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A Historic Review of the Environmental Protection Agency's Market Readiness Projections of Compliance Technologies

Overview

The U.S. Environmental Protection Agency (EPA) has relied on its assessment of emerging abatement technologies as a central element in its setting of emission reduction regulations during the past 50 plus years to provide public health protection. Since 1970, when EPA was established, the agency has considered and promulgated emission standards that required the use of abatement technologies and, in some cases, cleaner fuels. This analysis provides an overview of past regulatory action where EPA set an emission standard that relied on a nascent control technology that had limited use but had the potential for delivering significant emission reductions.

Using real-world examples allows for a retrospective analysis to show the approaches industry deployed to comply with EPA emission standards. The technical strategies used by industry to comply with emission standards have included a combination of EPA projected emission control technologies, new innovative technologies developed by industry, and operational efficiencies. EPA has also typically provided sufficient lead time prior to compliance deadlines to allow emission control technologies to mature, for the market to supply materials, and for the integration of controls on the various regulated sources. The four examples highlighted in this analysis demonstrate that EPA's control technology projections have been realistic or, in a few cases, control technologies that were not on EPA's radar emerged that permitted industry to comply more cost effectively.

Many of the Clean Air Act (CAA) provisions require EPA to set pollution limits based on emission performance data and the cost of available emission control technologies, thereby considers technical feasibility, as well as cost. Note, this analysis does not attempt to address whether EPA's cost estimates were accurate but, rather, if technologies included in proposed regulations would be sufficiently market ready by the time compliance needed to be achieved. For example, New Source Performance Standards (NSPS) for fossil fuel-fired generators are based on emission performance data from available control technologies that have been adequately demonstrated. Under Section 112 of the CAA, the Mercury and Air Toxic Standards (MATS) is based on the performance of the top 12% of similar sources.

While EPA is required to consider technology feasibility, costs, and industry feedback in its rule makings, acceptance by industry and other stakeholders is not assured. For each rule making, EPA solicits input from all stakeholders, including from the affected industry, in meetings and through the public comment process prior to issuing a final regulation. Industry concerns with proposed regulations commonly include that the required control technology is not sufficiently mature to comply with the proposed standards, compliance deadlines may be unrealistic, the rule may lead to electricity reliability issues, and compliance costs may be economically burdensome for both businesses and consumers. EPA has always had the challenge of assessing these concerns and making technical judgements in the process of making regulatory decisions.

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This analysis highlights four examples of EPA emission standards for both fossil fuel-fired power plant and vehicle emissions where EPA technology projections were questioned by industry, but actual outcomes show that industry was able to effectively deploy the technology EPA anticipated or complied by using new innovative technology that emerged in the marketplace. Once EPA has issued a final rule, regulatory certainty emerges in the marketplace, allowing engineers and entrepreneurs to develop effective technical approaches and solutions to comply with the standards. In several cases, industry was able to comply earlier than EPA anticipated and at lower costs than expected. This analysis of these four examples supports a number of key takeaways:

Key Takeaways

- EPA works closely with industry and stakeholder groups and EPA includes flexibility in its standards to address legitimate industry concerns.
- Regulatory certainty can spur technology innovation and enable compliance. Once final standards are adopted, higher levels of engineering and innovation related to control technologies take place and can lead to technology innovations.
- Regulatory design and incentives can lead to novel technological innovations.
- Unpredicted changes in market operating frameworks can shift the economics of compliance.
- Projections based on first-of-kind use and even second-of-kind use of technology often fail to capture operational efficiencies.

Table 1: Key Takeaways and Supporting EPA Case Studies

	EPA works closely with industry and stakeholder groups and EPA includes flexibility in its standards to address legitimate industry concerns	Regulatory certainty can spur technology innovation and enable compliance	Regulatory design and incentives can lead to novel technological innovations	Unpredicted changes in market operating frameworks can shift the economics of compliance	Projections based on of first-of-kind use and even second-of-kind use of technology often fail to capture operation efficiencies that develop over time
Federal Vehicle Emission Standards	X	X			X
Acid Rain Program	X	X	X	X	
NOx SIP Call	X	X	X	X	X
MATS	X	X	X		X

1. The Federal Vehicle Emission Standards Established Under the 1970 and 1977 Clean Air Act Amendments and Three-Way Catalytic Converters

