

## Supporting Information

### 1. Pre-CTP Regulation of SO<sub>2</sub> and NO<sub>x</sub> Emissions

#### SO<sub>2</sub>

The U.S. first regulated SO<sub>2</sub> emissions in the 1970 Clean Air Act Amendments (CAA), which directed the newly formed Environmental Protection Agency (EPA) to establish National Ambient Air Quality Standards (NAAQS) for several “criteria” air pollutants in order to protect public health and welfare without consideration of economic or technical feasibility. Each state had to develop a state implementation plan (SIP) for controlling *existing* stationary sources and submit it for EPA approval. SIPs were submitted in 1972, and almost all called for continuous reduction of SO<sub>2</sub> emissions, which in effect gave utilities the opportunity to use low sulfur fuels, pre-combustion treatment, or FGD systems to comply with the standards, rather than tall stacks or intermittent controls.

Meanwhile, major *new* sources (or significantly modified existing sources) of SO<sub>2</sub> were to be subject to New Source Performance Standards (NSPS) based on the agency’s determination of whether relevant SO<sub>2</sub> control technologies were adequately demonstrated for commercial use. In the case of SO<sub>2</sub> control, the EPA determined that FGD (“scrubber”) technologies developed in Japan were demonstrated enough to provide the technology basis for standard-setting. The 1971 NSPS set a maximum allowable emission rate of 1.2 lbs of SO<sub>2</sub>/MBtu heat input (2.2 kg/Gcal), a rate that effectively required 0-85% SO<sub>2</sub> removal, depending on coal properties. This standard was technologically flexible, as it could be met through the use of low sulfur fuels, pre-combustion treatment, and FGD systems. The 1979 NSPS for SO<sub>2</sub>, however, required a 70% reduction of potential SO<sub>2</sub> emissions from generation based on low sulfur coal and a 90% reduction of potential SO<sub>2</sub> emissions from high sulfur coal. This was not technologically flexible, as it essentially required that any new power plant operate a dry or wet scrubber, respectively, no matter the sulfur content of the fuel. Note that existing sources were not subject to this requirement (see 1 for more details).

More than 70 bills were unsuccessfully introduced in Congress to reduce SO<sub>2</sub> emissions from power plants after the 1979 NSPS before the passage of the 1990 CAA, which introduced the national CTP for SO<sub>2</sub> control in Title IV (2). One of the most important successes of Title IV was its ability to overcome the political logjam that had arisen on SO<sub>2</sub> emissions control in those years (3).

#### NO<sub>x</sub>

As in SO<sub>2</sub> regulation, the U.S. first began to regulate NO<sub>x</sub>-relevant emissions in the 1970 CAA, which identified NO<sub>2</sub> and O<sub>3</sub> as two criteria pollutants for which it set NAAQS. The role of NO<sub>x</sub> in ozone formation was not recognized until the mid-1980s, however, so most of the pre-CTP policy experience with NO<sub>x</sub> emissions relates to reducing NO<sub>2</sub> emissions. For the NAAQS NO<sub>x</sub>-relevant pollutants, the existing vs. new source dichotomy and NSPS revision timeline applied as it did in the SO<sub>2</sub> case, at least in the 1970s and 1980s. The EPA established NAAQS for criteria pollutants, required states to

submit SIPs for controlling emissions from existing sources, and created NSPSs based on the agency's determination of whether relevant control technologies were adequately demonstrated for commercial use.

