combat SO_2 and NO_x emissions; (2) increased inventive activity with an eye toward improving such technologies either in current operation or in future generations of the technology; or (3) increased diffusion of new strategies to combat SO_2 and NO_x emissions. The results of measuring innovation relevant to Title IV and the OTC/NBP according to these three definitions are provided in the next section of the paper.

Results

Table 2 summarizes the primary strategies available for SO_2 and NO_x reduction, with a particular focus on strategies for coal-fired power plants, which are the primary source of SO_2 emissions and the primary stationary source of NO_x emissions in the U.S. The dominant SO_2 and NO_x reduction technologies – physical coal cleaning (which is primarily conducted in coal preparation plants), flue gas desulfurization (FGD), low-NO_x burners (LNB), and selective catalytic reduction (SCR) – are listed in Table 2, in addition to their typical commercial pollutant removal efficiencies and the costs they present to power plant managers, excluding operation and maintenance. The costs of these technologies are both a useful proxy for each technology's complexity and an important element of the decision that utility managers face between purchasing emissions allowances or installing proven technologies. SO_2 and NO_x reduction strategies omitted from Table 2 include: (1) shutting down (or reducing the utilization of) high-emitting power plants; (2) burning naturally lower-sulfur coals; (3) installing tall gas stacks to reduce acute exposure; and (4) utilizing intermittent controls in response to atmospheric conditions. Although these strategies have some claim to being a relevant technology strategy, options 3 and 4 are not viable today, given the broader scientific and legal understanding of the environmental effects of atmospheric SO_2 and NO_x, while options 1 and 2 involve much lower technological complexity than the entries in Table 2 and do not offer significant scope for innovation. For more on these technologies and those contained in Table 2, see (18, 19, 36).

Table 2: Technologies to Combat SO_2 and NO_x Emissions from Coal-Fired Power Plants (adapted from 37)

				Capital Cost	
Pollutant	**Reduction Strategy**	**Dominant Technology**	**% Removed**	**New ($/kW)**	**Retrofit ($/kW)**
SO_2	Pre-combustion	Physical coal cleaning (in preparation plants)	10-40	2.9-14.3$/kW, assuming 500 MW plant burns 1,430,000 tons coal/yr at 1-5$/ton coal	Same as new
	Post-combustion	Flue gas desulfurization (FGD)	90-99	70-150	100-150
NO_x	Combustion modification	Low-NO_x burners (LNB)	40-60	1-3	5-10
	Post-combustion	Selective catalytic reduction (SCR)	50-95	50-100	Same as new

Innovation as increased diffusion of existing technologies

This definition of innovation is perhaps easiest to operationalize, as market data provides a ready measure. Figure 2 depicts U.S. market data for the dominant technologies listed above for combating SO_2 (Figure 2a, b) and NO_x emissions (Figure 2c, d) from power plants, as defined either by the number of coal-fired boiler units installing FGD, LNB, or SCR technologies or by the number of preparation plants in operation in a given year. In three of the four technologies – preparation plants, FGD systems, and LNBs – the U.S. market conditions for the technology were more favorable in periods before active trading of emissions allowances began. Diffusion increased only for SCR during the trading period, primarily among non-OTC states that were erroneously anticipating high allowance prices under the NBP.