Table 2: Summary of Vehicle Emission Standards and Catalytic Converter Technology

Standard	1977 CAA amendments updated emission reduction standards for these vehicle pollutants: hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx).
Compliance Timeline	The final vehicle emission standards that industry had to meet included limits for hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx), and the final standards were: • 0.41 gram/mile for HC for model year 1980. • 3.4 gram/mile for CO for model year 1981. • 1.0 gram/mile for NOx for model year 1981.
Technology	• Phase-out of leaded gasoline to support the adoption of catalytic converters. • The three-way catalytic converter was invented to reduce HC, CO, and NOx emissions simultaneously.
Compliance Outcome	• In 1981, EPA stated the federal vehicle emission standards were successfully being met with the three-way catalytic converter.

In the 1960s, California established statutes to address smog from vehicles in major cities such as Los Angeles. The transportation sector was one of the largest sources of pollution in the U.S., although during the 1960s there was very limited vehicle pollution control technology. The regulatory certainty from the California standards were driving technological breakthroughs in vehicle emission control technologies and in 1964 California certified four new pollution control devices to be installed on 1966 model year vehicles. California's early regulatory initiatives in the 1960s encouraged the U.S. Congress to establish federal vehicle tailpipe standards for hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NOx) in the 1970 CAA amendments, which were updated in the 1977 CAA amendments. The final vehicle emission standards were:

- 0.41 gram/mile for HC for model year 1980
- 3.4 gram/mile for CO for model year 1981
- 1.0 gram/mile for NOx for model year 1981

The auto industry was initially critical of the federal vehicle emission standards, due to limited existing control technology. The industry thought the compliance timeline was too short and the industry was resistant to requiring add-on pollution control devices, such as catalytic converters, finding air injection modifications more cost effective at the time. While catalytic converter development had been underway since the late 1950s, the auto companies' chose to comply with the initial set of tailpipe standards with air injection modifications and carburetor adjustments, which were effective for meeting HC and CO interim standards but not for NOx. Additionally, while these adjustments were successful at meeting the interim HC and CO standards, the catalytic converter became the only technological solution to address all three emission standards for HC, CO, and NOx.

In the mid 1970s, an effective catalytic converter was developed in partnership between Volvo and the emission control manufacturers, which reliably delivered significant HC and CO emission reductions, but research and support from EPA was still needed. EPA and the auto companies recognized that widespread deployment of catalytic converters would only be effective if leaded gasoline was permanently phased out, because leaded gasoline can severely damage catalysts' effectiveness at controlling vehicle emissions. Automakers requested help from EPA to take steps to support widespread access to unleaded gasoline and EPA worked to address industry concerns and mandated a phase-out of leaded gasoline. EPA regulations were promulgated in 1973 and required lead-free gas to be sold at qualifying gasoline stations by July 1974. By 1975, a high percentage of new automobiles were using catalytic converters, which lower HC and CO emission and also had the additional benefit of fuel economy improvements.

In 1977, NOx emissions were addressed when another key innovative technology breakthrough occurred. Volvo developed and introduced the three-way catalytic converter, which effectively reduced HC, CO, and NOx emissions simultaneously. Just four years later, in 1981, the three-way catalytic converter was used by the majority of new vehicles in the U.S. fleet and the auto industry was able to successfully comply with the current federal vehicle emission standards. Since 1981, more restrictive federal and California vehicle emission standards have been adopted and corresponding three-way catalytic converter optimizations have occurred. The successful deployment of the three-way catalytic converter in the U.S. has led to its use globally, delivering substantial public health benefits.

The three-way catalytic converter is an example of where EPA's policy action produced sufficient regulatory certainty, spurring the necessary investments for technology innovation to occur. A 2000 NESCAUM report highlights that "today, the success achieved in reducing motor vehicle emissions stands out as one of the great technological accomplishments of the last half-century of environmental regulation" and the first federal standards were eventually achieved and exceeded. This example also illustrates the benefits that resulted from EPA's willingness to collaboratively work with the auto companies and the emission control manufacturers to encourage such a critical technological development such as the three-way catalytic converter.