In December, 1971, the NSPS for NO<sub>2</sub> was published, based, in part, on findings of an earlier report that noted that although many primary NO<sub>x</sub> controls had been proven commercially, mostly in California, SCR was a "speculative" control technique and should not be the technical basis of the NSPS (4). The 1971 NSPS set a limit of 0.7 pounds of NO<sub>2</sub> per million Btu (lbs/MBtu) heat input for coal-fired units and 0.2 lbs/MBtu for gas-fired units. In 1979, the NSPS was revised, and the limits shifted to 0.5 lbs/MBtu (bituminous coal) and 0.6 lbs/MBtu (sub-bituminous coal), with the NSPS for gas-fired units unchanged. This was not as strict a standard as was being met in Japan at the time; the successful contemporaneous Japanese SCR application to a coal-fired plant was not considered to be on a large enough unit to be a "proven" technology for the NSPS. If SCR had been accepted as an adequately demonstrated technology, the NO<sub>x</sub> emissions limit in 1979 could have been set as low as 0.034 lb/MBtu heat input (44 FR 33602). It took until 1998, after SCR had been installed worldwide in almost 70 GWe of coal-fired capacity (data from 5), that SCR was finally considered to be adequately demonstrated enough for the U.S. to allow it to serve as the NSPS technology basis (6). In that year, the federal NSPS was revised for utility boilers, requiring reductions on the order of 80% or more from new and modified sources.

Although there was considerable progress in achieving the NAAQS for SO<sub>2</sub> and NO<sub>2</sub> in the 1970s and 1980s, the U.S. had less success in achieving the NAAQS for O<sub>3</sub>. The 1990 CAA, therefore, focused on this problem, in part by recognizing the role of NO<sub>x</sub> as an important contributor to O<sub>3</sub> formation. It also addressed the role of NO<sub>x</sub> as a contributor to acid rain by introducing a two-phase, rate-based emissions reduction program. Continuing the tradition of distrusting the performance of the more expensive and effective post-combustion NO<sub>x</sub> control technologies employed internationally, the technical basis of the 1990 CAA was combustion modification techniques.

Finally, the 1990 CAA established an interstate organization – later known as the Ozone Transport Commission (OTC) – to recommend to the EPA Administrator the measures states in the OTC could take to attain the ozone NAAQS as a region. The OTC (until by-laws adopted in 1991, it was the Northeast Ozone Transport Commission) consisted of government leaders and environmental officials from the District of Columbia, the EPA, and twelve states: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia. In addition to its policy recommending duty, it was charged with assessing the degree of interstate transport of ozone and its precursors in the northeast. The work of the OTC led to a multi-state CTP for NO<sub>x</sub> control in the late 1990s in the OTC area.

## **2. CTPs for SO<sub>2</sub> and NO<sub>x</sub> Emissions Control**

### *Title IV*

Title IV of the 1990 CAA established a two-phase CTP program for SO<sub>2</sub> emissions control. Phase I (1995-1999) applied a modest aggregate emission limit to 263 existing “Table A” generating units from 110 power plants that had been “grandfathered” out of the NSPS. Firms could also voluntarily enroll additional “compensation and substitution” generating units in Phase I. The “substitution” provision was intended to enable owners of Table A units to substitute less costly emission reductions from other units for reductions from the Table A units. The “compensation” provision was designed to prevent owners of Table A units from meeting their emission reduction obligations simply by reducing generation from those particular units and increasing generation from other units. Although these provisions were “much more heavily used than had been anticipated,” the Table A units accounted for at least 95% of the emission reductions in both 1995 and 1996 (7).

Phase II (2000-10) applies the maximum allowable emission rate established in the 1971 NSPS, in aggregate, to about 2,500 existing units, or all fossil-fueled power plants larger than 25 MWe. The 2010 cap was set at 8.95 million annual tons (8.06 million annual tonnes) of SO<sub>2</sub>. A unit’s compliance is judged annually in a “truing-up” period when sources have to be able to demonstrate sufficient allowances to cover emissions. Penalties are based on a 1990 fine of \$2,000 per ton (\$2,197 per tonne) of SO<sub>2</sub> above allowance levels, adjusted for inflation (e.g., \$3,042 per excess ton, or \$3,343 per excess tonne, by 2005) (8).