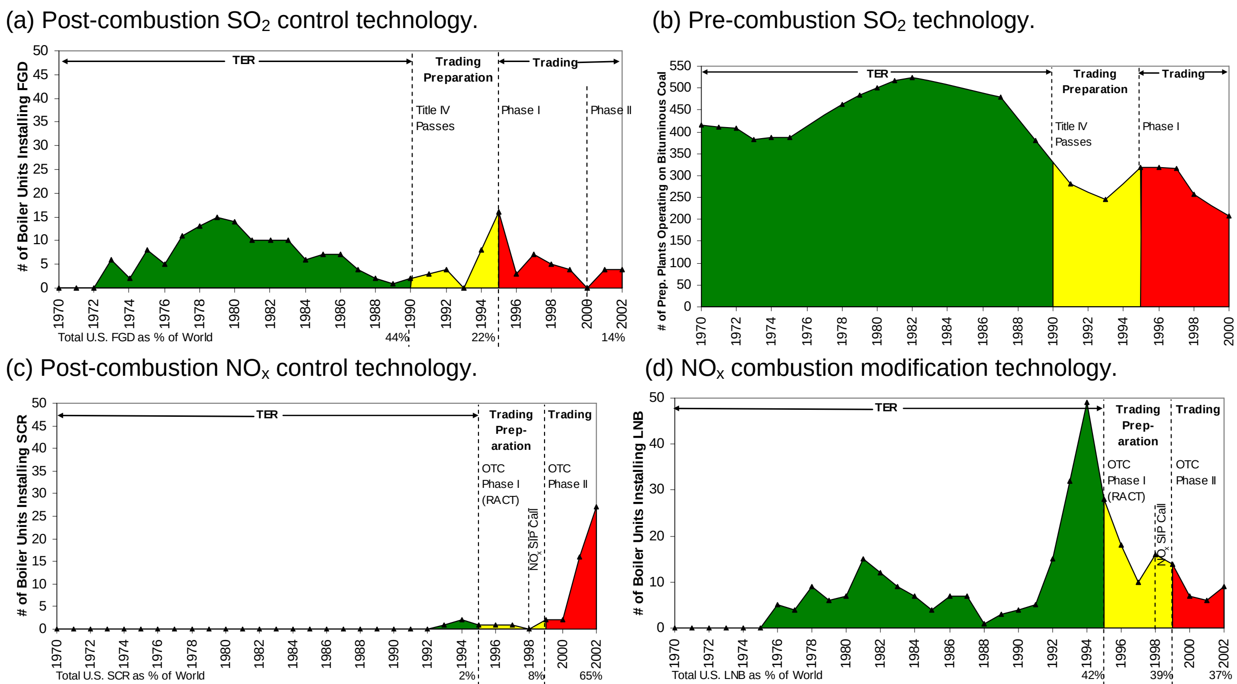

Figure 2: U.S. market data for key technologies for combating SO_2 and NO_x emissions from power plants. Figures 2a, c-d depict on the same scale the number of power plant boiler units installing a given technology, during the eras of TER, trading preparation, and trading, while Figure 2b depicts the number of preparation plants operating on bituminous coal, according to those same periods of time. For reasons of calibration, Figures 2a, c-d include U.S. market data as a percentage of the world market over time. Note that neither world market data nor a complete set of annual U.S. market data could be obtained for preparation plants. As a result, in Figure 2b actual data points are marked with a triangle while estimates are not (Preparation plant data from 38, 39-62, and FGD, LNB, and SCR data from 63, as updated through 2003).

In both CTPs, less control technology was employed than expected during trading, as befits situations in which most actual allowance prices were much lower than expected (21). The case of Title IV is particularly well-documented: published survey data show that lower-than-expected allowance prices resulted in cancellations of FGD orders by emissions sources on the order of 3,600 MW_e of planned capacity (64). This is equivalent to 19% of the FGD capacity brought online in the U.S. in Phase I. FGD cancellations even occurred in a case in which up to $35 million had already been spent on construction (21).

Innovation as increased invention in existing technologies, with commercial expectations

This definition of innovation can be operationalized using patent analysis, which is not only the most widely used technique in the literature to measure the output of inventive activity, but also provides a glimpse into the expectations about future markets for these technologies, as might be held by innovation management and strategy teams at innovator firms. Patents are required by law to publicly reveal the details of a completed invention that meets thresholds of novelty, usefulness, and non-obviousness. Studies have shown that patenting activity parallels R&D expenditures, which are often difficult to find at a disaggregated enough level for research purposes, and can also be linked to events that occur outside the firm. Surveys (65-67) demonstrate that 40–60% of the innovations detailed in patent applications are eventually used by firms. This indicates that patents are probably best thought of as a well-accepted intermediary outcome of inventive activity, one that is tied both to the input of R&D expenditures and to hopes of commercialization. See (68) for a review of the use of patent statistics as economic indicators, including some of their strengths and weaknesses.

Figure 3 presents patent counts for each of the dominant technologies laid out in Table 2; dataset construction details are provided in the Materials and Methods section and in the Supporting Information. Note that in all four sets of technologies, patenting levels reach their highest points in periods before active trading begins. More strikingly, instead of patenting activity increasing during trading, it noticeably *declines* for each technology during trading.

