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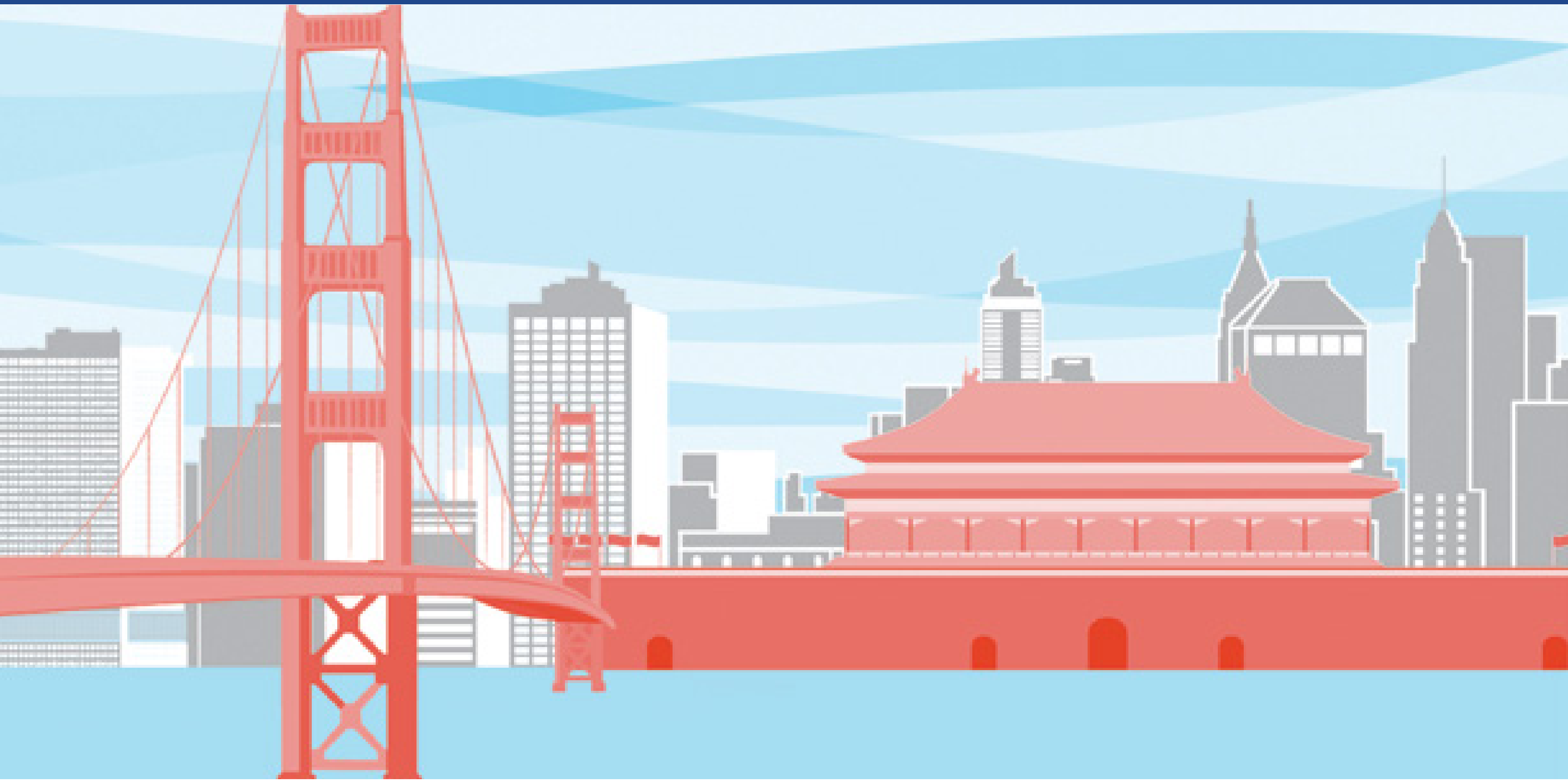

A Clear Opportunity:

U.S.-China Collaboration on Clean Air

A PARTNERSHIP AMONG:

Asia Society

CAAC 中国清洁空气联盟 Clean Air Alliance of China

ENERGY FOUNDATION 能源基金会

A CLEAR OPPORTUNITY:
U.S.-CHINA COLLABORATION ON CLEAN AIR

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An Asia Society Special Report

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Clean Air Alliance of China

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A CLEAR OPPORTUNITY: U.S.-CHINA COLLABORATION ON CLEAN AIR

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FOREWORD

CHINA'S EMERGENCE AS A GLOBAL ECONOMIC POWERHOUSE has been remarkable. However this economic success was not achieved without environmental consequences. China is now one of the world's largest greenhouse gas emitters and the country is facing severe air pollution challenges. The Chinese government sees poor air quality as a critical public health issue and is implementing a number of measures to tackle this challenge, ranging from industry regulations, regional action plans to national policies and laws. This has not only spurred a huge market for clean air technology development but also has created abundant new opportunities for the United States and China to work together to support the global climate change goals.

This report, *A Clear Opportunity: U.S.-China Collaboration on Clean Air*, was drafted through a unique collaboration between the Asia Society, the Clean Air Alliance of China—a leading consortium of top research institutes studying China's clean air challenges—and the Energy Foundation. As awareness of the detrimental effects of urban air pollution on public health grows, this report seeks to build from a number of earlier efforts undertaken by the Asia Society to promote and encourage a productive partnership between China and the U.S. on clean air and climate change. We believe that air quality management is one of the most fruitful areas for collaboration between the two countries, because it can also benefit both countries in their quest to reduce greenhouse gas emissions.

Indeed, the U.S. and China already have a long history of successful collaboration on climate change, most recently through the ratification of the Paris Climate Agreement. And while at the time of this writing it remains unclear if the incoming U.S. President will continue America's engagement with China (and the world) to address global climate change, we believe that the two nations' collaboration on the environment provide some common ground for improving the bilateral relationship, which we hope can further catalyze cooperation in other areas.

Throughout the course of its own development, the U.S. has confronted its own air pollution challenges in many of its cities. This report seeks to identify the critical regulatory and technological needs of China to help improve its air quality, highlight some of the best practices the U.S. has achieved in tackling its own air quality challenges, and explore further opportunities for U.S.-China collaboration. From the deployment of monitoring equipment and new technologies to the establishment of new rules and regulations for high polluting industries, the report highlights the most promising strategies that have been implemented in the U.S. and that China can now draw from in managing its own air pollution challenges.

California's experience is especially illustrative. The state is home to some of the most innovative cleantech companies in the world, and has some of the country's most stringent regulations on polluting industries. Moreover, California has demonstrated that it is possible to enact strong clean air regulations while sustaining high level of economic growth. For China, cleaning its air while maintaining growth is an important goal.

Our report demonstrates how the U.S. and China can benefit from greater collaborations on air quality and climate change. In addition to new market opportunities for U.S.-based clean air technology providers, the sheer scale of the challenges in China provide companies in both countries with fertile testing grounds for the large-scale deployment and scaling up of technologies that can broaden the opportunities for new innovations.

On the regulations side, U.S. regulators can monitor how markets in China respond to new rules and standards, which can provide new insights into if, where, how, and when new regulations are most effective. Finally, air pollution is ambulatory; poor air quality in one country or region can also have impacts on other countries or regions. While California, for example, still copes with air quality problems in its large cities, severe air pollution in China has been found to travel across the Pacific and into the state. As such, air pollution is not just a local problem, it is an international one.

This project benefited from our partnership with the State of California and the many agencies tasked with spearheading the State's ambitious clean energy goals. These include California's Air Resources Board, Environmental Protection Agency, and Energy Commission.

The private sector was also consulted in the process of drafting this report and provided invaluable insights. Numerous companies were found to be developing and bringing to market new technologies that support clean air and clean energy goals here in the U.S.

Non-governmental organizations and consulting firms conducting their own independent analyses of the technologies and regulations already in place also offered invaluable advice.

This report hopes to highlight the large ecosystem of partnerships consisting of government, the private sector, and non-governmental organizations working toward cleaner air and lowering greenhouse gas emissions in the U.S. and China.

Clean air has enormous public health benefits and is central to livability in today's cities. China's leaders recognize this, and are aggressively pursuing solutions to clean its air, through stronger regulations and wider deployment of clean air technologies, but are now confronting the challenge of implementing solutions at an unprecedented scale and speed. Meanwhile, the U.S. continues to consume a large share of the world's energy, and air pollution in many parts of the country persists, but it has also put into place some of the most comprehensive clean air rules and regulations which other countries are looking to emulate. Because there is a natural synergy here and because the U.S. and China have an important responsibility to collaboratively lead this effort in the world today, it is our hope that this report will provide some new ideas and suggest some new opportunities for greater cooperation between the two countries.

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LIST OF ABBREVIATIONS

ARB Air Resources Board

ASHRAE American Society for Heating Refrigerating, and Air Conditioning Engineers

BACT Best Available Control Technology

CAAC Clean Air Alliance of China

CADR Clean Air Delivery Rate

CCS Carbon Capture and Sequestration

CO Carbon Monoxide

CPCFA California Pollution Control Financing Authority

DIAL Differential Absorption Light Detection and Ranging

ECE Economic Commissions for Europe

EGR Exhaust Gas Recirculation

EIA US energy Information Administration

ELR European Load Response

EPA Environmental Protection Agency

EPB Environmental Protection Bureau

ESP Electrostatic Precipitators

ETC European Transient Cycle

EVAP Evaporative Emissions Control

FGD Flue-gas Desulfurization

FIP Federal Implementation Plan

GDP Gross Domestic Product

GHG Greenhouse Gasses

GWC Global Warming Compound

GWP Global Warming Potential

HAP Hazardous Air Pollutant

HC Hydrocarbon

LAER Lowest Achievable Emission Rate

LDAR Leak Detection and Repair

MARPOL International Maritime Organization's International Convention for the Protection of Pollution from Ships

MEP Ministry of Environmental Protection

MOS Metal-oxide-semiconductor

NAAQS National Ambient Air Quality Standards

NESHAP National Emissions Standards for Hazardous Air Pollutants

NH_3 Ammonia

NMHC Nonmethane Hydrocarbon

NH_x Mononitrogen Oxides

NSPS New Source Performance Standards

ODC Ozone Depleting Compound

ORVR On-Board Vehicle Refueling Vapor Recovery

PLACE Providing Loan Assistance for California Equipment

PM Particulate Matter

PN Particle Number

SARS Severe Acute Respiratory Syndrome

SCR Selective Catalyst Reduction

SIP State Implementation Plan

VDECS Verified Diesel Emission Control Strategies

VGT Variable Geometry Turbocharger

VOC Volatile Organic Compounds

WHSC World Harmonized Stationary Cycle

WHTC World Harmonized Transient Cycle

WHVC World Harmonized Vehicle Cycle

WNTE World Harmonized Not-To-Exceed

EXECUTIVE SUMMARY

AIR POLLUTION CONTINUES TO POSE A MAJOR THREAT to human health in China. China's recent Air Pollution Prevention and Control Law and Atmospheric Pollution Prevention Action Plan demonstrate the government's resolve to significantly improve air quality. Achieving the vision and goals laid out in these documents will require a rapid and extensive deployment of clean air technologies and an enabling regulatory environment that encourages manufacturing innovation and technology adoption. With appropriate planning, this large-scale deployment of clean air technologies could also reduce China's greenhouse gas emissions, helping achieve the country's longer-term climate policy goals.

China and the United States have a long history of collaboration on air quality and climate policy, driven by common interests. Air pollution from China affects parts of the United States, providing an impetus for federal and state agencies in the United States to work together with their counterparts in China on air quality issues. The U.S.-China Climate Change Working Group and other bilateral initiatives reflect recognition by both countries that their joint leadership is critical for mitigating climate change. Cooperation on air quality and climate change has become a pillar of the U.S.-China relationship.

The benefits of continued collaboration will grow over the next decade. As China seeks to achieve dramatic improvements in air quality, regulatory experience from the United States could play an important supporting role. In turn, regulators in the United States will have much to learn from China's experience as it struggles with its own air quality challenges. Greater harmonization of longer-term air quality and greenhouse gas regulations between the two countries would also provide an important signal for investments in clean technology innovation. A common, competitive market for these technologies would be vast, resulting in lower costs.

This report, drafted through a unique collaboration among the Asia Society, the Clean Air Alliance of China (CAAC), the Energy Foundation China, and an extensive group of advisors and experts, explores the potential for continued U.S.-China collaboration on clean air technologies and policies. It seeks to identify priority areas for collaboration on clean air technologies, enabling regulations, and market facilitation. Cleaning the air will also support broader efforts between the U.S.-China collaboration to mitigate climate change.

China is entering a new phase of air quality management, transitioning from an era in which the main concern was primary pollutants (sulfur dioxide, large particulate matter) emitted directly from industrial smokestacks to one in which secondary pollutants (fine particulate matter, ozone) resulting from a diverse combination of stationary and mobile sources are a larger concern, particularly in large urban areas. This transition occurred over several decades in the United States. In China, the speed at which it has occurred – less than 20 years – is requiring equally rapid transformations in technology and regulation.

China's longer-term emission reduction goals reflect both this new reality and the scale of air quality problems. China, for instance, required that all cities should strive to meet the national annual emission standard for fine particulate matter ($PM_{2.5}$) by 2030. Achieving this and other air quality targets will require reducing primary $PM_{2.5}$, sulfur dioxide (SO_2), and nitrogen oxide (NO_X) emissions by more than 50% below 2013 levels over the coming decade-and-a-half.[1] These emission reduction goals can only be realized through a dramatic scale-up in clean technologies, from diesel pollution controls to renewable energy, which will create the world's largest market for many of these technologies.

To support this transformation in technologies, in 2015 CAAC inaugurated a Bluetech Award aimed at identifying key technologies that could have transformative effects in improving air quality and human health in China.[2] For its 2016 Bluetech Award, CAAC identified five priority areas based on its analysis of needs for meeting longer-term national air quality goals. These five areas, the focus of this report, include the following:

- Diesel vehicles and equipment;
- Sources of volatile organic compounds (VOCs);
- Coal-fired power plants;
- Residential and industrial coal use; and
- Air quality monitoring and indoor air purifiers.

For the first four of these categories, there are strong synergies between efforts to improve air quality and efforts to reduce greenhouse gas emissions. For instance, it may be more economical to replace older coal-fired generation with non–fossil fuel generation than to retrofit it with advanced emissions control equipment. For cars and buses, vehicle electrification may be a more cost-effective approach to meeting air quality and long-term climate goals than focusing on emissions control equipment for internal combustion engine vehicles.

PRIORITY AREAS FOR COLLABORATION ON CLEAN AIR TECHNOLOGIES

The United States is a technology leader in a number of the five Bluetech areas. Based on a review of emerging technologies (Section 2 of the report), we identify five priority technology areas for China-U.S. collaboration on clean air technologies:

- **Advanced air quality monitors.** Emerging air quality monitoring technologies are enabling a clearer picture of the timing, location, and exposure impacts of air pollution. In China, careful deployment of these technologies would enhance understanding of the sources of air pollution, enable more effective air quality and emissions standards based on a deeper understanding of pollution exposure and health impacts, and allow regulators to prioritize strategies that reduce the most harmful sources of pollution.
- **Integrated designs and clean fuels for heavy-duty vehicles.** Federal regulations in the United States have spurred a new generation of heavy-duty vehicles that are able to meet stringent emissions limits while improving fuel efficiency and performance;

[1] Hao, Yin, and Cen (2016).
[2] See http://en.bluetechaward.com/

California and other U.S. states are exploring longer-term alternative fuel sources for heavy-duty vehicles. In China, new engine and pollution control designs for diesel heavy-duty vehicles would enable lower emissions standards for new vehicles, while planning for cleaner fuels for heavy-duty vehicles would help achieve longer-term air quality and climate goals.

- **Electrification of passenger vehicles and buses.** Both China and the United State have been leaders in supporting the early development and deployment of electric cars, buses, and short-haul heavy-duty vehicles that have no tailpipe emissions; when combined with renewable or nuclear electricity generation, these vehicles can have zero total emissions. New technologies for vehicles and charging infrastructure can lower the cost of transportation electrification as an air quality and climate policy strategy in China.
- **Low environmental impact solvents.** Solvents – used in paints, lubricants, inks, adhesives, and cleaning products – are a major source of urban ozone pollution and may contribute to ozone depletion, toxic air, and climate change. An emerging generation of solvents is able to meet multiple environmental standards, which will help China achieve a range of environmental goals.
- **Leak detection and repair for refineries, chemical plants, and pipelines.** Remote sensing technologies are enabling more accurate detection and lowering cost control of fugitive pollution and greenhouse gas emissions from refineries, chemical plants, and pipelines. In China, advanced leak detection and repair technologies would enable regulators to rapidly and cost efficiently achieve significant emissions reductions from these sources.

PRIORITY AREAS FOR COLLABORATION ON ENABLING REGULATION

Regulation – from emissions standards to technology mandates – plays a critical role in enabling the development and deployment of clean air technologies. The United States has more than 50 years of experience in developing regulatory frameworks to encourage clean air technologies. This experience has been and could continue to be a valuable reference for regulators in China, as they plan and develop implementation programs to meet local and national air quality goals. In turn, regulators in the United States will be able to learn from emerging practices in China.