The main supply of allowances for each source is the annual allocation made by the EPA, based on the product of the phased emission rate and a baseline heat input (9). For Table A units in Phase I, the baseline heat input was generally the 1985-87 average. For Phase II, the emissions rate was the lower of either the 1985 actual emissions rate or 1.2 lb/MBtu (2.2 kg/Gcal), converted to tons. There are also several additional supply streams. First, there is a small annual allowance auction designed to help new entrants; between 1995 and 2002, this accounted for between 1.7% and 2.6% of the total amount of allocated rights per year (10). Second, there is a small pool of opt-in allowances provided to units entering the program voluntarily (for example, eight units opted in during 2005 (8)). Third, there is a complex series of “bonus” allowances (9, 11).

Banking in Title IV is unlimited, and 75% of the allowances generated in Phase I were banked for use in future compliance, regardless of phase, rather than traded (11). 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 (8), as predicted in the late 1990s (12).

### *OTC/NBP*

In 1994, the OTC agreed to a Memorandum of Understanding (MOU) which established a three-phase program for reducing NO<sub>x</sub> emissions from large combustion sources. Phase I, which began on May 1, 1995, applied year-round, region-wide emissions limits based on “reasonably available control technology” (RACT) standards for large stationary sources in O<sub>3</sub> non-attainment areas; this amounted to roughly a 40% NO<sub>x</sub> reduction from 1990 levels.

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 (Maine, Vermont, and Virginia did not join the OTC trading program). Coincidental with the start of Phase III, the EPA established another ozone season CTP, the “NO<sub>x</sub> Budget Trading Program,” which superseded the OTC Phase III but also involved additional non-OTC states; this CTP allowed the affected states to meet the mandatory “NO<sub>x</sub> SIP Call” reductions that EPA issued in 1998 (New Hampshire is not subject to the requirements of the NO<sub>x</sub> SIP Call). Litigation, however, delayed its implementation for non-OTC states. As a result, the non-OTC states of Alabama, Illinois, Indiana, Kentucky, Michigan, North Carolina, Ohio, South Carolina, Tennessee, Virginia, and West Virginia began the first compliance period on May 31, 2004. As of the writing of (13), affected parts of Missouri were required to comply with the NO<sub>x</sub> SIP Call by May 1, 2007. EPA had stayed the requirements for Georgia pending determination on a petition to reconsider Georgia’s inclusion in the SIP Call. The NBP will be superceded in 2009 by the Clean Air Interstate Rule.

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), and so far, emissions in the NBP have only exceeded allowances in two years: 2003 and 2005 (14, 15). The NBP uses a system called “progressive flow control” to restrict banking. In this system, once the allowance bank becomes larger than 10% of the emissions budget in a given year, if a source wants to use banked allowances for compliance, only a portion of that source’s allowances can be redeemed on the basis of one allowance for each ton of emissions. The rest are redeemed on the basis of two banked allowances for each ton of emissions. The portion of banked allowances subject to the 2:1 requirement is set annually by the EPA, based on the amount by which the total bank exceeds the 10% threshold. Flow control has applied in 2000-03 and 2005-07.

To cope with the transition from the OTC to the NBP, all OTC allowances were officially retired, although the EPA created a small “compliance supplement pool” (CSP) of allowances for the NBP that most OTC states apportioned in exchange for banked OTC allowances. There were a few exceptions: no 1999 vintage allowances were eligible for the CSP; Pennsylvania additionally excluded 2000 vintage allowances; and Maryland apportioned allowances according to an emissions-based formula instead of according to banked allowances (16).

### **3. Allowance Market Behavior**

#### *Title IV*

In early 1992, the EPA announced Title IV allowance allocations and made it possible for firms to trade and to obtain allowances via a small annual auction held in March 1993 and 1994. The prices revealed in these auctions were considerably lower than the price estimates for Phase I, and were accurate, if initially disbelieved, predictors of the low, true Phase I allowance prices (11). These price expectations and true prices are depicted

in Figure 1 in the main article, which uses price estimates published in (2, 11, 17), converted to August 2007 dollars using the Consumer Price Index (CPI) monthly data contained in (18). In cases in which only annual price estimates were available, the CPI from June of the relevant year was used for the conversion. Figure 1 also uses true allowance prices from (19), as compiled in (20) and (21), then converted to August 2007 dollars.