2. The Clean Air Act 1970 and 1990 Amendments and Scrubbers to Reduce Sulfur Dioxide

Table 3: Summary of the Acid Rain Program and Scrubbers

Standard	• The Acid Rain Program established through the 1990 amendments to the CAA required significant emission reductions of sulfur dioxide (SO_2) and nitrogen oxides (NOx). (Note: this example focuses on the SO_2 emission reductions.) • The Acid Rain Program created a cap-and-trade program that added compliance flexibility. The final emissions cap would reduce SO_2 emissions from qualifying power plants to 8.95 million tons by 2010, reducing SO_2 emission by approximately 50% compared to 1980 levels.
Compliance Timeline	• Phase I: 1995-1999 • Phase II: 2000-2010
Technology	• A dramatic fall in the price of low-sulfur coal (due to the deregulation of railroads) allowed many utilities to meet emission reduction targets without investing in scrubbers. • Scrubber capture efficiency improved from 90% to 95% or higher. • Fuel blending with low-sulfur coal increased from 5% to 40%.
Compliance Outcome	• Phase I and II had 100% compliance with affected units and both exceeded the program's emissions cap. • In 2010, the Acid Rain Program reduced SO_2 emissions by 12.1 million tons compared to 1980 levels.

The reduction of sulfur dioxide (SO_2) has had a long history under the CAA. The 1970 CAA amendments introduced new source performance standards (NSPS) and required EPA to rely on adequately demonstrated technologies for SO_2 emission reductions. The standards required new fossil fuel electric generating sources to have an emission rate below 1.2 lb/mmBtu, but existing fossil fuel power plants (those operating prior to the adoption of the NSPS rule) were not included in the program. The standard could be met using low-sulfur fuels, pre-combustion treatment, or flue gas desulfurization (FGD) systems also known as scrubbers. There was initial concern with complying with the NSPS from utilities using high-sulfur coal and utilities expressed their concern that scrubbers had not been adequately demonstrated.

In the 1970s, because of the NSPS, there was a significant demand from fossil fuel-fired electric unit generators and an incentive for FDG suppliers to enter the market. During this time, U.S. scrubber vendors increased dramatically, with the number of U.S. vendors growing from one to 16. Additionally, operation and maintenance costs were reduced drastically due to a large learning curve related to SO_2 control technology. Operating data collected from 88 power plants that had a minimum of 12 years of FGD operation in the U.S. showed FGD operation, maintenance, and supervision costs to be, on average, lower by 83% relative to their original cost estimates. Prediction for operating costs and capture rates for nascent technologies are based on limited operating data, which will often not reflect efficiencies that will decrease costs and increase capture rates over time.

The Acid Rain Program established through the 1990 amendments to the CAA required significant emission reductions of SO_2 and NOx for existing fossil fuel electric generating units. For this analysis, the focus will be on the SO_2 program, which set an emissions cap and established a market-based cap-and-trade program for qualifying power plants. The emissions cap would reduce SO_2 emissions from power plants to 8.95 million tons by 2010, reducing SO_2 emission by approximately 50% compared to 1980 levels. The program was implemented in two phases, with

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Phase I from 1995-1999 and Phase II from 2000-2010. While this program did not require specific technology retrofits to comply, utilities expressed concern that the Acid Rain Program's compliance timelines were unrealistic and could cause reliability risks, increase electricity costs, and create disruptions to long-term utility planning. There were also concerns from utility companies, especially power plants that used high-sulfur coal, that there was not readily available technology to meet the required SO_2 reductions.

Many ex-post analyses have highlighted that utilities were able to meet the SO_2 emission reduction targets due to a dramatic fall in the price of low-sulfur coal that resulted from the deregulation of railroads that led to lower shipping costs. The availability of low-sulfur coal allowed many utilities to meet emission reduction targets without investing in scrubbers. EPA originally estimated 37 scrubber retrofits would be needed to comply with the rule but, due to this unforeseen decrease in price of low-sulfur coal, only 28 scrubber retrofits were constructed. Changes in market operating frameworks, such as the deregulation of railroads and the cost efficiencies of cap-and-trade programs, cannot often be predicted but can shift the economics of compliance drastically.