Our identification of priority areas for regulatory collaboration draws on a review of three regulatory areas in California (Section 3 of the report):

- The Diesel Risk Reduction Plan, which seeks to reduce particulate matter from all diesel emissions sources by 85% by 2020;
- Regulations for controlling VOC emissions, focusing on regulations for solvent emissions; and
- Joint planning for air quality management and greenhouse gas emissions reductions, which have enabled better integration between the state's efforts to achieve compliance with federal air quality standards and its goal of reducing greenhouse gas emissions by 80% by 2050.

Across these three areas, we distill a number of regulatory design considerations that may be valuable for regulators in China. These include the importance of the following:

- A **science and technology foundation** that provides a firm basis for air quality management;
- **Stakeholder engagement** that builds the consensus, trust, and commitment necessary to enable manufacturing innovation and technology adoption;
- **Long-term vision and clear goals** that provide long-term visibility and certainty on forthcoming regulations to manufacturers, equipment owners, government agencies, and the general public;
- **Integrated planning** that enables goals for multiple pollutants ($PM_{2.5}$, ozone, SO_2) and greenhouse gas emissions to be met simultaneously and at lowest cost;
- **Incentives** that encourage adoption of clean air technologies, as well as a source of **funding** to pay for incentives; and
- **Proactive enforcement** that uses the latest available technologies, matches enforcement programs to compliance strategies and technologies, imposes meaningful penalties for noncompliance, provides performance guarantees through warranties, and encourages transparency through accurate labeling and certification.

PRIORITY AREAS FOR COLLABORATION ON INNOVATION AND MARKET FACILITATION

As part of this study, we conducted a small survey of 18 clean technology manufacturers in the United States to gauge their interest and experience with the market for clean air technologies in China. The survey included interviews with manufacturers in most of the five Bluetech areas.

Survey respondents identified five areas where support from governmental and non-governmental organizations could facilitate smoother market entry into the Chinese market for clean air technologies:

- Assistance in building **local partnerships**;
- Stronger protection of **intellectual property rights**;
- An enhanced **regulatory framework** that provides stronger enforcement, clear incentives, greater transparency, and clearer roles and responsibilities;
- Greater **public awareness** of air pollution issues; and
- Greater international **harmonization** of air quality and greenhouse gas standards and the technologies used to meet those standards.

RECOMMENDATIONS

Going forward, we recommend three kinds of activities in which continued collaboration between China and the United States could produce transformative results:

- **Joint collaboration on strategies for meeting long-term air quality and climate goals.** By coordinating planning on longer-term air quality and greenhouse gas emissions goals, China and the United States can provide manufacturers, financial institutions, and entrepreneurs with greater certainty regarding the technologies and the potential size of markets for different technologies needed to meet these goals.

- **Deeper collaboration on enabling regulations.** Deeper collaboration on enabling regulations for clean technologies would allow more in-depth exchange on the details of U.S. regulatory experience to support China's air quality goals. It would also build a foundation for engagement that enables regulators in the United States to learn from China's experience over the next decade, as U.S. regulators look for solutions to longer-term air quality challenges in the United States.
- **Joint efforts to facilitate market entry, innovation, and healthy competition.** Promoting open markets for clean air technologies in both countries would facilitate innovation and competition, lowering the costs of meeting longer-term air quality and climate goals. By harmonizing the requirements and timing of regulations, such as emissions standards, the two countries would create a much larger market for clean air technologies.

INTRODUCTION

THIS REPORT INVESTIGATES PRIORITY AREAS for deepening collaboration between China and the United States on clean air technologies and policies. Its origins lie in a basic question: What is the potential role of U.S. government agencies, manufacturers, and non-governmental organizations in supporting China's efforts to achieve dramatic improvements in air quality, and where should collaborative efforts be focused? To facilitate a deeper conversation around this question, the Energy Foundation's China office and the Clean Air Alliance of China engaged the Asia Society to produce this report.

The report is organized into five main sections:

- **SECTION 1** (*China's Air Quality Challenges: Emerging Issues and Priority Areas*) describes China's evolving air quality challenges and five priority areas in which new technologies for pollution monitoring and control could be transformative.
- **SECTION 2** (*Current and Emerging Clean Air Technologies in the United States*) provides an overview of current and emerging clean air technologies in the United States for the five areas identified in Section 1.
- **SECTION 3** (*Creating an Enabling Environment for Emissions Control Technologies: California's Experience*) explores California's experience in creating an enabling environment for cleaner diesel and solvent technologies, and in aligning planning and regulation for air quality and greenhouse gas emissions reductions.
- **SECTION 4** (*Priority Areas for China-U.S. Collaboration on Clean Air Technologies and Policies*) identifies priorities for China-U.S. collaboration in three areas: technologies, enabling regulation, and market facilitation.
- **SECTION 5** (*Conclusions and Recommendations*) synthesizes the report's main conclusions and provides recommendations for collaborative activities that could have high nearer-term impact.

1. CHINA'S AIR QUALITY CHALLENGES: EMERGING ISSUES AND PRIORITY AREAS

OVER THE PAST THREE DECADES, rising levels of air pollution have been a by-product of rapid economic growth in China, though the sources of pollution and the air quality management system for reigning in pollution are both evolving. This section begins with an overview of China's evolving air pollution trends, recent policies, regulations for reducing air pollution, and challenges and gaps that remain.[3] It then describes five priority areas for clean air technologies and policies in China, where incremental efforts could have transformative results for human health and the environment.

1.1 CHINA'S EVOLVING AIR QUALITY CHALLENGES

1.1.1 China's Evolving Pollution Trends

Air pollution in major Chinese cities has shifted in the past three decades from an industrial pollution regime characterized by stationary sources that emit primary pollutants (SO_2, PM, NO_2), to a hybrid regime characterized both by stationary and mobile sources and a mix of primary and secondary pollutants (ozone, $PM_{2.5}$). Mobile sources have emerged as a primary air quality concern in a number of major cities. For instance, vehicle emissions are responsible for approximately 30% of, $PM_{2.5}$ emissions in Beijing and Shanghai.[4]

Compared with stationary sources, such as power plants and factories, mobile sources of emissions are more difficult to monitor and control. Over the years, China's environmental regulators have created an extensive program to regulate emissions from stationary sources, but they have less experience regulating mobile sources of pollution. Regulating mobile sources is a particular challenge for densely populated regions, such as Beijing, Tianjin, and Zhejiang, where the number of vehicles per 100 persons averaged more than 15 in 2013, approximately twice the national average.[5]

While persistent air quality issues from primary pollutants remain, rising concentrations of secondary pollutants are making China's air quality situation worse and more complex to manage.

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[3] In creating this report, Asia Society Northern California conducted an internal gap analysis of clean air technologies and policies in the United States and China. The findings of this analysis are contained within the report that follows.
[4] Data from CAAC (2015). "China Clean Air Quality Management Assessment Report 2015." http://en.cleanairchina.org/product/7386.html
[5] Data from CAAC (2015). "China Clean Air Quality Management Assessment Report 2015." http://en.cleanairchina.org/product/7386.html

1.1.2 Policy Changes and Results

Although China had an extensive system of policies, laws, and industry regulations for managing air quality, more intensive efforts at air quality management began in 2013. In the early spring months of 2013, the entire eastern region of China experienced serious smog conditions that caused extremely low visibility conditions and posed a public health risk. In Beijing and its surrounding areas, the concentration of $PM_{2.5}$ reached "beyond index" on the Air Quality Index scorecard, making international media headlines and causing widespread concern. Li Keqiang, China's then vice-premier, pledged to take action on air pollution prevention and control.

Echoing this commitment, the State Council issued a national Air Pollution Prevention and Control Action Plan in September 2013, popularly referred to as the "Ten Measures on Air." This Action Plan set forth a roadmap for the nation's air pollution control efforts for the period from 2013 to 2017, and it marked the beginning of a new era in China's clean air efforts. Chinese central and local governments subsequently promulgated a series of policies, laws, regulations, standards, and technical guidelines to support the implementation of the Action Plan. These included the establishment of a regional collaboration mechanism for more effective air pollution control, special funds to subsidize environmentally friendly industries, pricing and taxation mechanisms to encourage investment in emissions control technologies, an air quality ranking system for key cities, and a mandatory environmental information disclosure system for companies that are causing heavy pollution.

According to the air quality attainment schedule for cities across the country made by the Ministry of Environmental Protection (MEP) in 2013, all the cities should strive to reach the national standard (annual average $PM_{2.5}$ concentration equals $35 \mu g/m^3$) by 2030. In order to reach this target, primary $PM_{2.5}$ emissions need to be reduced by 53%, SO_2 emissions by 51%, NO_X emissions by 64%, and VOC emissions by 36% from 2013 levels; ammonia (NH_3) emissions cannot be higher than 2013 levels.[6]

In late 2015, China revised its 1987 Air Pollution Prevention and Control Law to enhance accountability for air quality management on the local governance level. It required that the performance of local government officials be based not only on GDP growth but also on how well they meet air quality targets and tasks. Other new elements of the law include articles on regional control of pollution, a warning system for weather conditions that worsen smog, emissions control from mobile sources, stronger penalties for violations, and an emphasis on the co-benefits of controlling both air pollutants and greenhouse gases.

China's 13th Five-Year Plan (2016–2020) sets ambitious targets for air quality progress, requiring hundreds of cities to achieve "good" air quality, a score under 100 on the Air Quality Index, or better on at least 80% of the days in a year.[7]

Those tracking policy changes found these new developments in air pollution control to be more responsive and intensive compared with previous efforts. A new report from Clean Air Asia found that China passed more air-related laws and regulations in the past three years than in the past three decades combined.[8]

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[6] Hao, Yin, and Cen (2016).

[7] Data from China's 13th Five-Year Plan (Chinese), "十三五规划纲要（全文）." http://xinhuanet.com/politics/2016lh/2016-03/17/c_1118366322.htm

[8] For more, see Clean Air Asia (2016). "China Air 2015: Air Pollution Prevention and Control Progress in Chinese Cities." http://cleanairasia.org/wp-content/uploads/2016/03/ChinaAir2015-report.pdf

As a result of these efforts, concentrations of many air pollutants have decreased in most of the 74 key cities.[9] According to the Clean Air Alliance of China's 2016 China Air Quality Management Assessment Report, China has made sustained improvements in air quality over the past two years. Eleven of 74 key cities tracked by the central government attained their air quality targets, compared with 8 in 2014. On average, the 74 key cities met "good" air quality standards 71% of the days in a year, a 5% increase from 2014 and 11% from 2013.[10]

1.1.3 Air Quality and Climate Policies

Air pollution control efforts in China also support its climate change goals. Meeting air quality targets could generate significant benefits in curbing climate change and accelerating China's pace in achieving its climate goals committed in the Paris Agreement. Fully enforcing China's new (and binding) air quality laws and emissions targets will only be possible by making fundamental changes to China's energy and economic structures. According to recent modeling analysis, China's cities and provinces cannot meet new air quality standards through end-of-pipe solutions alone.[11] Therefore, the only scenario in which China can meet air quality standards will be one in which China moves away from coal and fossil fuel energy sources and shifts toward renewable energy sources, public and non-motorized transit-oriented mobility, electrification of transport, and major reductions in over-capacity of heavy industries. Taken together, these technological, energy, and economic transformations represent a fundamentally different, and greener China, and could lead to enormous GHG reductions.

While the air pollution reduction targets in China are mandatory, low-carbon pilot programs are voluntary, meaning the former are more effectively carried out. According to the newly revised Air Pollution Prevention and Control Law, all cities not meeting their air quality targets must develop a mandatory air quality attainment plan, meaning that more than 260 cities in China will need to develop new plans for implementing measures to meet the air quality targets, which may help reduce CO_2 emissions at the same time.

In addition, China is conducting a series of measures to strengthen enforcement of air quality regulations. These include an annual assessment of provincial leaders, which will have an impact on their political standing, strategic reevaluation meetings arranged by air quality management authorities with local government leaders when air quality standards are not met, rankings of cities based on air quality and their progress in meeting goals, and regular audits from national regulators. This strengthening of regulatory enforcement will also have benefits for efforts to regulate greenhouse gas emissions.

All these efforts show that China's air pollution control work is becoming a key driving force that will greatly impact the nation's overall CO_2 emissions reductions. An example of this already taking place is a study produced by CAAC, in which it found that the prevention and control of air pollution in the Jing-Jin-Ji region will help reduce CO_2 emissions by about 2.1 million tons by 2030, a decrease of 19% from the 2013 levels.[12]

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[9] Starting from January 2013, real-time air quality monitoring data on PM2.5 intensity in China's 74 major cities are available at the website www.cnemc.cn. A total of 496 monitoring sites have been set up in the 74 cities.
[10] CAAC (2016).
[11] Wang, Zhao, and Fu (2016).
[12] He, Zhang, and Tong (2016).

1.1.4 Challenges and Gaps

As described earlier, China has made important progress in pollution prevention and control in recent years. However, there are still a number of challenges to making continued improvements in China's air quality. Greater efforts need to be made to control motor vehicle pollution. Particulate pollution is still an outstanding issue in China, and ozone pollution is emerging as a major health hazard. In some regions, the atmospheric pollution levels are not decreasing but are instead increasing.[13] Considering the complexity of air quality management, and that China is still in the process of large-scale urbanization, the need to further strengthen clean air efforts persists.

While challenges such as a lack of sufficient funding, data accessibility, and personnel expertise have frequently been identified as factors obstructing China's air pollution efforts, on a broad level, stronger regulation enforcement and technology revamping have been identified by many experts as the key factors to improve China's overall air quality management efforts. Analyzing China's current regulatory structure and technology portfolio and comparing them with countries that have more developed air quality control programs such as the United States will reveal opportunities for collaboration and China's needs for greater air quality improvement.

The challenges of creating enabling policies and promoting advanced technologies are two aspects of the same issue. Experience from developed countries shows that government and businesses must work side by side to fight air pollution. Traditionally, the government sets emission caps while industries determine the best strategies and technologies to achieve those targets. For emerging clean air technologies to be timely and effectively adopted in China, a similarly enabling regulatory environment also needs to be strengthened. Good compliance also requires close collaboration among governments, the private sector, and the general public. This point was already expressed in the Ten Measures on Air, which stresses a focus on "air pollution control led by government, implemented by companies, driven by market and participated in by the public."

1.2 FIVE PRIORITY AREAS FOR POLLUTION MONITORING AND CONTROL

China's targets for emission control in 2030 will create a huge market for the deployment of clean air technologies in the years to come, with a total market value estimated to be more than 5 trillion RMB.[14] China's need for clean air technologies will continue to rise, and the market potential is huge for global clean air technology providers. Air quality management is complex. Different cities are faced with very different sources of pollution because of variations in economic development levels, energy mixes, and urban modes. How to help cities develop their own clean air action plans around advanced technologies is a key to accelerating the pace of restoring blue skies in China.

As a key player assisting in China's efforts to adopt the best available clean air technologies, CAAC analyzed the different technology needs from cities and identified five priority areas

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[13] CAAC (2016).

[14] Li et al. (2015). In the report 《十三五"大气污染防治战略建议汇编》, it says the direct investment needs to implement the Ten Measures on Air are 1.84 trillion RMB. Further calculations based on this gives the estimate of 5 trillion yuan.

for technology development and application, where improvements in technology and enabling regulation will have the most significant air quality and health benefits. The significance of each technology is judged on its performance results, an analysis of the potential environmental benefits, technical performance, and assessment of financial models to find disruption potential in today's industry. The following technology categories were chosen to be the five Bluetech Award categories in 2016: emissions control technologies for diesel vehicles, emissions control technologies for VOC emissions, air quality monitoring and indoor air purification, alternative fuels for industrial and residential use, and ultra-low emissions control technologies for coal-fired power plants. The remainder of this section discusses the significance and current regulating policies of each category in China.

1.2.1 Emissions Control Technology for Diesel Vehicles

Diesel vehicles are one of the most significant sources of air pollution in China, contributing a large share of $PM_{2.5}$ and NO_X emissions. The category "diesel vehicles" includes heavy-duty freight trucks, city transit buses, coaches, light-duty commercial vehicles, rural vehicles, off-road construction machines and agricultural equipment, port haulers, and marine ocean-going vessels. Diesel vehicles are an especially numerous and significant source of air pollution in economic centers such as Beijing, Shanghai, and the Pearl River Delta.[15] The Ministry of Environmental Protection's 2015 Annual Report of Vehicle Exhaust Emission Control states that diesel vehicles are the source of nearly 70% of total NO_X emissions from vehicle exhaust and more than 90% of PM emissions in urban areas.[16] The total number of diesel trucks in China has leapt from 9 million in 2000 to almost 33 million in 2013, demonstrating the rapid growth of this pollution source.[17]

Over the past decade, China adopted a suite of policy measures to reduce emissions from diesel engines. These including phasing out high-sulfur diesel fuel, introducing more stringent emissions standards for new vehicles, in-use inspection and maintenance programs (I/M), and strong incentives to retire the dirtiest and oldest vehicles (so called "yellow label" vehicles). China's emissions standards for heavy-duty vehicles began implementation as China I in 2001 and have been ratcheted in subsequent China II (2004), China III (2008), and China IV (2013) standards.[18] These standards have forced the adoption of emissions control technologies for new trucks and buses, such as diesel oxidation catalysts and exhaust gas recirculation systems. The emissions factors of diesel trucks and buses in China were reduced significantly from pre-China I to China III for all pollutants except NO_X (see Table 1 and Figure 1).