True allowance prices stayed much lower than expected until the start of 2004, when they increased rapidly until they peaked in December, 2005, returning to lower-than-expected levels in September 2006. Observers believe that this price run-up occurred due to uncertainty about the final details of the Clean Air Interstate Rule (CAIR), which requires further SO<sub>2</sub> reductions from sources in many eastern states beginning in 2010 (8).

Analysts believe that two main things have been behind the lower-than-expected prices of the majority of Title IV allowances. First, substantial emission reductions were made before Phase I and in the early years of the program, when the high price expectations dominated decision-making on compliance options that either required significant lead times, like scrubbers, or involved long-term coal contracts. Second, 75% of the allowances generated through Phase I were banked for use in future compliance, regardless of phase, rather than traded (11). 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 (8, 12). In effect, the banked allowances have acted to keep the price of allowances low by increasing the supply of allowances available in a given year.

In terms of market depth, the initial firm reaction to Title IV was autarkic, as firms perceived the market to be a program to comply with, not an opportunity for economic gain (22). Title IV is now considered to be a liquid market.

### *OTC/NBP*

Figure 1 in the main paper also presents price expectations and true prices in the OTC/NBP. Although the majority of true allowance prices in the OTC/NBP were below estimates, two price spikes occurred in the OTC/NBP, one in mid-1998 to mid-1999, and the second in the first half of 2003. According to interviews reported in (17), the earlier spike occurred because, near the end of 1998, market participants thought that regulated firms had not installed enough control technology to meet the cap. This resulted in a shortage of allowances and higher prices. Prices dropped when plants in Massachusetts, New Hampshire, New Jersey, and Pennsylvania quickly installed control technology, early reduction allowances began to enter the market, and litigation and a consent order delayed the entry of several Maryland sources into the market. The latter price spike is attributed in (17) to two things: (1) regulatory uncertainty stemming from “expectations and court-issued complications” to the program due to litigation by newly regulated firms under the NO<sub>x</sub> SIP Call; and (2) the desire of some sources to purchase allowances because they were uncertain about the performance of control technologies.

In terms of market depth, the initial firm reaction to the OTC trading phase was autarkic (17). The NBP is now considered to be a liquid market.

#### 4. Patent Data

##### *Patent Data-Set Construction*

Table 1 and Table 2 display the patent classes and definitions used in generating Figure 3 in the main article. The Delphion commercial patent database generated the data, which consist of patents issued through September 30, 2007.

**Table 1: USPTO classes (USPC) and subclasses that compose the SO<sub>2</sub> datasets.**

<b>USPC Class/ Subclasses</b>	<b>Definition of USPC Class/Subclasses</b>
423/242.1-244.11	Class 423, the “chemistry of inorganic compounds,” includes these subclasses representing the modification or removal of sulfur or sulfur-containing components of a normally gaseous mixture.
095/137	Class 095, “gas separation processes,” includes this subclass representing the solid sorption of sulfur dioxide or sulfur trioxide.
110/345	Class 110, “furnaces,” includes this subclass representing processes to treat fuel combustion exhaust gases, for example, in order to control pollution.
44/622-5*	Class 044, “fuel and related compositions,” includes these subclasses to treat coal or a product thereof in order to remove “undesirable” sulfur.

**Table 2: USPTO classes (USPC) and subclasses that compose the NO<sub>x</sub> datasets.**

<b>USPC Class/ Subclasses</b>	<b>Definition of USPC Class/Subclasses</b>
423/235, 239.1	Class 423, the “chemistry of inorganic compounds,” includes these subclasses representing (235) the modification or removal of nitrogen or nitrogenous components of a normally gaseous mixture, (239.1) including through use of a solid sorbent, catalyst, or reactant
122/4D	Class 122, “liquid heaters and vaporizers,” includes this subclass for miscellaneous boilers and boiler parts that are not otherwise classifiable.
110/345, 347	Class 110, “furnaces,” includes these subclasses representing (345) processes to treat combustion exhaust gases, for example, in order to control pollution and (347) processes related to the burning of pulverized fuel
431/4, 8-10	Class 431, “combustion” includes these subclasses representing a combustion process or burner operation that includes (4) feeding an additive to a flame in order to give it a special characteristic; (8) flame shaping or distributing components in a combustion zone; (9) whirling, recycling, or reversing flow in an enclosed flame zone; (10) supplying a distinct stream of an oxidizer to a region of incomplete combustion.