The design of the Acid Rain Program created strong economic incentives to improve SO_2 scrubber removal efficiency because additional reductions could be traded and sold in the cap-and-trade program. This is a departure from previous command-and-control policies, such as the NSPS, that required a 90% SO_2 emissions reduction. Once the 90% removal rate was attained under the NSPS, there was no incentive to improve removal rates. In contrast, the cap-and-trade program design incentivized increased SO_2 emission reductions to be sold in the emissions trading market. This incentive led to technology innovation that increased SO_2 scrubber efficiency to 95% or higher. Regulatory design and incentives can often lead to novel technological innovations that business models are unable to predict.

Another technology innovation from the Acid Rain Program was fuel mixing. Prior to the Acid Rain Program, a common belief was that blending over 5% low-sulfur coal with high-sulfur coal would damage boilers and degrade performance. Experimentation driven by the Acid Rain Program found that higher blending levels of up to 40% low-sulfur coal was achievable. The regulatory design of the Acid Rain Program had incentivized the increase in fuel blending with low-sulfur coal, creating another pathway for compliance for utilities that was not previously identified.

The Acid Rain Program overall was seen as a great success and the emissions cap set out to reduce SO_2 emissions from over 2,000 power plants to 8.95 million tons by 2010 was exceeded early in 2008.

- Phase I (1995 – 1999): A 1999 EPA compliance report concluded:
    - There was 100% compliance from affected units and affected units exceeded the program's goal.
    - 1999 SO_2 emissions from Phase I were 5 million less than 1980 levels.

- Phase II (2000 – 2010): A 2010 EPA compliance report concluded:
    - There was 100% compliance from affected units and affected units exceeded the program's goal.
    - By 2010, the Acid Rain Program reduced SO_2 emissions by 12.1 million tons compared to 1980 levels.

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3. Nitrogen Oxide State Implementation Plan Call and Selective Catalytic Reduction

Table 4: Summary of the Nitrogen Oxide State Implementation Plan Call and Selective Catalytic Reduction

Standard	• In 1998, the Nitrogen Oxide (NOx) State Implementation Plan (SIP) Call required qualifying power plants to reduce their NOx emissions rates to below 0.15 lb/mmBtu.
Compliance Timeline	• Compliance was required by May 2004 (six years).
Technology	• Selective Catalytic Reduction (SCR) technology was easier to install than anticipated and had greater capture rates than expected.
Compliance Outcome	• In 2004, a report found there was almost 100% compliance with the program – only two out of over 2,500 units were out of compliance and had to pay the penalty deduction of three allowances per excess ton of emissions.

In 1998, EPA's NOx SIP Call required qualifying power plants to reduce their NOx emissions rates to below 0.15 lb/mmBtu to improve regional air quality and decrease NOx emissions that contributed to smog. The NOx SIP Call regulation required each state in the program to ensure that NOx emissions from fossil fired electric generating facilities do not significantly contribute to poor air quality in a neighboring state by ensuring that affected sources on average do not exceed a NOx emission rate of 0.15 lb/mmBtu. EPA chose this limit because the agency believed it represented the highest level of improvement to air quality, while also staying within the bounds of cost-effective, available technology. EPA determined in the rulemaking process that for most coal-fired boilers to operate at or below the 0.15 lb/mmBtu rate, selective catalytic reduction (SCR) technology would be necessary. EPA's technology assessment for the final rule was based on SCR performance at four electric generating boilers located in U.S. and eight located in Europe, all of which were achieving emission rates below 0.15/mmBtu. The final rule was published in October 1998 with an implementation date of May 1, 2003. Ultimately, due to litigation, the NOx SIP call was extended until May 31, 2004.

Although SCR was commercially available at the time and used overseas, there were only a few power plants in the U.S. that had been retrofitted with SCR. During EPA public hearings, stakeholders highlighted their concerns about the limited number of SCR venders in the U.S., the potential for scheduled outages for SCR retrofits to cause reliability issues, unfamiliarity with SCR technology, and a desire for more field tests of the technology.

A progress report published by NESCAUM in May 2001 found announced SCR installations covered approximately 100 generating units, equal to over 61,000 MWs of capacity. These announced commitments also represented about 75% to 90% of NOx reductions needed to comply with the summertime NOx budgets established in the NOx SIP call. The NESCAUM report found that "Two to three years ahead of applicable compliance dates, the power industry appears well positioned to achieve the successful and timely implementation of new NOx control requirements." The NESCAUM report also found recent SCR installations paired with low-NOx burners could consistently reduce NOx emission by over 90%, as low as 0.05 lb/mmBtu, well below the 0.15 lb/mmBtu rate set in the rule. Additionally, the NESCAUM report found that the reliability concerns that drove industry apprehension about the NOx SIP rule had not occurred. SCR retrofits could be completed within about four weeks and could often be installed during planned maintenance outages.