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[15] Huo (2012).

[16] For more, see Ministry of Environmental Protection of China (2015). "2015 Annual Report on Vehicle Exhaust Emission Control." http://english.mep.gov.cn/News_service/news_release/201603/t20160307_331615.htm

[17] See the National Bureau of Statistics of China's Statistical Yearbook (2014). www.stats.gov.cn/tjsj/ndsj/2014/indexeh.htm

[18] For more on emissions standards, see Transportpolicy.net, "China: Heavy-duty Emissions." http://transportpolicy.net/index.php?title=China:_Heavyduty:_Emissions

Table 1: Emission Standards for Heavy-Duty Diesel Engines

STANDARD	TEST CYCLE	CO	HC	NMHC	NO_X	PM	PN	SMOKE	NH_3
		g/kWh					kWh-1	1/m	ppm
CHINA I*	ECE R-49	4.9	1.23	—	9.0	0.68			
CHINA II*		4.0	1.1	—	7.0	0.15			
CHINA III	ESC + ELR	2.1	0.66	—	5.0	0.10		0.8	
	ETC	5.45	—	0.78	5.0	0.16		—	
CHINA IV	ESC + ELR	1.5	0.46	—	3.5	0.02		0.5	
	ETC	4.0	—	0.55	3.5	0.03		—	
CHINA V	ESC + ELR	1.5	0.46	—	2.0	0.02		0.5	10
	ETC	4.0	—	0.55	2.0	0.03		—	10
CHINA VI**	WHSC	1.5	0.13	0.13	0.40	0.010	8.0×10^{11}		10
	WHTC	4.0	0.16	0.16	0.46	0.010	6.0×10^{11}		10
	WNTE	2.0	0.22	0.22	0.48	0.012			

* PM limits are for engines with power of 85 kW or less.
** Expected China VI limits.
NMHC is nonmethane hydrocarbons
PN is particulate number

Source: Data for table and figure are compiled from the Ministry of Environmental Protection of China (MEP), "Limits and Measurement Methods for Exhaust Pollutants from Compression Ignition Engines of Vehicles." http://www.mep.gov.cn/image20010518/1923.pdf (for China I); and from DieselNet, "Heavy-Duty Truck and Bus Engines." www.dieselnet.com/standards/cn/hd.php (for China II-VI)

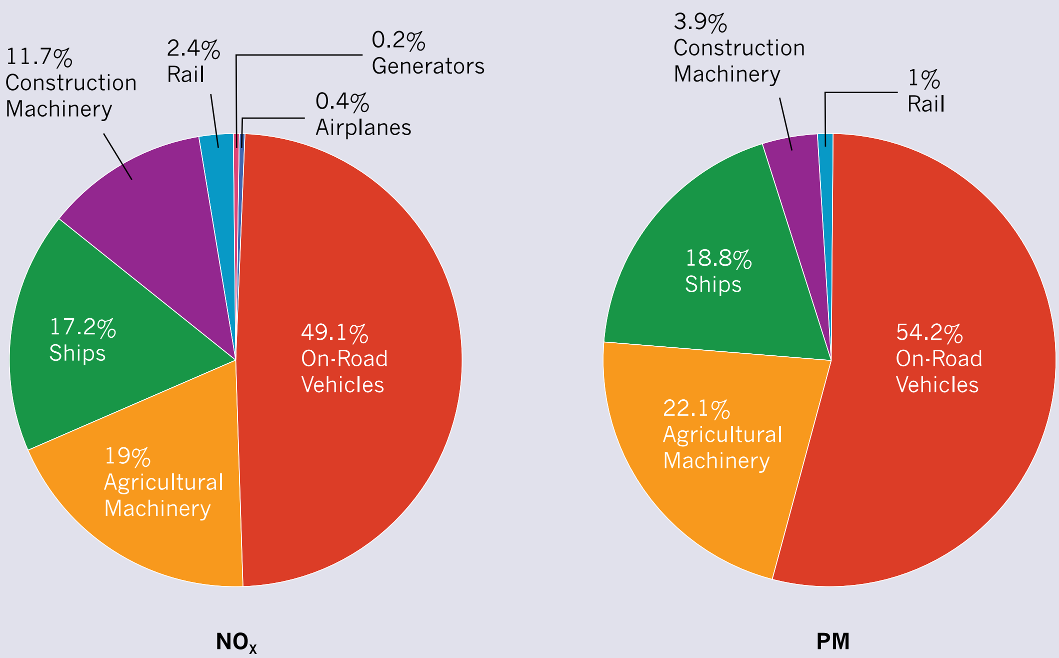
Subnational regions and cities in China are permitted to implement national standards with an accelerated schedule in their individual regions, pending State Council approval. Beijing has historically led in the advanced implementation of vehicle emissions standards, followed by Shanghai, Guangzhou, and some other major cities. China V has been in effect in Beijing since June 2015 and currently only applies to public buses and municipal service vehicles in Shanghai and Guangzhou.[19] The Beijing Environmental Protection Bureau proposed Beijing VI in late 2015, the strictest emissions standards for heavy-duty vehicles in China thus far. The Ministry of Environmental Protection also circulated the draft China VI standard in May 2016 for feedback, which is expected to be officially released by the end of 2016.

Diesel fuel quality, particularly sulfur concentration, affects potential emissions controls. Nationwide, China IV standards (2013) were delayed for two-and-a-half years due to fuel quality problems. Certain emissions control technologies, such as diesel particulate filters and selective catalytic reduction systems, require low-sulfur fuel to operate properly. However, many fuel refineries in China still produce fuel with high levels of sulfur.[20] Nationwide China V implementation, originally scheduled for 2012–2013, has also been delayed until July 2017. The stated reason for the delays was the inadequate nationwide supply of high-quality fuel. For many years, China's regulators and oil companies could not agree on a suitable time line for increasing the national low-sulfur fuel supply.[21] The heavy air pollution episodes of the winter of 2013 finally catalyzed high-level government intervention. Subsequent fuel quality standards have been aligned with emissions standards, requiring sulfur concentrations of 10 ppm by January 2017.[22]

For off-road vehicles and equipment, used in the agricultural and construction sectors, China has adopted standards based on European regulations. The current standards, Stage III, are based on EU Stage IIIA and have been in effect since October 2014,[23] while the effective date for Stage IV standards has not yet been set. Emissions limits for the smallest engines (50 hp) are consistent with US Tier 1/2 standards. In 2014, the Vehicle Emission Control Center of the Ministry of Environmental Protection estimated that off-road vehicles and equipment were responsible for 31% of total NO_X emissions and 26% of total PM emissions from mobile emission sources (Figure 1).

[19] For more on emissions standards, see DieselNet (2015). "Emission Standards: China: Heavy-duty Truck and Bus Engines." www.dieselnet.com/standards/cn/hd.php
[20] Eveland (2012). "China IV Diesel Emissions Legislation Further Delayed." www.integer-research.com/integer-alert/china-iv-diesel-emissions-legislation-further-delayed/
[21] For more on the history of clean air policy, see International Council on Clean Transportation (2013).
[22] Data from the State Council of China (2015). "李克强主持召开国务院常务会议（2015年4月28日）." www.gov.cn/guowuyuan/2015-04/28/content_2854625.htm
[23] For more, see DieselNet, "Emissions Standards: China: Non-road." www.dieselnet.com/standards/cn/nonroad.php

Figure 1: Mobile Source Contributions to NO_X and PM in China in 2014



Source: Data are from Ding Yan for the Vehicle Emission Control Center of MEP (2014). "Challenges and Countermeasures of Mobile Source Pollution Control in China." www.efchina.org/Attachments/Foundation-News/news-efchina-20140918/4-15.DING%20Yan_EN.pd

Inland waterway ships in China feature old models and low tonnage. Most of them are equipped with outdated small and medium-sized diesel engines. To reduce costs, inferior fuel oil is used in some ships, resulting in more complicated and serious pollution. No specific standards for the emissions of inland waterway ships have been formulated. Emissions from small diesel engines with power less than 37 kW, however, are regulated as off-road mobile machinery and have equivalent China I and China II standards.[24] Emissions standards for medium-sized diesel engines with power greater than or equal to 37 kW are currently in preparation and will likely require similar emissions control technologies as on-road vehicles. Low-sulfur diesel requirements will also have implications for pollution from inland ships.

With the previously mentioned control measures in place, clean fuel is expected to become one of the major measures to meet the needs of both air pollution control and carbon emissions

[24] For more information, see the Environmental Standards Institute of MEP (2014), "Latest progress on shipping emission standard in China".

Market-Entry Strategy for Diesel Emissions Control in China

Selective catalytic reduction (SCR) systems have become the most widely used compliance strategy for meeting more stringent NO_X emission standards for heavy-duty vehicles. In China, SCR systems are still at an early stage of deployment, but the prospect of tightening NO_X standards presents a significant opportunity for SCR manufacturers.

Umicore Automotive Catalysts has developed and deployed SCR systems for heavy-duty engines in the United States. The company is headquartered in Europe but has offices and research and development centers globally, including in the United States and China, despite the fact that the current enforcement system in China has not yet enabled widespread SCR adoption. Fuel quality also continues to be a challenge in China for SCR systems, as sulfur and manganese in the diesel fuel damages the catalyst systems.

Umicore has found a unique way of entering the Chinese market in anticipation of tightening NO_X regulations, by only supplying large international vehicle manufacturers in China. Umicore's business in China has been successful within this industry corner, and 90% of its suppliers for the SCR systems in China are now domestic Chinese companies. In the coming years, as China's regulation of diesel vehicles becomes stricter, Chinese heavy-duty vehicle manufacturers may reach out to companies like Umicore that have a preestablished presence in China to provide their SCR systems.

reduction. With continued growth in the number of diesel vehicles, which is expected to be around 36–45.6 million in 2020,[25] a huge market will be created for diesel particulate filters and associated equipment, with an estimated market value of 1 to 3 trillion yuan.[26]

1.2.2 Emissions Control Technologies for VOC Emissions

VOCs are organic chemicals that have a high vapor pressure at room temperature and are a key contributor to ozone and $PM_{2.5}$ concentrations in China. Some VOCs are also carcinogenic or mutagenic. VOCs were not listed as a major air pollutant in China until 2010, and air pollution control strategies did not specifically target VOCs until the 2012 Airborne Pollution Prevention and Control Plan for Key Regions (2011–2015), and even then VOC emissions were only set to be reduced beginning 2015.

[25] Data from 《2016年中国机动车管理年报》 and《2015年中国机动车污染防治年报》.
[26] CAAC estimated number based on 《深圳市人居环境委关于公开征集在用柴油车改造产品的通知》 and《关于开展移动源颗粒物治理技术环保信息公开工作的通知》.

In 2013, the national Air Pollution Prevention and Control Action Plan was the first law to mandate that VOC emissions be considered in environmental impact assessments for construction of new industrial facilities. That same year, Beijing released its own Clean Air Action Plan, which enacted emissions control targets for VOCs, granting their local Environmental Protection Bureau the authority to collect emission fees from industrial sources starting in 2014 and set a goal to reduce VOC emissions from industrial sources to 2012 levels by 2017. The 2015 revised Air Pollution Prevention and Control Law was the first law to provide a legal basis for local Environmental Protection Bureaus (EPBs) to regulate VOC emissions and has since been implemented on a provincial basis in Beijing, Shanghai, Jiangsu, and Hunan.

Most recently, in July 2016 the Ministry of Finance and the Ministry of Industry and Information Technology jointly issued an Action Plan for Reduction of VOCs in Key Industries, which ruled that by 2018 the emissions of VOCs in key industry sectors must decrease by more than 3.3 million tons from 2015 levels (Table 2). In addition, the plan stated that consumption of benzene and methylbenzene, both VOC emissions sources, must be reduced by more than 20%, and the percentages for "green" pesticides, coatings, inks, adhesives, and tire products with low or no VOCs should reach 70%, 60% 70%, 85%, and 40%, respectively.[27]

While local VOC regulations from EPBs emphasize specific operations and pricing policies, national policies emphasize overall emissions reduction targets and calculation methods. Preliminary targets for the plan are to reduce annual VOC emissions by 4.3 million tons (compared to 2009 levels) to 17 million tons by 2020, and again reduce emissions to fewer than 15 million tons in 2030.[28] CAAC estimates that this reduction will induce 173 billion yuan of investment in VOC-reducing technologies by 2020.[29]

Industrial sources contributed a large share of VOC emissions in China, accounting for an estimated 55% of VOC emissions in 2009 (Figure 2). The top polluting industries are those that are dependent on VOC-laden coatings or inks, such as for architectural surface coating, and the packaging and printing industries.[30] A CAAC study estimates that in 2012, emissions from these two industries were at an annual rate of 2.5 million tons and 2.4 million tons, respectively.[31] The State Council has called for VOC emissions limits to be imposed on the industrial use of VOC-containing solvents in the 2013 Air Pollution Prevention and Control Plan.

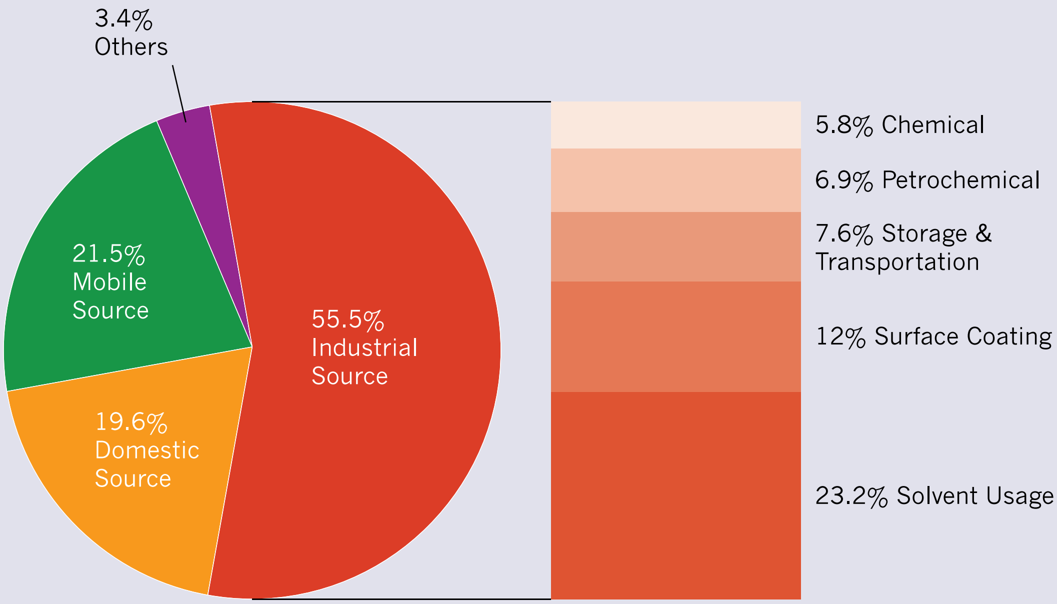
[27] For more on the "Action Plan for Reduction of Volatile Organic Compounds in Key Industries," see https://hk.lexiscn.com/latest_message.php?access=show_detail&id=195814
[28] Environmental Standards Institute, MEP (2014).
[29] CAAC (2015). 《VOCs治理：千亿投资空间》。 www.cleanairchina.org/product/6972.html
[30] Data from He (2016).
[31] Data from CAAC (2015).