##### *Continuation Correction*

To use patents as a proxy for inventive activity, it is necessary to back-date an issued patent as close to the time of invention as possible; this has traditionally been done by using the application date on a patent’s front page. Recent evidence concerning the prominence in the overall USPTO dataset of “continuing” patent applications, or one of several different types of patent applications that cover new improvements or different aspects of an initial patent application but receive new application dates when filed, highlights the need to back-date issued patents to the initial patent application date, or the “Original U.S. Priority Date” (see 23). Approximately 22.7% of all USPTO patents are

continuing patent applications (according to 1975-2001 data in 23), while 29.9% of patents in the combined SO<sub>2</sub> datasets and 26.8% of patents in the combined NO<sub>x</sub> datasets are continuations. In order to correct for this problem, the datasets in Figure 3 in the main article use Original U.S. Priority Dates determined via two datasets: (23), for patents issued between 1/1/1975 and 12/31/2004, and Delphion for the rest.

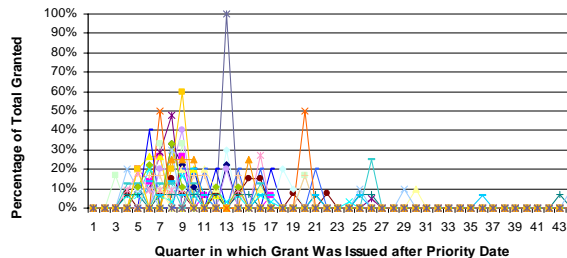
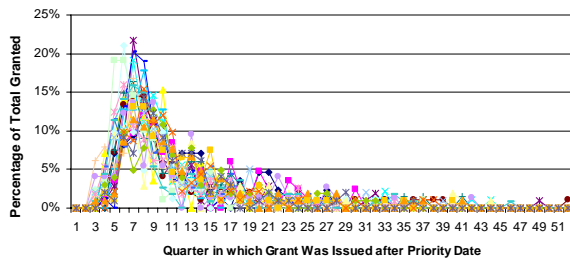
### *Pendency Correction*

The American Inventors Protection Act (AIPA) of 1999 requires publication – after the expiration of an eighteen-month period – of patent applications filed on or after November 29, 2000, unless an applicant requests that the invention not be published because it will not be filed in a foreign country in which inventions are subject to publication eighteen months after filing, as occurs under the Patent Cooperation Treaty. As a result, if a patent in the SO<sub>2</sub> or NO<sub>x</sub> datasets was filed either before the AIPA, or after the AIPA but only in the U.S., it will not be published until it is issued. This creates a problem for any study interested in analyzing relatively recent years of patent activity, as an undetermined number of patents may be pending publication at the time of study, and will therefore be unobservable. This situation is particularly likely to occur in the case of energy equipment suppliers; because of long-standing national security concerns regarding the electricity sector (true in many countries), these firms are typically in closed, long-standing relationships with domestic energy providers and have a greater reason to file patents domestically, rather than in foreign countries (3).

This creates a problem for any study interested in analyzing relatively recent years of patent activity, as an undetermined number of patents may be pending publication at the time of study, and will therefore be unobservable. But this situation is particularly likely to occur in the case of energy equipment suppliers; because of long-standing national security concerns regarding the electricity sector (true in many countries), these firms are typically in closed, long-standing relationships with domestic energy providers and have a greater reason to file patents domestically, rather than in foreign countries (3). In order to characterize the potential problem, pendency lag distributions – determined on a quarterly basis – were generated for each year, based on the Original U.S. Priority Date of each patent in the SO<sub>2</sub> and NO<sub>x</sub> technology dataset and the number of days it took each patent to be issued. Figure 1 portrays pendency lag distributions by the year of the Original U.S. Priority Date (priority year) for the four technology datasets as of September 30, 2007. Note that between 1975 and 1997, over 70% of the priority years have patents with pendency lags of more than five years, while approximately 10% of the priority years have patents with pendency lags up to 10 years.