The EPA report Evaluating Ozone Control Programs in the Eastern United States: Focus on the NOx Budget Trading Program, 2004 reported greater than 99% compliance with the NOx SIP program. In 2004, this report found that all affected states complied with the NOx SIP Call through participation with EPA's NOx Budget Trading Program. EPA's NOx emission control technology assessment, as a component to the NOx SIP Call proposal, proved to be accurate, as SCR retrofits were the technology of choice for most fossil fuel-fired electric generating facilities for achieving compliance. In addition to SCRs, the industry effectively deployed low-NOx burners to reduce emissions and took advantage of the compliance flexibility that the NOx trading market provided.

4. The Mercury and Air Toxics Standards and Activated Carbon Injection and Dry Sorbent Injection

Table 5: Summary of Mercury and Air Toxics Standards, Activated Carbon Injection, and Dry Sorbent Injection

Standard	• In 2011, EPA proposed the Mercury and Air Toxics Standards (MATS) to reduce hazardous air pollutants, such as mercury and acid gases, from the power sector. • MATS sets emission limits for mercury, particulate matter (a surrogate for all toxic metals), hydrochloric acid (HCl), and hydrofluoric acid (HF) for different subcategories identified by EPA.
Compliance Timeline	• EPA finalized its MATS rule in 2012, with a compliance date of 2015 or 2016 for certain sources that need additional time for their technology installations.
Technology	• Suppliers of activated carbon injection (ACI) and dry sorbent injection(DSI) reagents or sorbents invested in these technologies and improved capture rates that made other emission control retrofits unnecessary. • Operating experience improved capture rates.
Compliance Outcome	• 6% of the coal generating capacity choose to retire prior to 2015. • 55% achieved compliance in just 3 years by 2015. • 99% achieved compliance within 4 years by 2016.

In 2011, EPA proposed the Mercury and Air Toxics Standards (MATS) to reduce hazardous air pollutants, such as mercury and acid gases, from fossil fuel power. MATS was the first national standard to regulate mercury and air toxics from power plants. The MATS rule was established under Section 112 of the CAA, which requires emission standards for existing sources to be set based on best performers. EPA is required to set MATS standards at the level of performance achieved by the top 12% of similar sources. EPA finalized its MATS rule in 2012, requiring compliance by 2015, with the option for sources that demonstrated the need for an additional year to install control technologies to comply in 2016.

Many utilities and industry coalitions opposed the rule, arguing it was based on unproven technology and that the industry would not be able to achieve the emission reductions by the compliance date. The two main control measures criticized in the proposal were activated carbon injection (ACI) and dry sorbet injection (DSI). The industry said that ACI technology could only reduce mercury emissions between 30% to 80%, as opposed to EPS's prediction of 90%. The industry argued that EPA's position on DSI technology performance was based on insufficient information and experience. There was also disagreement with EPA's finding that DSI could achieve a 90% reduction in acid gases. EPA finalized the MATS rule based on its technical position regarding emission control effectiveness and availability, as well as the expected pollutant removal effectiveness of both ACI and DCI.

The post 2015 assessments of the MATS rule determined that EPA's initial technology projections included the combination of existing emission control systems (PM filters, ESPs and scrubbers) with sorbent injectors (ACI and DCI). These projections were directionally correct, but they did not account for the technological improvements that took place during the period between issuing the final rule and the years leading up to the compliance date. Once the final rule was published, the regulatory certainly that MATS provided spurred ACI and DSI reagent company investment of hundreds of millions of dollars--up to almost one billion dollars-- within the U.S. to build new manufacturing plants, support plant expansions, increase staff, and build out supply chain infrastructure for current and future demand for MATS control technologies. These investments were critical for the manufacturing and development of improved reagents. EPA's predictions for operating costs did not factor in improved performance of reagents or sorbents.