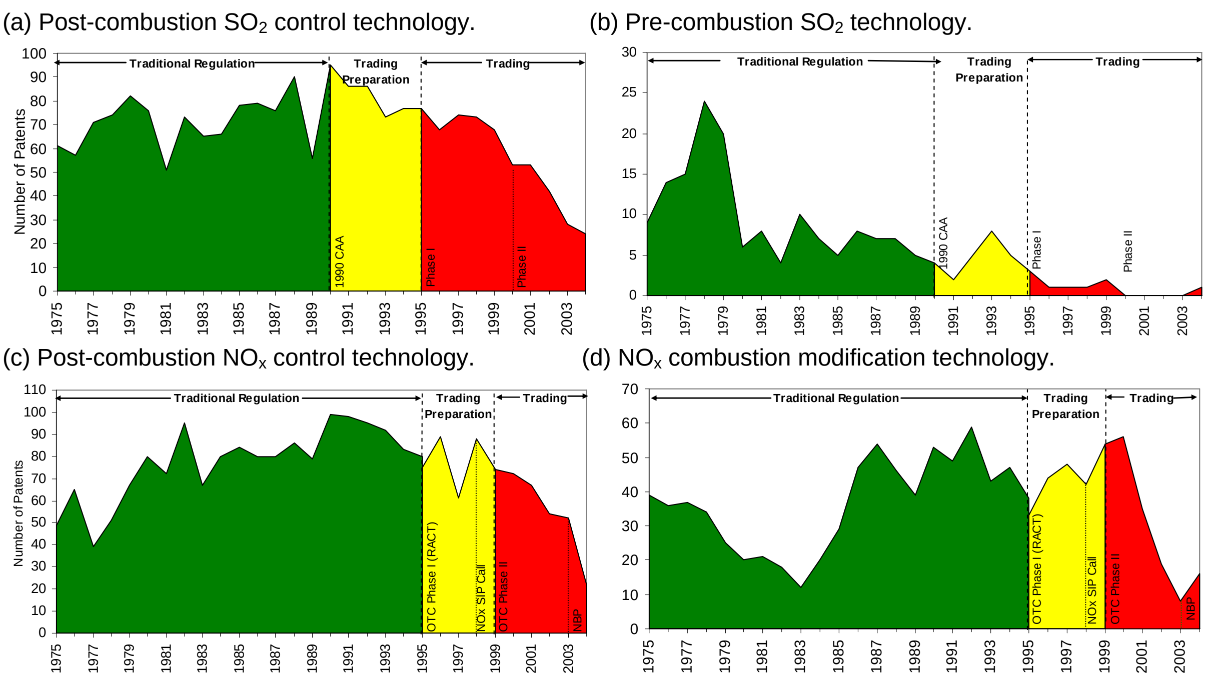

Figure 3: Patenting in SO_2 and NO_x emissions reduction technologies under Title IV (a-b) and OTC/NBP (c-d).

What can explain these trends? They cannot be explained by patent reclassifications, according to the USPTO Reclassification Alert Reports issued from October 1999 to June 2005. Nor can they readily be explained by trends in overall USPTO patent applications or issues in 1975-2004 (portrayed in the Supporting Information for this paper). It is also highly improbable that all four, widely varied technologies reached physical limits at about the same time beyond which innovation became impossible.

The simplest explanation of these patent declines is that fewer resources were invested in improving these technologies during the trading phases of Title IV and the OTC/NBP. Managers, in essence, may have decided that these technologies were "good enough" for market conditions for the foreseeable future, and diverted R&D funds away from these technologies accordingly. It follows that with this diversion of R&D funding would go experienced R&D workers with non-codifiable "tacit" knowledge (itself an important source of innovation) regarding these technologies. Future qualitative research should be done to verify this and consider its implications on the rate or direction of innovation.

Innovation as diffusion of new technologies or strategies

This definition of innovation is more difficult to operationalize, as it involves both identifying and assigning "newness" values to relevant technologies or strategies. Government compliance reports for the target CTPs provide valuable information on the approaches used to achieve emissions reductions; these approaches can reasonably be defined as the most significant technologies or strategies that occurred under this policy instrument. Academic research is a useful secondary source, particularly for the identification of more subtle developments that enabled these significant approaches.