Table 2: National VOC Regulation in China

DATE	GOVERNMENT AGENCY	POLICY/REGULATION NAME	SUMMARY (VOC RELATED)
Dec. 2011	Ministry of Environmental Protection	National Environmental Protection 12th Five-Year Plan	Mandated VOC exhaust control and emission monitoring
Oct. 2012	Ministry of Environmental Protection	Air Pollution Prevention and Control Plan for Key Regions	Mandated VOC pollution control must be included in environmental impact assessments
June 2013	Ministry of Environmental Protection	VOC Pollution Control Technology Policy	Outlined pollution control methods for VOC-containing products, manufacturing, and use
Sept. 2013	State Council	National Air Pollution and Prevention Control Plan	Mandated full implementation of VOC pollution control by the end of 2017
Sept. 2013	Ministry of Environmental Protection (and others)	Jing-Jin-Ji Region Practical Air Pollution Prevention and Control Action Plan	Actively promote clean production technology, and by the end of 2017 complete an audit of the pollutant output of steel, cement, chemical, petrochemical, nonferrous metals and other industries
July 2014	Ministry of Environmental Protection (and others)	Air Pollution Control Action Plan Implementation and Assessment Methods	Work plan for monitoring and control of VOCs in Beijing, Tianjin, Hebei, and surrounding regions for 2014–2017
Dec. 2014	Ministry of Environmental Protection	Petrochemical Industry VOC Improvement Program	Establishment of VOC management and monitoring system for pollution control
June 2015	Ministry of Finance, Development, and Reform Commission	VOC Pollution Charges Pilot Program	Pilot VOC emission charges for petrochemical, packaging, and printing industries
Aug. 2015	National People's Congress	Air Pollution Prevention Law (new)	First introduction of VOCs into environmental regulatory structure
July 2016	Ministry of Finance, Ministry of Industry and Information Technology	Action Plan for Reduction of Volatile Organic Compounds in Key Industries	By 2018 the emissions of VOCs in key industries will decrease by more than 3.3 million tons compared to 2015 levels

Source: Information gathered by China Investment Securities (2016), Chinese only.
http://pg.jrj.com.cn/acc/Res/CN_RES/INDUS/2016/7/14/c726b2bf-ec09-4895-a613-5087ad1ff827.pdf

Figure 2: 2009 Estimated Source Apportionment for VOC Emissions in China



No official VOC emission data released in China yet
Man-made VOC emissions were 22-26 million tons/year from 2006–2010

Source: Data for this figure are from Li Xiaoqing of the Chinese Academy for Environmental Planning, "Environmental Tax – A potential Policy Tool on VOC Control in China." http://conferences.au.dk/fileadmin/conferences/gcet/Presentations_in_the_detailed_programme/O_052_Potenti al_Tool_on_VOC_control_in_China-_Li_Xiaoqiong.pdf

Refining is another major source of VOC emissions. Infrastructure used in the refining, transportation, and storage of fuels may accumulate small cracks where small amounts of VOCs can escape, coalescing into a significant source of VOCs in the atmosphere. The Air Pollution Prevention and Control Plan requires the petrochemical industry to retrofit its facilities with leak detection and repair (LDAR) and vapor recovery technology to try to mitigate these risks and effects. More specifically, in 2015 the Ministry of Environmental Protection released a Petrochemical Enterprises Leak Detection and Repair Work Guide, which stated that industrial piping and components with VOC content of 10% or greater by weight in the process stream must implement an LDAR process.[32] Local EPBs have also begun releasing their own LDAR requirements that may include even more robust requirements.

[32] 《石化企业泄漏检测与修复工作指南》。 www.mep.gov.cn/gkml/hbb/bgt/201511/W020151124546328688845.pdf

The Air Pollution Prevention and Control Plan similarly calls on the MEP and local EPBs to regulate other industrial sources of VOCs, such as the manufacture of vehicles, equipment, furniture, electronics, and pharmaceuticals. On-road tailpipe emissions of VOCs have significantly decreased under increasingly strict vehicular emissions standards, from China I to China IV. However, an estimate from 2009 found that 21% of VOC emissions still come from mobile sources, likely due to evaporated VOCs from gasoline in fuel tanks or during the refueling process (see Figure 3). The current standard for China's evaporative emissions from gasoline vehicles is the European-based Stage II vapor recovery, which only has a 46% control efficiency of combined evaporative emissions scenarios such as refueling, permeation, and running-loss.[33]

1.2.3 Air Quality Monitoring and Indoor Air Purification

After enjoying more than three decades of rapid development and industrialization, China now has to face daunting environmental problems including heavy smog that plagues large parts of the country in the winter months. While in the past there have been gaps in the information reported about outdoor air quality, in more recent years the situation has been improving. One air quality milestone in China was the amendment of the National Air Quality Standards in 2012, prescribing the first-ever limits for $PM_{2.5}$ and O_3. The amendments also outlined a three-step urban air quality program for China, in which capital cities and key cities in the Jing-Jin-Ji region, the Yangtze River Delta, and the Pearl River Delta started monitoring and reporting $PM_{2.5}$ and O_3 levels in 2012. A total of 113 cities key to environmental protection started the same program in 2013, and 333 prefectural-level cities are set to follow suit in 2016. These real-time air quality data and monitoring networks have offered an effective means of supervision for local governments to tackle air pollution.

The heavy smog in the winter is also forcing people to spend more time indoors, particularly children and elderly people, making indoor air quality an important health factor. Although there are indoor air pollution sources, such as building materials, furniture, decorations, paints, and coatings, the outside atmosphere also has a big impact on indoor air quality. In fact, the smog in China has recently become the biggest source of indoor air pollution in the winter months. While China is implementing many measures to improve its urban air quality, progress does not happen overnight, making indoor air purification technology a necessary strategy to improve people's health in the interim.

The SARS event, worsening air pollution, publicly accessible air quality monitoring information, and widespread media coverage have all led to broad public awareness of this issue and a rapid expansion of the markets for both indoor air quality monitoring devices and indoor air purifiers, particularly beginning in 2010. In 2012, there were a total of 223 air

[33] For more, see MECA, "Reducing Evaporative Emissions – the Largest Source of VOC Emissions Leading to Haze, PM2.5 and Ozone Formation in China's Major Cities: A Macro and Micro Analysis with Information on International Experience and Related Implications for China" (2014). www.meca.org/resources/MECA_China_Evap_English_June_2014.pdf

purifier producers in China and 6 million units installed in urban households.[34] This represents a market size growth of 50% in sales volume compared with 2011. The smog outbreak in 2013 further spurred the market growth in these areas. China's Science and Technology Daily estimated that by 2020, the air purification market would reach 100 billion yuan.[35]

1.2.4 Alternative Fuels for Industrial and Residential Use

A significant portion of coal consumption in China comes from its use in the industrial sector. Approximately 23% of China's total coal consumption in 2013 was direct coal consumption in industry, with another 15% of total consumption used to make coke for industrial processes.[36] Although there are regulations around the burning of coal in larger sources, such as steel mills and cement kilns, enforcement can be difficult, limiting the actual impact of those regulations.[37] China's industrial boiler systems alone account for 18% of the nation's coal consumption, 33% of its soot emissions, and 27% of its CO_2 emissions. The industrial sector presents an opportunity to switch to natural gasses, biomass oil, and electricity in some sectors, which would help reduce the emissions caused by coal-burning sources.[38] The impact of the implementation of alternative-fuel sources is not limited to the industrial sector, however. Residential use of coal is another large contributor to the growing air quality and health problems in China.

Many non-urban households in China use coal briquettes and biomass – wood and crop residues – for space heating, water heating, and cooking. Burning coal and biomass indoors releases large amounts of particulate matter, black carbon, and organic carbon, and it is a significant contributor to indoor air pollution and local haze formation. Indoor air pollution from residential fuel use causes respiratory illness, lung cancer, and chronic obstructive pulmonary disease.[39] Concentrations are especially high during winter months, when biomass is intensively used for heating. Even though residential coal use is less than 1% of total coal use, its health effects are magnified because exposures are much higher.[40]

To address this issue, China banned the use or sales of coal in large cities with the revision of the Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution in 2000. The provincial governments selected 113 "key cities" in China,[41] where the local EPBs were required to define restricted areas where the sale and use of high-pollution briquettes are prohibited.[42] Non-prohibited areas were also required to only use sulfur-fixed

[34] For more, see Pim China's "China's Home Air Purifiers Market Research" (2014). www.pimchina.com/uploads/soft/150826/1_1152293511.pdf
[35] *Science and Technology Daily* (January 28, 2015). 《空净市场未来五年将破千亿》。
[36] Data are from China's National Bureau of Statistics website, www.stats.gov.cn/
[37] Clifford (2015). "China's Economic Slowdown: We May have Seen Peak Coal." www.forbes.com/sites/mclifford/2015/09/03/chinas-economic-slowdown-we-may-have-seen-peak-coal/#22061ba31c00
[38] Shen, Price, Lu, Liu, and Tsen (2015) "Curbing Air Pollution and Greenhouse Gas Emissions from Industrial Boilers in China: An Analysis and Implementation Roadmap for Improving Energy Efficiency and Fuel Switching with Case Studies in Ningbo and Xi'an" https://china.lbl.gov/sites/all/files/lbnl-1003860-curbing-air-pollution-lbnl_boiler_assessment_final_report.pdf.
[39] Zhang and Smith (2007).
[40] Data from National Bureau of Statistics of China (2013).
[41] Large and medium-sized cities, including 31 capital cities of each province.
[42] Duan and Zhang (2014).

briquettes and other fuels cleaner than raw coal. However, no data have been released that assess the impact of this law. In rural areas, coal use has increasingly begun to replace biomass burning, as higher resident incomes allow these commercial products to become more affordable.[43] Honeycomb coal briquettes, denser than raw coal, emit less PM and SO_2 and are subsidized along with clean stoves by the Chinese government to encourage higher adoption rates.

In addition to setting restrictions on residential fuel use, China is also focusing on "stove interventions," which include incentive, research, and distribution programs for cleaner stoves for cooking and heating. From the early 1980s to the mid-1990s, the government ran a National Improved Stoves Program that distributed 180 million stoves with much lower emissions relative to biomass. China joined the Global Alliance for Clean Cookstoves in 2012 to promote stove distribution and research. China's stove industry, however, faces several challenges, including an incomplete standards system, low-quality products, and lack of a robust certification and evaluation system.[44]

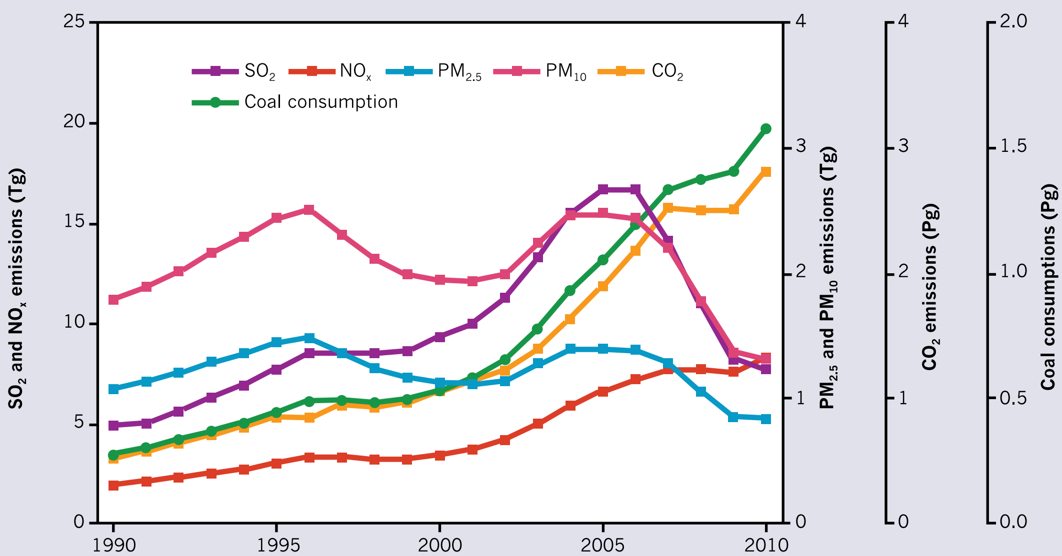
Based on the information released by the Ministry of Environmental Protection, the annual "scattered coal"[45] consumption in China is between 600 and 700 billion tons, which accounts for 20% of the overall annual coal consumption in China. The firing of scattered coal emitted around 10 million tons of SO_2 and 3.2 million tons of NO_X.[46] To address this, China is going to tighten its emissions control on scattered coal use. According to statistics, annual scattered coal consumption in the Jing-Jin-Ji area is 36 million tons. If all of that coal consumption could be replaced by alternatives, a study estimated that by 2020, the market size would reach 58 billion yuan just for the Jing-Jin-Ji area.[47]

1.2.5 Ultra-low Emissions Control Technologies for Coal-fired Power Plants

Coal is a naturally abundant resource in China and has historically been the country's lowest-cost source of electricity. China's coal consumption in 2012 reached 3.6 billion tons, half of the total global consumption. In 2014, more than 70% of the electricity sector was supplied by coal-fired power plants, accounting for almost half of the annual coal consumption in China.[48] Historically, coal-fired power plants were the largest emission sources of SO_2, PM, and also large amounts of NO_X, mercury, and CO_2.[49] One recent study estimates that coal-fired electricity generation still contributes 60% of SO_2 emissions and 40% of CO_2 emissions in China.[50] Coal-fired power plants are also large emitters of greenhouse gases (Figure 3).

43 Duan and Zhang (2014).
44 China Agricultural University (2015)
45 This includes coal use for household heating, household cooking, and industrial small-scale boilers.
46 www.cnenergy.org, "年消耗达6-7亿吨，散煤成煤炭清洁高效利用难点" (2015).
www.cnenergy.org/tt/201512/t20151224_255791.html
47 Yang, X. D. presentation "京津冀地区清洁能源技术与分析" at 京津冀区域大气污染控制技术培训研讨会on January 22, 2016.
48 Thieriot, Tan, Nagpal, and Ferroukhi (2016). "Water Use in China's Power Sector: Impact of Renewables and Cooling Technologies to 2030." www.irena.org/DocumentDownloads/Publications/IRENA_China_Water_Risk_Power_brief_2016.pd
49 Wang (2012). "Emissions of Air Pollutants from Power Plants in China."
www.htap.org/meetings/2012/2012_10/Presentations/Tues/Plenary%20Session/Wang-HTAP-20121009(1).pdf
50 Data from Zhao, X. (2015).

Figure 3: Coal Consumption and Emissions of Coal-fired Power Plants in China (1990–2010)



Source: Figure is from F. Liu, Q. Zhang, D. Tong, B. Zhang, M. Li, H. Huo, and K. B. He, "High-resolution Inventory of Technologies, Activities, and Emissions of Coal-fired Power Plants in China from 1990 to 2010." www.atmoschem-phys.net/15/13299/2015/acp-15-13299-2015.pdf

In an effort to reduce emissions from coal power plants, emissions standards have become increasingly stringent since they first began in earnest in 2005 for the 11th Five-Year Plan. This plan mandated a nationwide shutdown of inefficient and polluting small coal-fired power plants, and a mandatory installation of flue gas desulfurization equipment on all power plants.[51] Outside of the regular Five-Year Plan cycle, the State Council Action Plan on Air Quality imposed a coal consumption cap in key regions, banned construction of new power plants in key regions except for combined heat and power, set a 2017 target to lower coal in the national power mix to 65%, and set a target for a 70% coal-washing rate.

A new policy, Coal Energy-saving Upgrade and Transformation Action Plan (2014–2020), includes an Ultra-low Emissions[52] and Energy-saving Coal-fired Power Plants Program, which now requires that all new and existing coal plants reduce emissions to the equivalent of a gas unit by 2020 nationally, 2017 in the Eastern region, and 2018 in the Central region (Table 3).[53] The program also seeks to increase efficiency from coal-fired power plants from 310 grams coal equivalent per kilowatt-hour (gce/kWh) to 300 gce/kWh.

[51] Zhao et al. (2014).

[52] The standard of ultra-low emission is as follows: at 6% oxygen ratio, the particulate matter, sulfur dioxide, nitric oxide emissions from the coal-fired power plant are set less than 10 mg/Nm³, 35 mg/Nm³, 50mg/Nm³, respectively.

[53] MEP (2015).

Ultra-low emissions transformation is a technology vigorously promoted by the Chinese government using special financial subsidies and credit financing support. The financial services industry estimates that the market for pollution control retrofits could be on the order of 40 billion yuan.[54]

Table 3: Emission Standards for Coal-fired Power Plants in China

	1996 CHINA	2002 BEIJING	2003 CHINA	2007 BEIJING	2011 CHINA	2020 CHINA
SO_2 (mg/m^3)	1200-2100	100-150	400-1200	50	200	35
NO_x (mg/m^3)	650-1000	—	450-1000	150-250	100-200	50
PM (mg/m^3)	200	50	50	10	30	10

Source: Wang, S. (2012).

[54] *Shanghai Securities News* (December 3, 2015.). http://finance.ifeng.com/a/20151203/14105567_0.shtml

2. CURRENT AND EMERGING CLEAN AIR TECHNOLOGIES IN THE UNITED STATES

THIS SECTION PROVIDES AN OVERVIEW of current and emerging technologies in the United States for each of the five areas described in the previous section:

1. Emissions control technologies for diesel vehicles
2. VOC emissions control technologies for stationary sources and gasoline-powered vehicles
3. Air quality monitoring and purification devices
4. Alternative fuels for industrial and residential use
5. Ultra-low emissions control technologies for coal-fired power plants

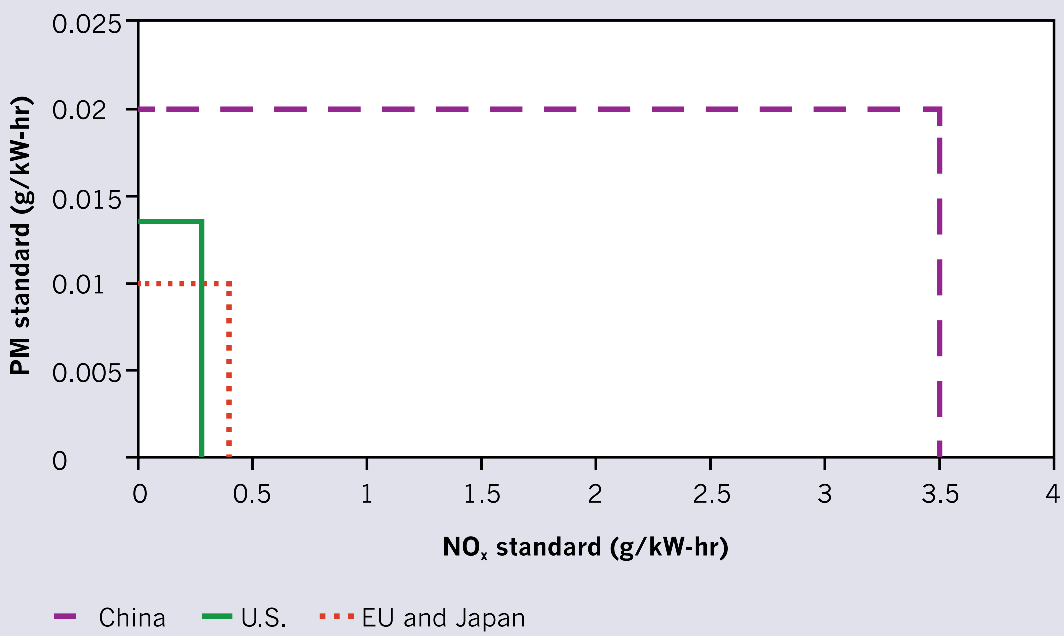
2.1 EMISSIONS CONTROL TECHNOLOGIES FOR DIESEL VEHICLES

"Diesel vehicles" is a broad category that includes trucks, buses, trains, construction vehicles, port vehicles, mining vehicles, off-road vehicles, and marine-going vessels. Among these, on-road vehicles are often the largest source of pollution and are the focus in this section, though control technologies for on-road vehicles are similar to those for other diesel vehicles. In specific applications, diesel engines are preferred over gasoline engines because of their higher efficiency and durability. Because they have a very different design and operating characteristics than gasoline engines, diesel engines typically use different emissions control technologies.