On top of the improvements to reagents, unpredicted operational efficiencies occurred. For example, DSI is commonly used upstream on an electrostatic precipitator (ESP) and the sodium-based sorbents used in DSI, such as Trona, improve ESP capture rates and make other emission control retrofit no longer necessary. These operational efficiencies and improved reagents allowed utility to comply with MATS with less emission control technology than estimated, complying at a much lower cost than either EPA or the industry had originally estimated. In fact, a 2015 study by Andover Technology Partners concluded that the actual total cost of MATS compliance was approximately $7 billion less that EPA's initial cost estimate.

The compliance outcome was impressive, given the strong skepticism expressed by industry during the rule-making process. 6% of the coal generating capacity choose to comply by retiring prior to 2015, 55% achieved compliance in just three years by 2015 and 99% achieved compliance within four years by 2016. The lower costs and high compliance levels are in large part due to EPA setting clear standards, which created the market certainty that brought about the ACI and DCI pollutant removal improvements that were cost effectively deployed using existing emission control systems. Data collected through the MATS program also show the success it had in reducing hazardous air pollutants. Mercury emissions from covered sources fell from 29 tons in 2010 (pre-MATS) to 4.2 tons in 2017 after units had installed emission control technologies. Mercury emissions continued to fall to 3 tons in 2021.

Conclusion

This retrospective analysis highlights several ways EPA has addressed legitimate initial industry concerns related to their technology projections. In the federal vehicle emission standards, MATS, NOx SIP Call, and the Acid Rain Program, EPA worked with stakeholders and included flexible approaches in setting its standards to allow sufficient time for technology development, for emission abatement technology retrofits, and to ensure that reliability concerns were accounted for.

These EPA program designs also highlight how regulatory certainty can spur unanticipated technology innovation and operational improvements. The regulatory certainty from the federal vehicle emission standards led to the development of three-way catalytic converters, noted by many as one of the greatest technological feats and a cornerstone to meeting EPA vehicle emission reduction standards. MATS regulatory certainty drove increased investments in ACI and DSI reagent companies that were critical for improving reagents resulting in improved capture rates and significantly lower costs.

Program design can also influence and encourage technological innovations. The Acid Rain Program design highlighted that, when additional emission reductions can be sold within a market, there is an incentive to increase capture efficiencies and reduce emissions beyond what is required. This compares to how setting a normal emissions limit, such as the NSPS from the CAA 1970 amendments, did not incentivize increased emission reductions once the standards were met.

The Acid Rain Program also showed that there are changes in market operating frameworks and structures that EPA cannot predict and that can shift the economics of compliance drastically. Many ex-post analyses of the Acid Rain Program point to the deregulation of railroads, which led to lower shipping costs that in turn, reduced the price of low-sulfur coal, as key to compliance. Many utilities used low-sulfur coal to meet SO_2 emission reduction requirements instead of investing in scrubbers as EPA had predicted. Also, although not expanded upon greatly in this analysis, the Andover Technology Partners MATS study found an overestimation of natural gas prices to be an unpredictable market change that lowered the cost of compliance.

Lastly, these examples show that nascent technologies' early usage does not reflect operational efficiencies that develop over time. Learning by doing leads to lower operation and maintenance costs, higher capture efficiencies, and better system design. Over a decade of operating experience gained after implementation of the SO_2 NSPS led to drastically decreased operation, maintenance, and supervision costs associated with the scrubbers. SCR technology used to comply with the NOx SIP Call was found to be easier to install and had higher NOx capture rates than expected. DSI operating data from the MATS standard also led to better system design and improvements to the DSI sorbent, which led to higher rates of acid gas removal. DSI systems additionally complemented ESP systems and, when used together, could improve ESP capture rates.

Throughout the history of the Clean Air Act, its programs have been initially met with concerns by many utility and industry stakeholders. These concerns focused primarily on technology readiness, compliance schedules, electricity reliability, and high compliance costs. Despite these concerns, EPA continues to set emission control standards to reduce emissions and protect public health, while relying on emerging control technology, incorporating compliance flexibility, and sufficient lead time. All four examples provide unique case studies of how technologies and markets develop over time to allow for compliance. Each program ultimately shows how EPA was able to address or overcome initial industry concerns and effectively achieve its goal of reducing targeted emissions.

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