There were two significant approaches to SO_2 emissions compliance with Title IV. First, a large number of power plants switched to coals with naturally lower amounts of sulfur, an approach pioneered in the early 1970s in response to the 1970 Clean Air Act Amendments and associated 1971 New Source Performance Standards. This approach, which is not capital intensive and involves relatively minor modifications to the power plant, is attributed with about half of the reductions in Phase I (69). Second, utilities balanced this widespread and inexpensive (indeed, for many facilities, cost-saving) fuel-switching approach, as necessary, with the more expensive and more effective FGD systems, either through the installation of a small number of new systems or through more extensive use of power plants previously outfitted with FGD systems (70, 71). In other words, Title IV compliance was achieved by approaching emissions reductions at the level of systems of power plants, but the most significant approaches cannot really be considered particularly new.

Government compliance reports attribute the major emissions reductions during the trading phases of the OTC/NBP to three main developments that similarly involve systems changes that are not particularly innovative. First, utilities utilized existing zero-emitting nuclear power plants and lower NO_x natural gas-fired power plants more extensively in the region. Second, utilities reportedly purchased off-peak power from outside the OTC region. Third, utilities benefited from better-than-expected performance from combustion modification technologies installed in response to the preparatory traditional environmental regulation phase of the OTC/NBP (24, 26).

Some academic research has focused on identifying the more subtle technical developments that enabled the significant emissions reduction approaches to compliance with Title IV (the OTC/NBP has not been as heavily studied, although a recent paper delves in more detail into the small-scale modifications to existing boilers that underlie the third of the above developments (72)). At least a few of the Title IV developments are relevant to the OTC/NBP as well, including organizational changes and information technology development, internal to the utilities, which allowed allowance trade management to occur at the level of firm strategy versus the level of environmental compliance (69). In addition, the diffusion of continuous emission monitors (CEMs) at power plants and more sophisticated databases have helped regulators cope efficiently with both CTPs. Specific to the significant strategies to reduce SO_2 emissions under Title IV have been several fuel-switching enabling technologies, including relatively simple, but effective, improvements in fuel blending and new rail technologies that assisted the increased transport of coal due to fuel switching (69). Relevant to FGD utilization have been improvements in design and materials (69), although the most significant improvements in FGD reliability and removal efficiencies occurred prior to Title IV (73).

Several of the more subtle enabling developments could be considered boundary-spanning, as they draw from innovations occurring in other technical areas such as information technology and material science. But the developments related to how one operates a CTP could be considered innovations "in excess" of what is needed, at base, to reduce emissions, while the fuel-switching and FGD changes are probably best considered as continuations of longer-term technological developments in existing technologies, rather than truly new approaches that were prompted by CTPs.

Discussion

None of the foregoing should be read as arguing that a CTP program with a clearly stated decreasing cap cannot induce technical innovation. However, the evidence from the U.S. Title IV and the OTC/NBP program, the two most successful operating CTPs in the world, also does not provide any empirical support for the argument that CTP is a superior policy instrument to induce innovation. Indeed, most of the development of the innovative technologies that were employed as part of the industry's efforts to meet the caps under these programs had previously been developed during a regime of more traditional environmental regulation.

Both Title IV and the OTC/NBP achieved emissions caps at low cost but with little innovation, if innovation is defined by any of three definitions. A first definition of innovation that involves increased diffusion of existing technologies to meet SO_2 and NO_x caps is not supported by market data in three of four dominant existing environmental technologies. A second definition of innovation that involves increased inventive activity in existing technologies is not supported by patent data in any major existing technology. And a third definition of innovation that involves the diffusion of new technologies is not supported by the "just enough" mix of approaches used to comply with Title IV and the OTC/NBP, including fuel-switching, shifting load to less-polluting or out of region plants, increased utilization of existing environmental technologies, as well as a generally more modest diffusion of existing technologies than historic levels.

Title IV and the OTC/NBP both experienced lower-than-expected allowance prices for most of their operations – as has also been the case with the over-allocated CTPs of RECLAIM and the EU-ETS climate CTP. In innovation terms, this is particularly problematic for any non-polluting innovators interested in marketing a compliance technology into a CTP, since that technology will not only have to compete for sales to polluting firms against a wide range of other compliance options under a CTP, but also against unpredictable allowance prices. This compounds the uncertainty inherent in R&D investment decisions, which already often involve long-term commitments with uncertain technical and financial outcomes.