Diesel vehicles emit a number of pollutants that are either directly or indirectly harmful to human health. In the United States, environmental regulators have recently focused on controlling PM and NO_X emissions from diesel on-road vehicles. The United States now has among the most stringent standards for PM and NO_X emissions from new heavy-duty diesel vehicles (Figure 4), which came into effect beginning in 2007.[55] As described in this section, there has been some degree of convergence in the technologies used by diesel engine manufacturers to comply with these standards.

[55] The EPA's PM standard went into effect in 2007. The NOX standard was phased in between 2007 and 2010. For the final rule, see EPA (2001).

Figure 4: Heavy-Duty Vehicle PM and NOx Standards in the United States, China, EU, and Japan



Source: Data are from TransportPolicy.net. China data are based on China IV. China V, which was originally planned for implementation in 2013 but has been delayed, would reduce China's NO_X standard to 2.0 g/kW-hr.

Some emissions control technologies can also reduce greenhouse gas (GHG) emissions from diesel vehicles, though achieving deeper reductions in GHG emissions in the transportation sector will require transitioning away from diesel fuels. Alternative-fuel vehicles for diesel engine applications are still only used in niche applications, such as short-haul trucking and buses.

2.1.1 PM and NO_X Control Technologies

PM and NO_X emissions have different causes. PM emissions result from incomplete combustion of diesel fuel and can be reduced through better mixing of air and fuel in the engine's combustion chamber. NO_X emissions result primarily from high temperature combustion in air. Because more complete combustion results in higher combustion temperatures, strategies to reduce PM emissions may increase NO_X emissions. Achieving significant reductions in total emissions from diesel vehicles thus requires controlling both pollutants.

In general, there are two approaches to PM and NO_X emissions control from diesel vehicles: (1) reducing PM and NO_X formation within the engine cylinders ("in-cylinder") and (2) removing PM and NO_X from the engine exhaust ("exhaust"). Across these two approaches, there are currently 11 key PM and NO_X emissions control technologies (Table 4).[56]

Table 4: Key Emissions Control Technologies for Diesel Engines

TECHNOLOGY	FOCUS	POLLUTANTS
Engine design	In-cylinder	All
Air management systems	In-cylinder	All
Fuel injection systems	In-cylinder	All
Diesel oxidation catalysts	Exhaust	PM
Diesel particulate filters	Exhaust	PM
Closed crankcase filtration	Exhaust	PM
Exhaust gas recirculation systems	In-cylinder	NO_X
Selective catalytic reduction systems	Exhaust	NO_X
Lean NO_X traps (NO_X adsorber)	Exhaust	NO_X
Lean NO_X catalysts	Exhaust	NO_X
On-board diagnostic systems	Total system	All

2.1.1.1 In-Cylinder Control Technologies

In-cylinder technologies control PM emissions by regulating how air and diesel fuel are mixed in the engine's combustion chamber, and NO_X by regulating combustion temperatures. Overall engine design has an important influence on air-fuel mixing, but engines are also normally equipped with specialized equipment to manage the air and fuel entering the combustion chamber. Air management systems precisely control the temperature, speed, composition, and pressure of air. Fuel injection systems allow for more precise control over the timing, rate, and pressure of fuel injection. In tandem, these systems can be calibrated to optimize PM and NO_X formation to meet a given standard.[57]

[56] For a more detailed description of these technologies, see Posada et al. (2016) and MECA (2007).
[57] More specifically, air management and fuel injection systems can be adjusted to generate lower or higher relative amounts of PM and NO_x, depending on regulatory requirements. For instance, earlier fuel injection tends to increase combustion temperatures, reduce PM emissions, and increase NO_x emissions, whereas later injection tends to decrease temperatures, increase PM emissions, and reduce NO_x emissions.

In the early 2000s, many heavy-duty on-road vehicle manufacturers began to install exhaust gas recirculation (EGR) systems to comply with the EPA's NO_X emissions standards. EGR recirculates exhaust gases from the engine back to the engine's cylinders, which reduces combustion temperatures and thus lowers NO_X formation. Variable geometry turbochargers (VGTs) are often used in conjunction with EGR systems to control the cooled gas into the intake manifold, optimizing trade-offs between engine performance and NO_X emissions. EGR systems continue to be used by manufacturers in tandem with selective catalytic reduction systems.

2.1.1.2 PM Control Technologies

In the 1990s, diesel engine manufacturers began to install diesel oxidation catalysts to meet the EPA's PM and NO_X emissions standards.[58] With diesel oxidation catalysts, exhaust gases are passed over a catalyst, which oxidizes the soluble organic fraction of PM, other unburned hydrocarbons, and carbon monoxide into CO_2 and water.[59] Diesel oxidation catalysts can generally achieve PM emissions reductions of 20% to 35%, depending on the fraction of soluble organic material, relative to dry, solid particles, in the exhaust (Table 5).

To meet the EPA's 2007 PM standards, all new heavy-duty diesel vehicles in the United States were required to install high-efficiency (wall-flow) diesel particulate filters. High-efficiency filters, which trap PM from the engine exhaust using an ultrafine porous material, can achieve PM reductions of more than 90% (Table 5). Their use requires low-sulfur diesel fuel, as higher sulfur fuels will affect their performance and durability. In preparation for its 2007 standards, the EPA began to require the production of low-sulfur diesel (15 ppm) throughout the United States in mid-2006.[60]

For complying with in-use diesel vehicle emissions standards, such as those in California, vehicle operators have used either high-efficiency wall-flow or partial-flow particulate filters, depending on the application and emissions control requirements. Partial-flow filters use different materials than high-efficiency filters do and typically have much lower collection efficiencies, but they require little to no maintenance and can be tailored to a variety of engine applications.

Diesel oxidation catalysts have a somewhat different function than diesel particulate filters, and the two are commonly used in tandem, with the former upstream from or integrated into the latter. Diesel oxidation catalysts oxidize hydrocarbons in diesel exhaust. In addition, they often also play two additional roles: (1) improving the efficiency of selective catalytic reduction systems and (2) reducing accumulation of PM on diesel particulate filters.[61]

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[58] Diesel oxidation catalysts do not reduce NOX emissions. However, their use allowed manufacturers to meet EPA requirements for steep reductions in NOX emissions, while still meeting stringent PM standards.
[59] Soluble organic fraction refers to the fraction of PM that can be extracted using an organic solvent, consisting of hydrocarbons that have adhered to solid, dry carbon particles.
[60] EPA (2001).
[61] Diesel oxidation catalysts improve the efficiency of selective catalytic reduction systems by converting nitrogen oxide (NO) in the engine exhaust to nitrogen dioxide (NO_2), which enhances conversion of NO_x to nitrogen and water at lower temperatures. NO_2 is also used as an oxidizer in passive regeneration systems, which burn PM off of the diesel particulate filter.

Table 5: Range of PM Reductions for Different Control Technologies

TECHNOLOGY	PM REDUCTION
Diesel oxidation catalysts	20–35%
High-efficiency diesel particulate filters	> 90%
Partial-flow diesel particulate filters	30–75%
Closed crankcase filtration	n/a

Source: Estimates are based on Posada et al. (2016) and MECA (2007).

In internal combustion engines, the crankcase is the large metal container that houses the crankshaft and other critical engine components. During combustion, gases escape from the engine cylinders into the crankcase. Before 2007, the EPA regulated crankcase PM emissions on all highway vehicles except for turbocharged heavy-duty engines, which were allowed to ventilate a significant fraction of these emissions to the atmosphere. In 2007, the EPA began to regulate crankcase emissions on all highway vehicles, citing the availability of closed crankcase filtration systems.[62] These systems collect crankcase gases and pass them through a filter that removes PM.

2.1.1.3 Exhaust Control Technologies for NO_X

To comply with EPA NO_X standards for new on-road vehicles, all heavy-duty diesel engine manufacturers are currently using selective catalytic reduction (SCR) systems. SCR systems inject urea into engine exhaust in the presence of a catalyst, reducing NO_X to nitrogen and water.[63] Urea is carried in a tank on board the vehicle, adding a significant amount of weight and often requiring electric heaters in cold regions to ensure that the tank does not freeze. SCR systems typically use sensors to determine the level of urea injection; excess urea injections can lead to ammonia emissions.

SCR systems can be operated over a wide temperature range, allowing higher temperature combustion of the diesel fuel and higher vehicle efficiencies. Higher temperature combustion reduces PM, improves fuel efficiency, and helps remove PM that accumulates on diesel particulate filters. The higher NO_X emissions in the engine exhaust that result from higher temperature combustion can be reduced through the SCR system.

[62] The EPA's PM standards apply to total emissions from the vehicle, allowing manufacturers flexibility in design. Allowing more crankcase PM to be ventilated to the atmosphere, for instance, requires stronger PM controls for exhaust gases. See EPA (2001).

[63] More specifically, urea is first converted to ammonia (NH_3) through hydrolysis in a decomposition reactor. NH_3 then reacts with NO and NO_2 to form nitrogen (N_2) and water (H_2O).

Although SCR is currently the dominant technology for complying with NO_X emissions standards for heavy-duty on-road vehicles in the United States, lean NO_X traps were initially seen as a viable alternative because of their high potential removal efficiencies (Table 6). Lean NO_X traps "trap" NO_X from the exhaust, catalytically converting it to nitrogen. Manufacturers have used lean NO_X traps on lighter-duty diesel vehicles. Researchers have explored combining the functionality of lean NO_X traps and SCR systems, where the former provides a source of ammonia for the SCR system, eliminating the need for an on-board urea tank.[64]

Research on the next generation of diesel NO_X control technologies is ongoing. For instance, California's Air Resources Board is supporting research on advanced diesel engine and control technologies capable of achieving a 90% reduction over current standards.[65]

Table 6: Range of NO_X Reductions for Different Control Technologies

TECHNOLOGY	NO_X REDUCTION
Selective catalytic reduction systems	75–90%
Lean NO_X traps	50–90%
Lean NO_X catalysts	10–30%

Source: Estimates are based on Posada et al. (2016) and MECA (2007).

2.1.1.4 Integrated Systems Design

Achieving very low levels of diesel emissions has increasingly required a more integrated systems approach to designing engines and emissions controls for new vehicles. Engine manufacturers design the engine and emissions controls as an integrated system, rather than as isolated components.[66] This approach allows manufacturers to optimize the design of engines and emissions control systems for fuel efficiency and vehicle performance while meeting emissions standards and minimizing the cost of emissions control equipment.

2.1.1.5 On-Board Diagnostics

As part of the implementation of more stringent diesel emissions controls, the EPA and the ARB require manufacturers to install on-board diagnostic systems to monitor the operation of on-board pollution control equipment. These systems play an important role in ensuring ongoing compliance for in-use vehicles. Diagnostic systems are often required to detect and

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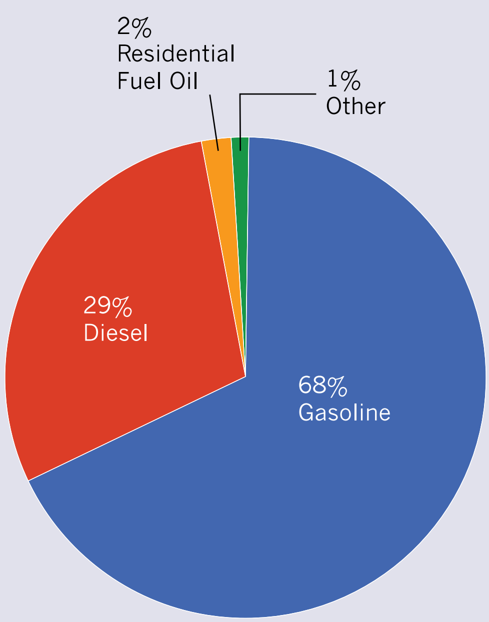
[64] See, for example, MECA (2007) and Zukerman et al. (2009).
[65] See ARB (2015a), "Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles." www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm
[66] For an example, see Cummins, "Meeting Emissions – The Cummins Solution." https://cumminsengines.com/cummins-aftertreatment-system

report a malfunction when emissions levels exceed a specific threshold. For instance, ARB requires the on-board diagnostic system to monitor the conversion efficiency of SCR systems based on NO_X emissions levels in the exhaust.[67] More stringent requirements for on-board diagnostic systems have led to the development of advanced sensor technologies – including temperature, oxygen, air-fuel ratio, and NO_X sensors – to ensure that the operation of engines and emissions control systems matches manufacturer specifications.

2.1.2 Alternative Fuels

The vast majority of vehicles in the United States are powered by petroleum fuels, and mainly by gasoline (light-duty vehicles) and diesel (medium- and heavy-duty vehicles) (Figure 5). Recently, alternative-fuel vehicles have made inroads in niche applications. For diesel substitution, these include fleet vehicles operating on electricity, natural gas, and biodiesel and short-haul electric trucks. Natural gas and biodiesel vehicles are a source of NO_X emissions and require control strategies. Electric vehicles may have upstream emissions associated with electricity generation.

Figure 5: Fuel Consumption for Vehicles in the United States, 2015 (estimated)



Source: Data are estimates from EIA (2015a).

[67] ARB (2013).

Alternative-fuel trucks and buses have been most successful in areas with air quality concerns, such as in cities or near port facilities. For instance, around 40% of transit buses in the United States are powered all or in part by biodiesel, electricity, or natural gas.[68] In California, most marine vessels are now required to use electricity, rather than running their diesel engines, while docked at ports. The South Coast Air Quality Management District, in partnership with Siemens, is currently demonstrating a catenary system – overhead electric lines – that would enable diesel hybrid electric trucks to drive in electric mode when in proximity to the ports of Los Angeles and Long Beach.[69]

Cleaner Trucks at the Ports

California's Ports of Los Angeles and Long Beach are among the largest ports in the United States and are also widely known for their air quality impacts. With public pressure mounting, port authorities, air regulators, and manufacturers are exploring new clean air technologies to reduce air pollution in and around the ports. For instance, the South Coast Air Quality Management District (SCAQMD), in partnership with Siemens, is currently demonstrating a catenary system – overhead electric lines – that would enable trucks to operate in electric mode when in proximity to the ports of Los Angeles and Long Beach.

In addition, the Department of Energy and the California Air Resources Board have provided funding through SCAQMD to help spur the development and adoption of advanced freight transportation technologies for use at the ports. Southern California–based TransPower, one recipient of these funds, has developed an advanced electric propulsion system for heavy-duty vehicles. The Port of Los Angeles provided TransPower with a proving ground to demonstrate the operating and economic performance of its ElecTruck technology. TransPower is building and testing around 20 electric yard haulers and freight trucks for use at the Port of Los Angeles and other warehouse facilities. The company also offers the ElecTruck technology for school bus, transit bus, and construction vehicle demonstration.

Although TransPower does acquire key components from companies in China and is interested in selling into the Chinese market, the company's current strategy is to continue to focus on the U.S. market until its technology is perfected and produced at scale. Financing and foreign transactions are a main concern for the Chinese market.

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68 Data are from the U.S. Department of Energy's Alternative Fuels Data Center, "U.S. Transit Buses by Fuel Type." www.afdc.energy.gov/data/10302

69 For more on this technology, see Siemens, "Electrification of Road Freight Transport." w3.siemens.com/topics/global/en/electromobility/pages/ehighway.aspx.

In wider applications, alternative-fuel vehicles have had less success. Falling prices for natural gas in the United States prompted projections that trucks powered by compressed and liquefied natural gas would become a larger share of the total fleet. This has, however, not occurred, for three main reasons: (1) falling diesel prices lengthened the payback period for natural gas trucks, which have higher upfront costs than diesel vehicles; (2) the refueling infrastructure for natural gas trucks is still limited; and (3) diesel vehicles have thus far been able to meet tightening emissions standards.