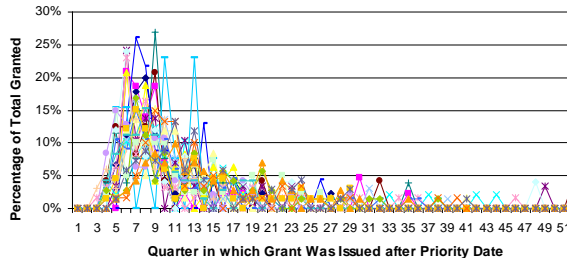
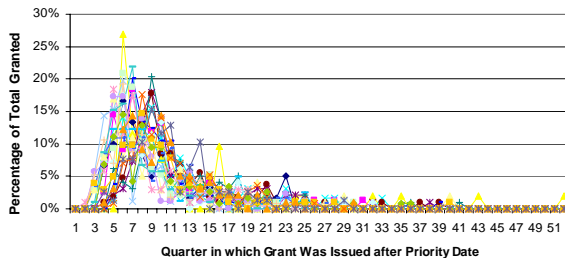
**Figure 1: Pendency lag distributions for the four patent datasets**

- (a) Post-combustion SO<sub>2</sub> control technology.                      (b) Pre-combustion SO<sub>2</sub> technology.

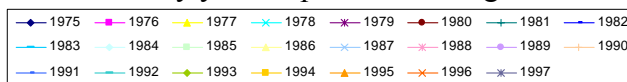


(c) Post-combustion NO<sub>x</sub> control technology.

(d) NO<sub>x</sub> combustion modification technology.



Priority years represented in figure:



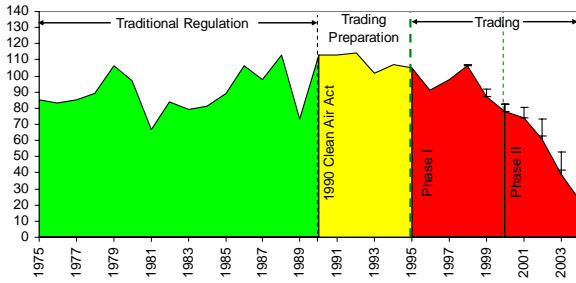
Although ideally, the pendency lag distribution of a combined set of priority years not subject to the non-publication bias could be applied to correct the patent counts in priority years likely to be affected by that bias, a Kolmogorov-Smirnov test revealed that the relevant cumulative distribution functions (cdfs) were statistically dissimilar, for indeterminate reasons. Instead, several patent trends were created for each technology dataset using sub-sets of the data that excluded all patents with pendency lags greater than  $x$  number of quarters, with  $x$  equivalent to the number of quarters between the end of the last year in the trend and March 31, 2008. Figure 3 in the main article uses thirteen quarters for  $x$ , for a trend ending in 2004. In cdfs of the four technology datasets, thirteen quarters captured 76.3% of the SO<sub>2</sub> post-combustion patents, 76.8% of the SO<sub>2</sub> pre-combustion patents, 82.4% of the NO<sub>x</sub> post-combustion patents, and 73.4% of the NO<sub>x</sub> combustion modification patents. The trends portrayed here are extremely similar to those of the full set of published patents.

An alternative way to display the patent data that excludes no patents is contained in Figure 2. In this figure, maximum and minimum error bars are displayed on recent years of the series, based on the distribution of pendency lags between Original U.S. Priority Dates and issue dates endogenous to each technology dataset. This “error-bar” display method is very conservative, providing the range of potential additions to later years of the series, but not the likelihood of that range. It is also potentially confusing, as in very recent years, it requires the use of two positive error bars. Note that the correlations between (Fig. 1 a-d) and (Fig. S3 a-d) are highly significant ( $p < 0.01$ ) for each technology set, with  $R^2$  values  $\geq 0.8$ .