Low allowance prices support the economic case for the use of CTPs as an environmental policy instrument to meet relatively short-term emissions targets at low cost when control strategies and technologies are available. But the fact that innovation does not seem to be a significant part of how low allowance prices came about in any of the world's four major existing CTPs raises several questions that are relevant to the policy goal of achieving a 50 to 80% reduction in GHG emissions by mid-century, a goal that is generally considered to necessitate innovation.

First, does the climate technology context somehow preclude low levels of innovation as a likely outcome of a properly allocated climate CTP? It could be argued that the SO_2 and NO_x control context is somehow unique because of the effectiveness of earlier TER – particularly performance-based standards in the U.S., Germany, and Japan – in supporting the development of the technologies that were useful in achieving the goals of Title IV and the OTC/NBP (as documented in 17, 19, 20, 73, among others). The counter-argument, however, is that climate technology options have also evolved under previous policy instruments such as targeted tax credits, energy efficiency standards, and renewable portfolio standards (RPS), even if not TER. Inexpensive and low-innovation options such as those that were successful under the OTC/NBP appear to be particularly relevant to a national CTP with modest CO_2 emissions or to a policy context dominated by regional CTPs.

Second, is innovation low in existing CTPs because of an inherent political economy issue with CTP design and implementation in the real world that would be relevant to climate CTPs, namely that caps are typically set (or allowances are distributed) at levels so loose that they do not require significant levels of innovation? One of the advantages of CTPs, after all, is its strength in terms of political economy. Title IV, for example, was able to overcome a political logjam on SO_2 emissions reductions that lasted throughout the 1980s, as Congress struggled to pass over 70 TER bills on the topic (17, 30). It did this by providing interested stakeholders with a means to exercise their institutional power in non-traditional ways, through negotiations on such things as extra allowances for specific interests rather than inspiring a general fight against the overall emissions cap (17).

Third, does it make sense in the climate context to support environmental innovation as its own policy goal, and if so, what is the best approach given the trend toward CTPs? After all, if emissions reductions occur in CTPs at low cost, why then worry about any innovation disincentives? The big concern is that policy-makers may lock in a set of emissions targets in CTP design today that are too weak to ensure climate safety, a concept that science appears to be rapidly redefining in alarming ways, as attested to in recent findings of an accelerating growth rate of atmospheric CO_2, faster-than-predicted ice melts, and growth in China's CO_2 emissions that is outpacing previous estimates (74-76). Sustained support of climate-focused innovation provides an important hedge against this, and as such, it should probably be a goal of climate policy. That support should apply to the R&D activities of both the public and the private sector, as the likelihood of finding innovative success is highest with the broadest set of searchers and the broadest field of search. Note that the private sector is a particularly important source of innovation, especially in the U.S. Of all the U.S. R&D expenditures tabulated by the National Science Foundation between 1953 and 2004, 57% was by industry without federal support, according to data in (77).

There are several options that policy-makers could take in support of this policy goal, although none is without flaws. First, climate CTP designs could be revised by focusing on a ratcheting process that is explicitly based on independent reviews of the state of climate science and emerging – not necessarily commercially demonstrated – technologies, or by increasing the predictability of allowance prices for non-polluting innovators through such options as allowance price floors. Second, a climate CTP could be coupled with significant public R&D investments in relatively expensive, high-potential technologies, although history teaches us that it is risky to count on sustaining high levels of public R&D funding over time because of budget exigencies and legislative fickleness.

Finally, it may be time to give greater attention to other more direct approaches. Possibilities include performance standards of the sort that California and Washington have introduced for new power plants (with a tightening limit over time), improved national energy efficiency standards, and "carbon portfolio standards" (with inter-firm trades allowed) for firms delivering electricity to customers (e.g. 78). Standards, after all, provide certainty relative to instruments like tax credits and R&D expenditures, but also create opportunities for environmental technologies to enter the marketplace and potentially capitalize on economies of scale and additional sources of post-commercial innovation.

Materials and Methods

The empirical evidence in this paper comes from government compliance reports, technology market data, published empirical studies, and patent data. The Supporting Information contains tables of the search terms used to put together the patent data; the data from these searches were first published in (19, 79-81). Only one patent dataset included in this paper relies on a non-reviewed dataset. This dataset, however, was used in (82). The Supporting Information also involves full details of patent dataset construction, including the approaches to: back-dating patents as close to the time of invention as possible, cleaning the data with regard to patent continuations, and coping with pending patents.

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