Still, interest has continued in natural gas engines for trucks to meet more stringent ozone and NO_X regulations. California is proposing to lower its current NO_X standard for heavy-duty vehicles by 90% by 2023, to 0.027 grams of NO_X per kilowatt-hour.[70] Current diesel control technologies are unable to meet this standard, though natural gas vehicles can. For instance, Cummins Westport Inc. has already certified a natural gas–powered heavy-duty engine that complies with this standard with the EPA and California Air Resources Board (ARB).[71]

Over the next decade, a number of states will need to begin to encourage the deployment of alternative-fuel vehicles to meet long-term GHG goals. Three possible low-GHG fuels for heavy-duty vehicles include

- Hydrogen produced from low-GHG electricity;
- Low-GHG compressed or liquefied gas produced from a blend of biogas, hydrogen, synthetic natural gas, and natural gas; and
- Advanced liquid biofuels.

Which of these will be the dominant fuels remains an open question.[72] The EPA anticipates that manufacturers will meet its 2021–2027 GHG standards for medium- and heavy-duty engines through fuel efficiency improvements.[73]

2.2 EMISSIONS CONTROL TECHNOLOGIES FOR VOC EMISSIONS

As in China, anthropogenic VOC emissions in the United States come from a number of different sources. Industrial sources are the largest contributor to total VOC emissions, with solvents accounting for nearly 50%.[74] VOC sources, however, vary by region and economic activity. In urban areas, mobile sources may be the largest contributor to outdoor VOC emissions.[75] In areas with significant petroleum refining activity, refineries and petrochemical

[70] See South Coast Air Quality Management District (March 2016), "SCAQMD to Petition U.S. EPA to Adopt Lower Emissions standard for Heavy-Duty Engines."
www.aqmd.gov/home/library/public-information/2016-news-archives/near-zero-nox-emissions
[71] See Cummins Westport, "ISL G Near Zero Natural Gas Engine Certified to Near Zero – First Mid-Range Engine in North America to Reduce NO_X Emissions by 90%" from EPA 2010
[72] See, for instance, Williams et al. (2014) and Fulton and Marshall (2015).
[73] EPA (2015).
[74] EPA (2012).
[75] Pang et al. (2015).

Cleaner Fleets in Los Angeles

Fleet vehicles, such as buses, garbage trucks, school buses, and delivery trucks, are often a focus of efforts to promote alternative fuels in heavy-duty vehicles. Natural gas–powered and dual-fuel vehicles are one strategy for alternative fuels. Dual-fuel vehicles are mainly powered by natural gas but use some diesel for ignition assistance. In-use diesel vehicles can be retrofitted with dual-fuel technology.

In 2001, the firm Clean Air Power successfully demonstrated the benefits of dual-fuel technology by equipping 10 Los Angeles Bureau of Sanitation refuse trucks with the proprietary technology in a pilot project initiated through a partial grant from the South Coast Air Quality Management District. The successful demonstration, combined with SCAQMD Rule 1193 that required refuse fleets to purchase alternative-fuel trucks, led to an additional purchase of more than 250 trucks by the city. Greenkraft Inc., another alternative-fuel truck manufacturer, has also taken advantage of government incentives to produce medium- and heavy-duty trucks that run on compressed or liquefied natural gas.

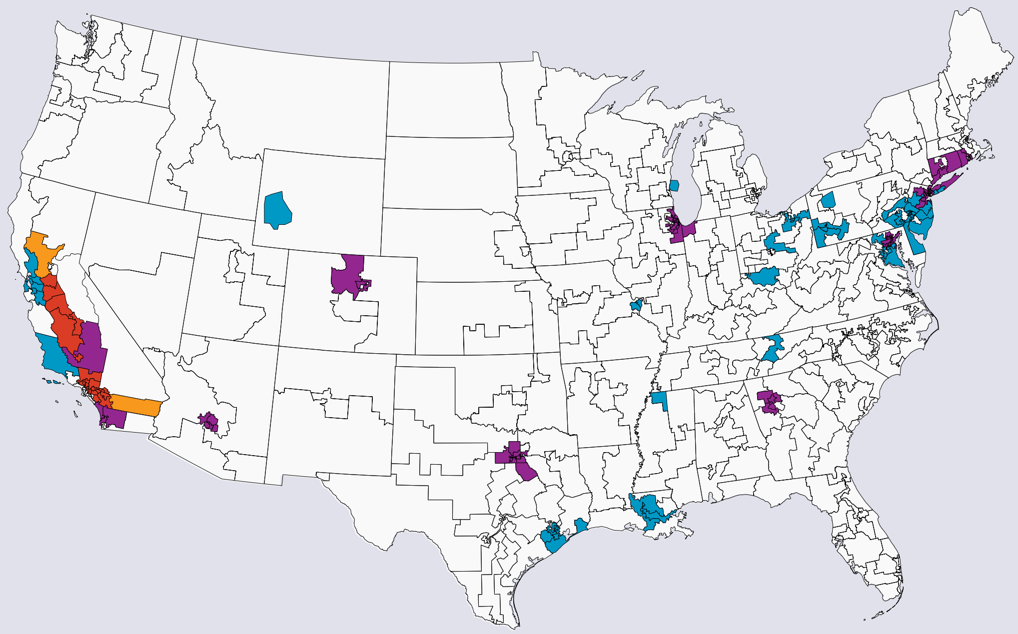
Although a growing multinational corporation, Clean Air Power's parent company, has yet to enter China and is looking for a strategic partnership with either a Western manufacturer with aligned technologies or via the retrofit industry for existing vehicle fleets. Market entry barriers for Vayon include concerns about intellectual property and that the components of Chinese truck manufacturers would not match their current technology offerings, requiring more time, research, and investment in the development phase of a partnership.

production may be the largest source of VOC emissions.[76] Reducing outdoor VOC emissions to levels required to meet standards for ambient ozone concentrations often requires a comprehensive approach that regulates most or all major sources of emissions.

The EPA has regulated VOC emissions from stationary, mobile, and area sources on an ongoing basis since the 1970s. Still, a significant number of areas in the United States do not meet 2008 federal 8-hour standards for ozone (Figure 6), let alone newer (2015) standards.[77] As Figure 6 shows, the most serious non-attainment areas are in California – including the South Coast Air Basin in Southern California and the San Joaquin Valley in Central California.

[76] Buzcu and Fraser (2006).
[77] In 2015, the EPA lowered the 8-hour ozone standard to 70 parts per billion.

Figure 6: Non-attainment Areas for the EPA's 2008 Eight-Hour Ozone Standard



Nonattainment areas are indicated by color. When only a portion of a country is shown in color, it indicates that only that part of the country is within a nonattainment area boundary.

8-hour Ozone Classification

- Extreme
- Severe 15
- Serious
- Moderate
- Marginal

Source: Figure is from EPA, "8-Hour Ozone Nonattainment Areas (2008 Standard)." www3.epa.gov/airquality/greenbook/map8hr_2008.html

2.2.1 Mobile Sources

Gasoline-powered vehicles have historically been the primary source of urban VOC emissions in many parts of the United States.[78] Gasoline engines operate at lower temperatures than diesel engines, leading to more incomplete combustion of hydrocarbons and higher VOC concentrations in the engine exhaust. Because of their comparatively lower boiling point, lighter hydrocarbons in gasoline often evaporate in warmer temperatures, producing VOC emissions. These evaporative emissions can occur when the vehicle is refueling, operating, or sitting idle, particularly on hot summer days.

[78] Pang et al. (2014).

In the United States, control of VOC emissions from the exhaust of gasoline vehicles has historically been through the use of catalytic converters. Since the mid-1970s, new light-duty gasoline-powered vehicles have been required to install these devices.[79] Catalytic converters use a catalyst to oxidize VOCs (hydrocarbons) in the vehicle exhaust, converting them to carbon dioxide and water. Although new catalytic converters can be efficient in reducing VOC emissions, as the catalyst ages its performance deteriorates.[80]

California has regulated evaporative emissions from gasoline vehicles since 1970, requiring manufacturers to install evaporative emissions control (EVAP) systems on new vehicles. EVAP systems collect evaporated hydrocarbons from the fuel tank and route them to a storage canister, where they stay until the engine is started. Once the engine has warmed, the hydrocarbons are siphoned into the engine where they are burned.

Over time, control technologies have evolved to include carbon canisters, low permeation materials, active purge systems, and on-board vehicle refueling vapor recovery (ORVR) systems. Carbon canisters and active purge systems improve the effectiveness of the EVAP system. Low-permeation materials reduce evaporative emissions from hydrocarbons that have permeated materials in the fuel tank. ORVR systems reduce emissions during refueling by directing vapors caused during refueling into the storage canister. The performance of EVAP systems is monitored through an on-board diagnostic system.[81]

Despite significant efforts to control exhaust and evaporative VOC emissions from new gasoline vehicles, total VOC emissions from gasoline vehicles remain high in parts of the United States. For instance, in Southern California, gasoline vehicles are still the largest source of VOC emissions.[82] Most of these emissions are likely from older vehicles with aged or malfunctioning catalysts.[83] To complement on-board control technologies until the vehicle fleet turns over and all vehicles have ORVR systems, states also require VOC recovery systems at gasoline dispensing facilities.[84]

Alternative vehicle mandates have been part of proposals to reduce VOC emissions from vehicles since the 1990s. In states that have greenhouse gas targets, alternative vehicle programs are now being considered to jointly reduce NO_X, VOC, and greenhouse gas emissions. California's zero emissions vehicle program is the most notable of these state programs. California aims to have more than 4 million zero-emissions vehicles (ZEVs) and plug-in hybrid electric, battery electric, and fuel cell vehicles by 2030.[85]

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[79] The EPA required the use of two-way catalytic converters to control carbon monoxide and hydrocarbon emissions beginning in 1975. In 1991, the EPA began to require three-way catalytic converters, which also reduce NO_X emissions.

[80] Catalytic converters also have much lower conversion efficiency at lower temperatures, which means that emissions during startup can be high. These are not a significant contributor to total ambient VOC concentrations.

[81] For more detail on evaporative emissions control technologies, see MECA (2010).

[82] Pang et al. (2015).

[83] Pang et al. (2014).

[84] For more on California's vapor recovery program, for instance, see ARB, "Vapor Recovery Program." www.arb.ca.gov/vapor/vapor.htm

[85] California's Zero Emission Vehicle Action Plan called for 1.5 million zero emissions and plug-in hybrid electric vehicles by 2020 (Governor's Interagency Working Group on Zero-emission Vehicles, 2013). The state's *Mobile Source Strategy*, finalized in 2016, calls for a significant increase in zero emissions and plug-in hybrid electric vehicles, to 4.2 million, by 2030 (ARB, 2016b).

2.2.2.1 Solvents

The EPA has regulated VOC emissions from solvents for nearly three decades. Those efforts have spurred a series of innovations by manufacturers to reduce VOC emissions from their products. For paints, for instance, manufacturers initially developed high-solids coatings and low-density solvents to meet new federal standards in the late 1970s. In states with more stringent standards, they turned to a nonreactive solvent (1,1,1-trichloroethane), though this was later found to be an ozone-depleting substance and was phased out. In the 1990s, the EPA began to regulate hazardous air pollutants, which required paint manufacturers to replace solvents that were classified as hazardous air pollutants.[86] California also began to regulate the use of solvents with high global warming potential (GWP) in 2010.

To meet increasingly strict environmental standards in states such as California, manufacturers of products that have historically used high-VOC solvents are turning to a number of alternatives:

- **Architectural coatings** – nonreactive ("VOC-exempt") solvents, acrylics, alkyd emulsions, 100% solids, and waterborne epoxy and urethanes;
- **Industrial products** – aqueous cleaners, bio-based solvents, VOC-exempt solvents; and
- **Consumer cleaning products** – aqueous cleaners, bio-based solvents, VOC-exempt solvents.[87]

In evaluations, California's air quality regulators have noted that a growing number of products are able to comply with VOC limits and restrictions on ozone-depleting substances, hazardous air pollutants, and high GWP gases.[88] California's experience highlights the importance of regulating multiple pollutants together, encouraging the development of technologies that are able to meet multiple standards.

2.2.2.2 Fugitive Emissions

Fugitive VOC emissions occur during the production, transport, and storage of hydrocarbons. The two main sources of fugitive VOC emissions are leaks in pressurized equipment – for instance, through valves, connectors, pumps, and mechanical seals – and evaporation from wastewater treatment ponds and storage tanks in refineries and chemical manufacturing facilities. Leaks are generally the largest source of fugitive VOC emissions.[89]

EPA and local air regulators require fugitive emissions sources to implement leak detection and repair (LDAR) programs. Identifying the source of leaks is often expensive, as the majority of emissions usually come from a small portion of the total equipment in a facility. Innovations in detection equipment are reducing the costs and improving the effectiveness of LDAR.

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[86] For an overview of the history of VOC regulations from solvents, see Litton (2013).
[87] See South Coast Air Quality Management District, "Reducing VOC Emissions from VOC-Containing Materials." www.aqmd.gov/docs/default-source/planning/architectural-coatings/reducing-voc-emissions-from-voc-containing-materials69bd9aefc2b66f27bf6fff00004a91a9.pdf?sfvrsn=7
[88] Ibid.
[89] EPA (2014).

High-Tech, Low-Cost LDAR

LDAR requirements have been in place in the United States for decades, and solutions are evolving to provide effective, low-cost monitoring strategies for facility operators. The San Francisco–based company Environment Intellect (Ei), for example, has developed LDAR inventory software that allows technicians to quickly begin monitoring with minimal training and cost. Instead of a multi-step process to inventory and monitor LDAR components, Ei's tablet-based software only requires one technician and one trip to conduct an assessment. The result is more efficient and cost-effective monitoring and repair, along with enhanced quality assurance and control features. Ei has implemented its software at more than a dozen refineries in the United States, including one recently in the Bay Area Air Quality Management District.

Ei recently began exploring the Chinese market by using its LDAR software at one of the largest oil refineries in Northern China, which had become subject to new regulations on fugitive emissions. During the project, Ei's software supported the inventorying and monitoring of more than 187,000 LDAR components. Emissions Monitoring Service Inc. (EMSI), another U.S. LDAR company, formed a joint venture company with a firm based in Shanghai after a successful collaboration on a demonstration project. This local partner helps keep EMSI informed about new LDAR regulations and business opportunities in China.

The most important of these technologies is optical remote sensing, which can be used to remotely monitor and record hydrocarbon concentrations around a facility. Among remote sensing technologies, differential absorption light detection and ranging (DIAL) is the most widely used. DIAL has been used to measure VOC concentrations at refineries in parts of Europe for two decades.[90] Use of optical remote sensing in refineries has indicated that VOC emissions from refineries are much higher than reported emissions.[91]

The monitoring applications of optical remote sensing extend beyond refineries and can also be useful for developing facility-specific inventories and mitigation strategies for other emissions, including NO_X, SO_2, and fugitive methane – a potent greenhouse gas. For instance, California's South Coast Air Quality Management District is currently supporting

[90] See, for instance, Frisch (2003).
[91] For an overview, see Cuclis (2012).

a demonstration project that will use advanced optical remote sensing to measure VOC, methane, NO_X, and SO_2 emissions from refineries; VOC and methane emissions from gas stations and oil and gas wells; and smokestack emissions from ships.[92] By detecting methane leakages, remote sensing will facilitate reductions in the state's GHG emissions.

2.3 AIR QUALITY MONITORING AND INDOOR AIR PURIFICATION

Air quality monitoring has long been a critical part of air quality management. New technologies are enabling higher spatial and temporal resolution monitoring of both outdoor and indoor air quality. These, in turn, promise to improve the assessment and mitigation of air quality problems by enabling more tailored solutions. Indoor air purifiers have not seen the same market success in the United States as they have in China, though new technologies are making them smaller, more affordable, and more effective.

2.3.1 Air Quality Monitoring

2.3.1.1 Outdoor Air Monitors

Outdoor air monitoring stations are most often large pieces of equipment that are deployed on a regional scale. These monitors provide crucial information to inform policy and regulatory decisions, but they often do not have the spatial resolution to identify air quality information for "hotspot" areas of interest, such as near highways, factories, and construction sites. To better understand emissions characteristics at higher resolution, two kinds of technologies are emerging in the United States that can complement more traditional air quality monitoring stations.

The first of these technologies is portable handheld devices: small, battery-powered devices with an LCD digital display and USB connector for data logging. Although handheld devices may be installed as fixed monitors on a short-term basis, they more often are used to survey local exposure to pollution. The second technology for higher resolution monitoring is remote sensing. Remote-sensing air quality monitors are a relatively new technology currently under active development by startups and academic institutions. Remote sensors can be installed throughout an area or on vehicles and connect wirelessly to a cloud system. This provides a network of data points, ultimately leading to deeper data resolution to understand how emission sources directly impact surrounding areas in real time.

Handheld and remote-sensing air quality monitors are not a substitute for a regional air quality monitoring network, which in the United States is required through the Clean Air Act to meet standards for quality assurance and control. Used judiciously, however, newer monitoring technologies can be an important complement to more traditional monitoring stations.