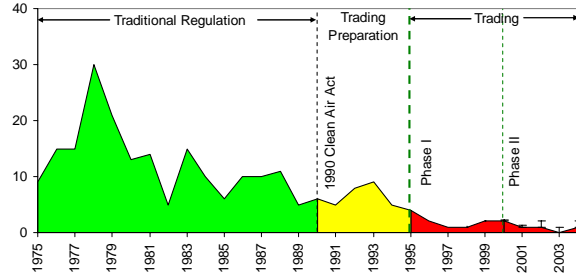


**Figure 2: Full data with error bars for the four patent datasets.**

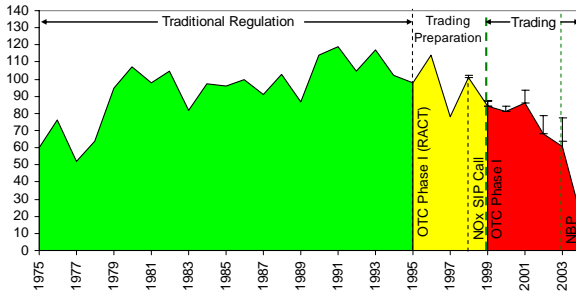
(a) Post-combustion SO<sub>2</sub> control technology.



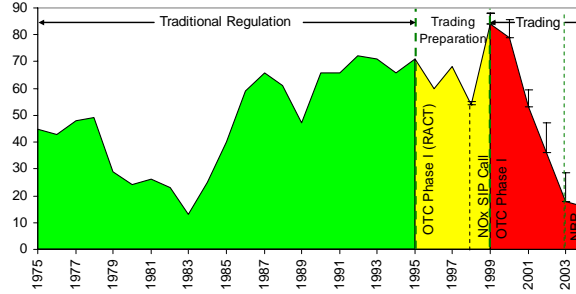
(b) Pre-combustion SO<sub>2</sub> technology.



(c) Post-combustion NO<sub>x</sub> control technology.



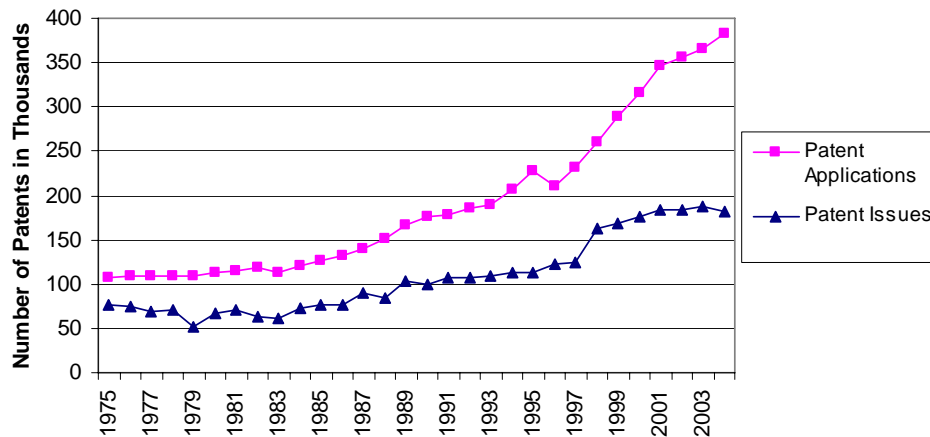
(d) NO<sub>x</sub> combustion modification technology.



### Check against Overall USPTO Patent Trends

Figure 3 shows total USPTO patent applications and issues between 1975-2004, the years covered by patenting activity in Figure 3 in the main article (24). The SO<sub>2</sub> and NO<sub>x</sub> technology trends during the trading phases of Title IV and OTC/NBP do not correlate with the trends in Figure 3 in the main article.

**Figure 3: Total patent applications and issues in the USPTO, 1975-2004.**



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