2.3.1.2 Indoor Air Monitors

Portable air monitors for home and personal use are an emerging technology for individuals who want to be more aware of the air quality in their spaces and the effects different activities

[92] See South Coast Air Quality Management District, "SCAQMD Awards $1.1 Million for Remote Sensing Projects to Enhance Emissions Monitoring at Oil Refineries, Ships, and Other Sources."
www.aqmd.gov/home/library/public-information/2015-news-archives/remote-sensing-projects

Mapping Air Pollution at the Street Level

Aclima, a San Francisco–based technology company, develops regional sensor networks for environmental monitoring. Aclima and Google have partnered to map air pollution at the street level, with Google Street View cars equipped with the Aclima Ei platform. Capturing street-level environmental data brings the relationships among transportation, infrastructure, urban planning, and air quality into view, at multiple resolutions – from a street corner, to a neighborhood, or an entire city. This work builds on Aclima's and Google's efforts to map the indoor environment across 21 Google offices around the world. The global environmental sensor network is the first of its kind, processing 500 million data points each day. Indoor air quality data will help Google support employee well-being, productivity, and creativity. Aclima also has scientific and research partnerships with the EPA and Lawrence Berkeley National Laboratory to advance environmental sensing technology and methods.

BioInspira, another Bay Area startup, is developing environmental sensors that use patterned viruses designed to bind to specific gas molecules, a technology that the company believes will enable precise monitoring of air pollutants. These emerging technologies could provide resources for regulators, the public, and policymakers to better understand pollution sources and exposures, and make more informed decisions in the future.

may have on pollution levels. Most commercial off-the-shelf devices only count particle level, using nephelometer technology that measures scattered light due to the presence of dust. In recent years, high-end products have been developed that are able to detect airborne particles, VOCs, temperature, and humidity. This involves combining the laser-scattering technology mentioned earlier with MOS-type sensors, which measure the extent to which VOCs obstruct the amount of ambient oxygen adsorbed to the surface of a tin dioxide surface on an electric circuit that permits current flow.[93] Some advanced devices are also able to connect with other smart devices such as smart air purifiers to regulate air quality automatically. To communicate data to the consumer, devices are equipped with an LCD screen, connected to smart phones via Wi-Fi or Bluetooth, or both.

[93] See, for instance, Figaro Engineering Inc., "Operating Principle."
www.figaro.co.jp/en/technicalinfo/principle/mos-type.html

2.3.2 Indoor Air Purifiers

Air purifiers can be used as an additional measure of indoor air pollution mitigation if source control and ventilation improvements are not sufficient to ensure occupant health and comfort, especially when outdoor air is too contaminated to provide clean ventilation. Air purifiers can be installed as a component of a commercial building HVAC system or purchased as a portable device to be plugged into a conventional power outlet and used locally in a single room.

Portable air purifiers of this type are certified by the Association of Home Appliance Manufacturers using a Clean Air Delivery Rate (CADR), which indicates the rate of filtered air delivered and the suggested room size for a particular device.[94] Regulators in China, particularly in coastal cities, have also recently begun to use CADR as the verification standard for air purifiers.[95]

For commercial office buildings in the United States, the American Society for Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) provides an Indoor Air Quality Guide for architects, engineers, and contractors who are designing or maintaining building ventilation systems. These best practices are often translated into building codes that local and state regulators adopt and enforce as standards for minimum ventilation for a building.

Table 7: Air Purifier Technologies

CATEGORY (POLLUTANTS ADDRESSED)	TECHNOLOGY
Particle removal (particulate matter)	Particulate filters
	Ion generators (ionizers)
	Electrostatic precipitators
Gaseous pollutant removal (e.g., VOCs, ozone, SO_2, NO_X)	Gas-phase air filters
Pollutant destruction (gaseous and biological pollutants)	Ultraviolet germicidal irradiation cleaners (biological pollutants)
	Photocatalytic oxidation cleaners (gaseous pollutants)

Source: EPA, "Guide to Air Cleaners in the Home."
www.epa.gov/indoor-air-quality-iaq/guide-air-cleaners-home

[94] See Association of Home Appliance Manufacturers, "What Is the Clean Air Delivery Rate (CADR)?" http://ahamverifide.org/search-for-products/room-air-cleaners/what-is-the-clean-air-delivery-rate-cadr/

[95] Sina, "Results from Sampled Tests of Xiaomi's Air Purifiers: Quality Problems are Serious" (小米空气净化器1被抽查结果：质量问题严重). http://tech.sina.com.cn/mobile/n/n/2016-01-14/doc-ifxnqriz9618705.shtml

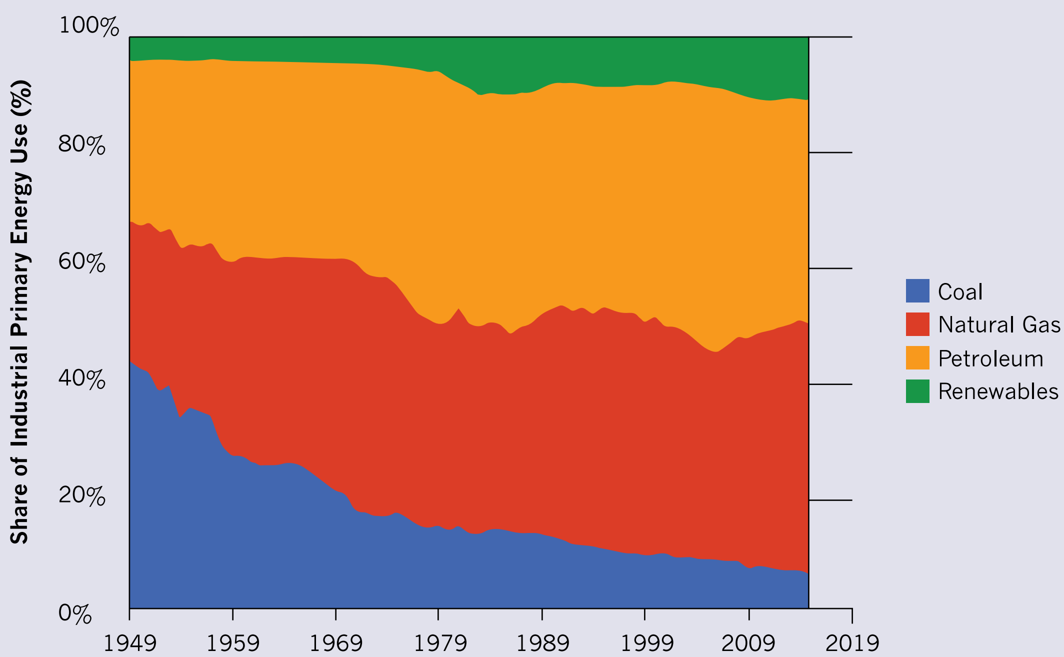
The technology for air purifiers can generally be divided into three categories, each of which addresses different kinds of pollutants (Table 7). These technologies can be integrated into a single air purifier device or used in tandem to optimize the range of pollutants that are eliminated.

2.4 ALTERNATIVE FUELS FOR INDUSTRIAL AND RESIDENTIAL ENERGY USE

The United States faces different challenges than those in China with regard to controlling direct emissions from industrial and residential energy consumption. Unlike in China, the vast majority (95%) of coal consumption in the United States is in the electricity sector.[96] Although coal was the dominant source of primary energy in the U.S. industrial sector in the early 1950s, over the latter half of the twentieth century it was largely replaced by natural gas and accounted for only 6% of total industrial sector energy use in 2015 (Figure7).

In the residential sector, coal, petroleum (heating oil), and biomass accounted for the majority of residential primary energy use in the early 1950s. Over time, natural gas has largely replaced these energy sources (Figure 8). Natural gas now accounts for nearly three-quarters of residential primary energy use, with a smaller share of heating oil (15%) and biomass (7%). Residential primary energy consumption is generally not seen as a major source

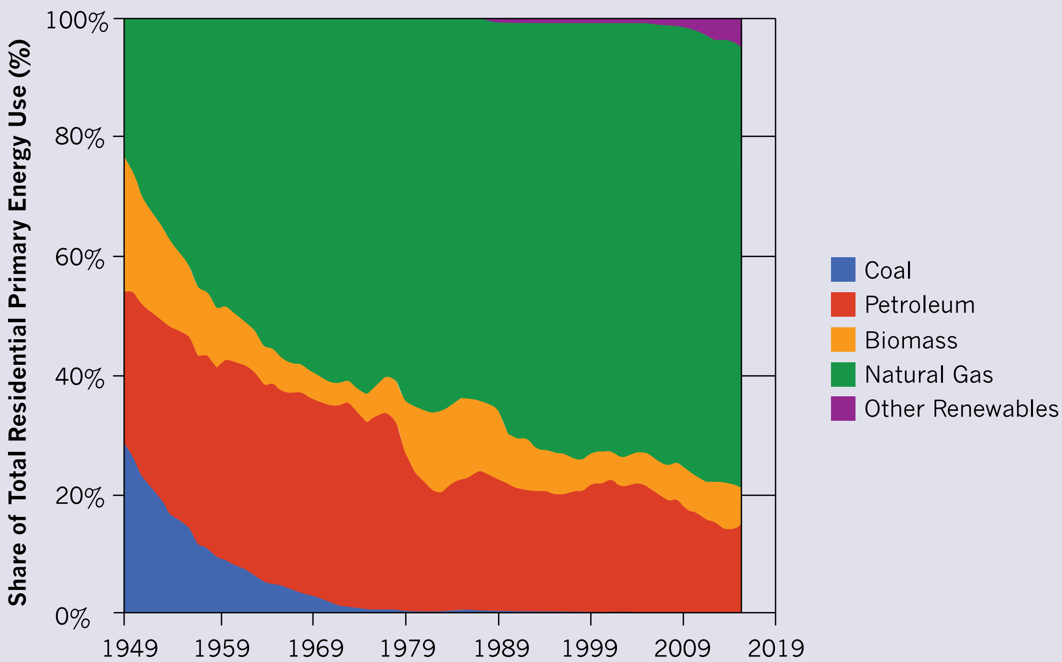
Figure 7: Industrial Primary Energy Consumption in the United States, 1949–2015



Source: Data are from the U.S. Energy Information Administration (EIA) website, www.eia.gov.

[96] Data are from the U.S. Energy Information Administration (EIA) website, www.eia.gov.

Figure 8: Residential Primary Energy Consumption in the United States, 1949–2015



Source: Data are from the U.S. Energy Information Administration (EIA) website, www.eia.gov.

of air pollution in the United States.

However, it is becoming increasingly clear that meeting longer-term GHG reduction goals will require finding substitutes for natural gas use in the residential sector.[97] In California, the two main strategies that have been proposed thus far are (1) blending natural gas with biogas, hydrogen, and synthetic natural gas[98] and (2) electrifying current natural gas end uses, such as space heating and cooking.

Heat pumps have been proposed as one potential technology for electrifying space heating. Heat pumps use electricity to pump a refrigerant that absorbs heat from a colder environment (e.g., outdoor air) and releases it in a heated building (Figure 9). Most of the energy for indoor heating comes from the absorption of outdoor heat, rather than electricity, making heat pumps much more energy efficient than electric resistance heaters. As a result of their greater complexity, heat pumps have a significantly higher upfront cost than electric resistance heaters. Because of their higher efficiency, however, they can be cost effective in areas with higher electricity prices.

[97] See, for instance, Williams et al. (2012) and Williams et al. (2014).
[98] For more on these fuel sources and decarbonizing natural gas supplies, see SoCal Gas, "Decarbonizing the Pipeline." www.socalgas.com/smart-energy/presentations-webinars/decarbonizing-the-pipeline

Figure 9: Typical Air Source Heat Pump

Source: Photo is from www.greenhomegnome.com/wp-content/uploads/2015/01/heat-pump.jpg.

2.5 ULTRA-LOW EMISSIONS CONTROL TECHNOLOGIES FOR COAL-FIRED POWER PLANTS

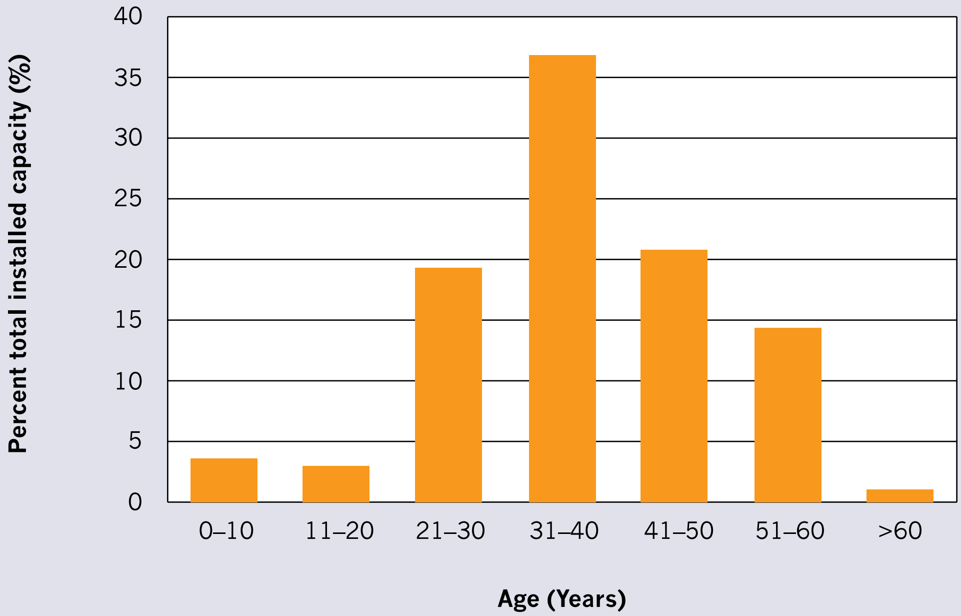
Coal-fired power plants in the United States are, on average, old and highly polluting. The average age of coal-fired generating units in 2010 was 37 years – nearly three-quarters of units are more than 30 years old (Figure 10). Many older coal-fired generating units have not installed pollution control equipment.

The EPA has recently issued a number of regulations that restrict the development of new coal-fired power plants without carbon capture and sequestration (CCS), and require significant emissions reductions for existing power plants. These include, among others:

- *Carbon Pollution Standards*, which establish maximum CO_2 limits on new, modified, and reconstructed power plants;
- *Clean Power Plan*, which creates national CO_2 emissions standards for existing coal-fired power plants;[99]

[99] The U.S. Supreme Court granted a stay for the Clean Power Plan in February 2016.

Figure 10: Age Distribution of Coal-Fired Generating Units in the United States as of 2010



Source: Data are from EIA, "Age of Electric Power Generators Varies Widely." www.eia.gov/todayinenergy/detail.cfm?id=1830

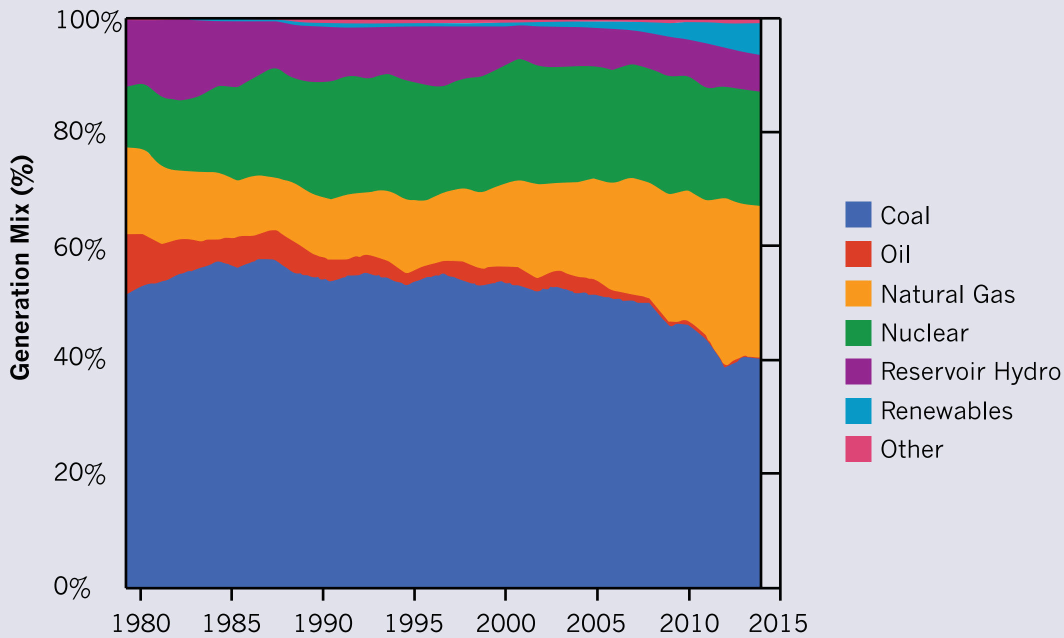
- *Cross-State Air Pollution Rule*, which requires a number of states to reduce sulfur dioxide (SO_2) and NO_X emissions from power plants; and
- *Mercury and Air Toxics Rule*, which regulates emissions of hazardous air pollutants from coal-fired power plants.

Driven by these environmental requirements and low natural gas prices, a number of power plant owners have recently begun to retire older coal-fired generating units. As a result, the share of coal-fired electricity generation in the United States fell from 53% in 2000 to 40% in 2014 (Figure 11). Newer units either meet emissions standards or are being retrofitted with pollution control equipment to meet them.

2.5.1 State-of-the-Art Controls for Coal-fired Power Plants

The four main air pollutants associated with coal-fired electricity generation are SO_2, NO_X, PM, and mercury, though coal-fired power plants also emit a number of toxic air pollutants. Technologies for controlling SO_2, NO_X, and PM from these plants are relatively well established and can achieve high removal efficiencies (Table 8), though even with high removal efficiencies residual emissions can still be significant.

Figure 11: U.S. Electricity Generation Mix, 1980–2014



Source: Data are from the U.S. Energy Information Administration (EIA) website, www.eia.gov.

As in China, flue-gas desulfurization (FGD) is the dominant technology for removing SO_2 in the United States, though only about 60% of coal-fired generation in the United States had FGD controls in 2010.[100] In FGD systems, the flue (exhaust) gas reacts with an alkaline solution ("wet" FGD) or powder ("dry" FGD), typically limestone, removing most SO_2 from the exhaust gases. The EPA reports that wet and dry FGD systems can have removal efficiencies as high as 98% and 93%, respectively,[101] though manufacturers report removal efficiencies as high as 99% for wet FGD.[102] Wet FGD systems can also co-control for other pollutants, such as mercury.[103]

[100] Data are from EIA (2011), "Coal Plants without Scrubbers Account for a Majority of U.S. SO2 Emissions." www.eia.gov/todayinenergy/detail.cfm?id=4410.
[101] EPA (2013), "Documentation for Base Case v.5.13: Emissions Control Technologies." www.epa.gov/sites/production/files/2015-07/documents/chapter_5_emission_control_technologies.pdf
[102] Hitachi reports achieving SO2 removal efficiencies of greater than 99% for wet FGD. See Hitachi (undated), "Recent Operating Results of the Five New Wet FGD Installations for Ameren Corporation." www.psa.mhps.com/supportingdocs/forbus/hpsa/technical_papers/Recent%20Operating%20Results%20of%20the%20Five%20New%20Wet%20FGD%20Installations%20for%20Ameren%202011.pdf
[103] Hitachi reports removal efficiencies of greater than 90% for oxidized mercury for its wet FGD systems. Ibid.

Table 8: Key Control Technologies for Coal-fired Power Plants

POLLUTANT	KEY CONTROL TECHNOLOGY	MAXIMUM REMOVAL EFFICIENCY (%)
SO_2	Flue-gas desulfurization	> 99%
NO_x	SCR	95%
PM	Baghouse filters	> 99%

Source: Table values are based on sources in the text.

As with diesel vehicles, coal-fired power plants in the United States have needed to install SCR systems to meet more stringent NO_X regulations. The EPA reports that SCR can achieve removal efficiencies as high as 90%,[104] though manufacturers report removal efficiencies of up to 95%.[105] To control PM emissions, coal-fired power plants in the United States use a mix of electrostatic precipitators (ESPs) and fabric filters ("baghouses"). Historically, ESPs were the dominant PM control technology, though to meet stricter $PM_{2.5}$ regulations many power plants are shifting to fabric filters. Fabric filters can have removal efficiencies of greater than 99% for both larger diameter (PM_{10}) and smaller diameter ($PM_{2.5}$) PM emissions.[106]

Coal-fired power plants face significant near- to medium-term uncertainty in the United States, in terms of their GHG compliance options. Complying with the carbon pollution standards, for instance, requires that new coal-fired power plants be equipped with CCS. The United States currently has only two CCS projects under construction, and none in operation.[107]

Responding to stricter air quality standards, falling renewable energy costs, low natural gas prices, and the prospect of CO_2 regulations, the share of coal in the U.S. generation mix is expected to continue to decline over time. The U.S. Energy Information Administration (EIA) projects that under the Clean Power Plan, the share of coal-fired generation would fall to 25% by 2030. The energy to replace coal-fired generation would be provided mainly by renewable (63%) and natural gas-fired (33%) generation (Figure 12).

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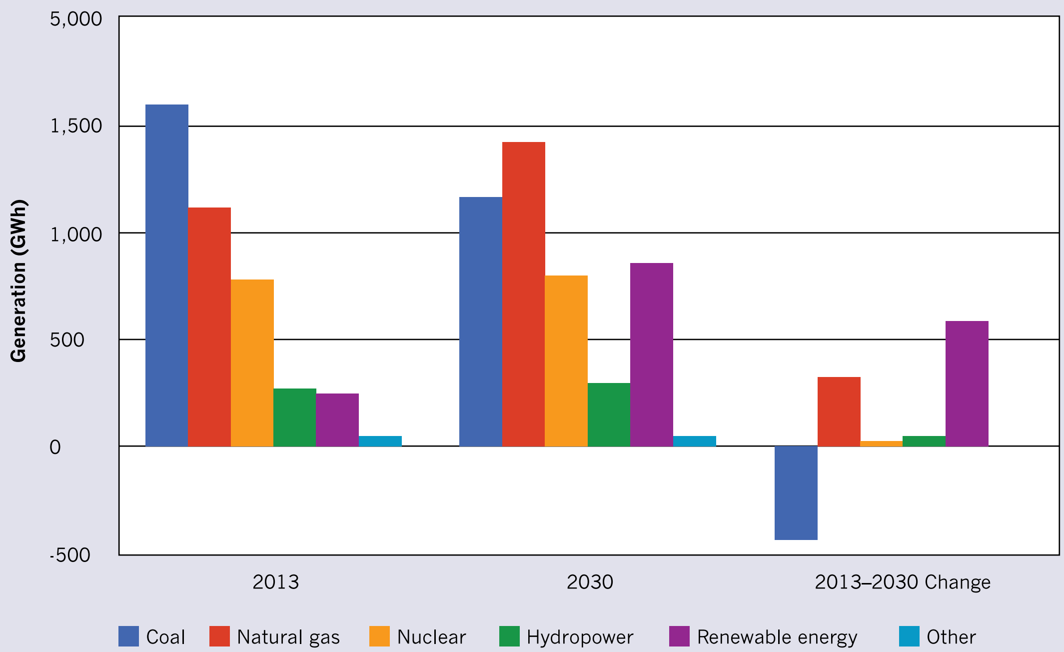
[104] EPA, "Documentation for Base Case v.5.13: Emissions Control Technologies."
[105] GE, "NO_x Control" www.gepower.com/steam/products/aqcs/nox-control.html
[106] See, for instance, Lindsay Morris, "Particulate Matters to EPA: Regulations Affecting PM and Controls for Compliance," Power Engineering, August 2011. www.power-eng.com/articles/print/volume-115/issue-8/features/particulate-matters-to-epa-regulations-affecting-pm-and-controls-for-compliance.html
[107] Data are from MIT's CCS Project Database. http://sequestration.mit.edu/tools/projects/index_capture.html

Figure 12: EIA Projection of U.S. Electricity Generation Mix under the Clean Power Plan



Source: 2030 projections in the figure are based on the EIA's CPP case. See EIA (2015b).

3. CREATING AN ENABLING ENVIRONMENT FOR EMISSIONS CONTROL TECHNOLOGIES: CALIFORNIA'S EXPERIENCE

THIS SECTION DESCRIBES CALIFORNIA'S EXPERIENCE in creating an enabling environment for the development and adoption of emissions control technologies. For context, the section first provides a brief overview of air quality management in the United States.

3.1 AIR QUALITY MANAGEMENT IN THE UNITED STATES

The regulatory framework for air quality management in the United States is rooted in the 1963 Clean Air Act. The Clean Air Act requires the EPA to establish, implement, and enforce national ambient air quality standards (NAAQS) for six "criteria" pollutants. The EPA sets two kinds of air quality standards: (1) primary standards, which are designed to protect human health with an adequate margin of safety and (2) secondary standards, which are designed to protect public welfare and ecosystem health.[108] Current standards are shown in Table 9.

The EPA's process for developing air quality standards consists of three steps:

1. **Standards establishment, review, and revision.** The Clean Air Act requires the EPA to periodically review and update its standards, based on the best available science. The review process is formal and structured, consisting of a review of available science, a quantitative assessment of human health or environmental risks, and an assessment of policy options. Once it has concluded the review process, the EPA issues a notice of proposed rules and begins a comment period during which all segments of the public are allowed to provide comments. The EPA then incorporates comments and issues into a final rule that establishes a new NAAQS.[109]
2. **Designation of attainment status.** Finalization of a new or revised NAAQS sets in motion the EPA's designation process. Within two years of a new NAAQS, the EPA must designate different regions as meeting the standard ("attainment") or not meeting

[108] Public welfare includes maintenance of visibility in key scenic areas and damage to animals, crops, vegetation, and buildings.
[109] For more, see EPA, "Process of Reviewing the National Ambient Air Quality Standards." www.epa.gov/criteria-air-pollutants/process-reviewing-national-ambient-air-quality-standards

Table 9: Current NAAQS for Six Criteria Pollutants

POLLUTANT		PRIMARY/ SECONDARY	AVERAGING TIME	LEVEL	FORM
Carbon monoxide (CO)		Primary	8 hours	9 ppm	Not to be exceeded more than once per year
			1 hour	35 ppm	
Lead (Pb)		Primary and secondary	Rolling 3-month average	0.15 μg/m³	Not to be exceeded
Nitrogen dioxide (NO_2)		Primary	1 hour	100 ppb	98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		Primary and secondary	1 year	53 ppb	Annual mean
Ozone (O_3)		Primary and secondary	8 hours	0.070 ppm	Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years
Particulate matter (PM)	$PM_{2.5}$	Primary	1 year	12.0 μg/m³	Annual mean, averaged over 3 years
		Secondary	1 year	15.0 μg/m³	Annual mean, averaged over 3 years
		Primary and secondary	24 hours	35 μg/m³	98th percentile, averaged over 3 years
	PM_{10}	Primary and secondary	24 hours	150 μg/m³	Not to be exceeded more than once per year on average over 3 years
Sulfur dioxide (SO_2)		Primary	1 hour	75 ppb	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		Secondary	3 hours	0.5 ppm	Not to be exceeded more than once per year

Source: This table is reproduced from EPA, "NAAQS Table." www.epa.gov/criteria-air-pollutants/naaqs-table.

the standard ("non-attainment"). This designation is based on data from air quality monitors and, in some cases, air quality models. States submit recommendations to the EPA on attainment status for different areas. The EPA determines its designation status based on state recommendations and its own review of available data.[110]

3. **Implementation planning for achieving attainment.** Within three years of new

[110] For more, see EPA, "NAAQS Designations Process." www.epa.gov/criteria-air-pollutants/naaqs-designations-process

> NAAQS, states must submit "infrastructure" state implementation plans (SIPs) to the EPA. Infrastructure SIPs are intended to demonstrate that a state has sufficient air quality monitoring and data systems, enforcement programs, and authority and resources to implement a SIP. In addition, within 18 to 36 months of a new NAAQS, states are required to submit SIPs for non-attainment areas. SIPs describe specific control measures to meet a NAAQS. States are required to allow the public to comment on SIPs and formally adopt the control measures laid out in the SIP. These measures are enforceable in federal court and are reviewed to determine their effectiveness. The EPA can issue penalties to states that do not comply with SIP provisions. If states do not submit SIPs, the EPA is required to develop a federal implementation plan (FIP).[111]

In addition to concentration standards for outdoor air, the Clean Air Act also authorizes and requires the EPA to regulate individual emissions sources. The EPA and state environmental agencies take different approaches to regulating different sources.

For mobile sources, the EPA sets national emissions standards and regulates the quality of fuels.[112] In principle, the U.S. Congress can provide specific instructions to the EPA on which emissions and sources should be covered under a standard, at what level the standard should be set, and when it should take effect. Typically, Congress provides broad guidelines and the EPA has more discretion in standard setting. In general, the EPA has broad authority in setting mobile source emissions standards provided it can justify that a proposed standard is necessary to protect public health.

The EPA and state environmental regulators have six "compliance tools" that they use to ensure compliance with mobile source emissions standards:

1. **Certification.** The EPA is required to certify that all new vehicles or engines can meet the emissions standard.
2. **Inspections and investigations.** The EPA has the authority to inspect manufacturers' certification records and facilities, and to pursue an investigation if it believes a manufacturer is submitting fraudulent information.
3. **Selective enforcement auditing.** The EPA requires manufacturers to conduct assembly-line testing of new vehicles.
4. **Recall.** When in-use vehicles are not performing as per their design specifications, the EPA can require a manufacturer to recall and repair or replace vehicles.
5. **Warranty.** The EPA establishes warranties for emissions control devices, such as catalytic converters.
6. **Inspection and maintenance.** States administer vehicle inspection and maintenance programs, which conduct periodic tests of emissions control equipment of in-use vehicles.[113]

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111 For more, see EPA, "NAAQS Implementation Process." www.epa.gov/criteria-air-pollutants/naaqs-implementation-process
112 The two most notable examples of the EPA's regulation of fuels are its mandates for unleaded gasoline and low-sulfur diesel fuel.
113 See MECA, "The U.S. Environmental Protection Agency's Motor Vehicle Compliance Program." www.meca.org/regulation/the-us-environmental-protection-agencys-motor-vehicle-compliance-program

For stationary sources, the EPA sets national emissions standards, it and state agencies review new or modified sources, and state agencies oversee a permitting program for major sources. The EPA's two categories of emissions standards include the New Source Performance Standards (NSPS), which cover criteria air pollutants for new or modified sources, and the National Emissions Standards for Hazardous Air Pollutants (NESHAP), which cover toxic emissions by new or existing sources.

NSPS and NESHAP are source-specific emissions standards, though they may apply to large ("major") sources, such as a boiler or refinery, or small ("area") sources, such as a diesel generator or a small business. EPA sets standards for source categories, and state and local agencies translate these into requirements for individual facilities.

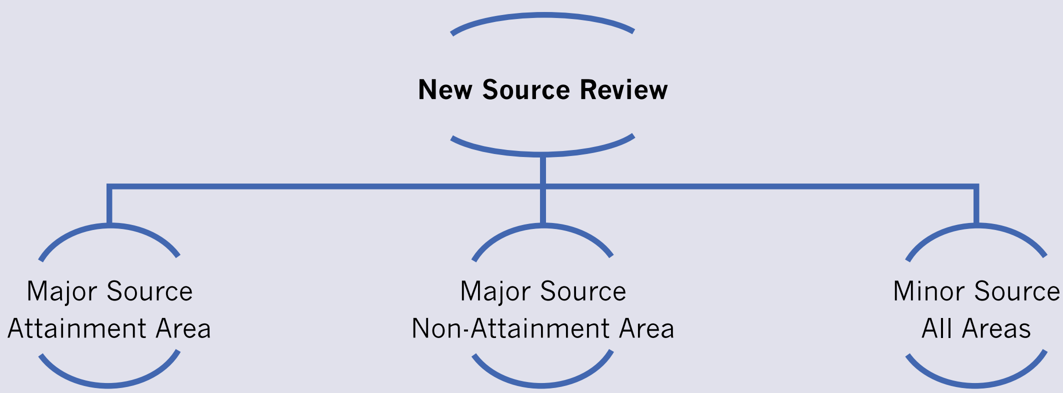
In addition to emissions standards, the EPA and state agencies review new or modified emissions sources through the New Source Review program. This program requires emissions sources to undergo environmental review and obtain a permit before they become operational ("new sources") or are significantly modified ("modified sources"). New Source Review permits are typically issued by state agencies and fall into one of three categories (Figure 13).

For major sources, state agencies issue a "prevention of significant deterioration" permit for sources in areas that are in attainment with national air quality standards and a non-attainment permit for sources in areas that are in non-attainment. The prevention of significant deterioration permit requires that new or modified sources install best available control technology (BACT), and that state agencies and sources ensure that air quality impacts are acceptable. The non-attainment permit requires that new or modified sources meet a lowest achievable emission rate (LAER) and purchase offsets from existing sources. Requirements for minor sources vary across states but are generally designed to ensure that minor sources do not impede states' ability to meet national air quality standards. The New Source Review process provides numerous opportunities for public involvement.

The Clean Air Act also requires owners of large facilities to obtain operating permits on an ongoing basis, once they have begun operation, and operate in compliance with the permit. Operating permits, also known as "Title V" permits, are typically issued by state and local agencies and include reporting requirements. They have a duration of five years, after which they must be renewed. The permit review process allows for public involvement.

At the heart of the U.S. regulatory framework for air quality management – setting of air quality and emissions standards, local implementation planning for achieving compliance, and evaluation and enforcement of compliance – is a science and technology foundation (Figure 14). This foundation provides a basis for identifying risks to human and ecosystem health, translating these risks into air quality and emission standards, and updating standards over time as scientific understanding and technologies improve.

Figure 13: Permits Issued through EPA's New Source Review



3.2 CALIFORNIA'S ENABLING ENVIRONMENT FOR CLEAN AIR TECHNOLOGIES

California has a long history of air quality management. The first reported incidence of smog in Los Angeles occurred in 1943, and the state began actively regulating air quality in the mid-1960s.[114] Improvements in air quality in California since that time have required extensive deployment of new technologies – from catalytic converters to low-VOC solvents. As a result, California has gained considerable experience in creating enabling environments for clean air technologies.

California occupies a unique position in air quality management in the United States. The Clean Air Act prohibits states from setting their own standards for motor vehicles, but it granted California a waiver that allows it to do so. Since then, California has often led the development of federal emissions standards for motor vehicles, working closely with EPA to harmonize standards, methods, and programs.

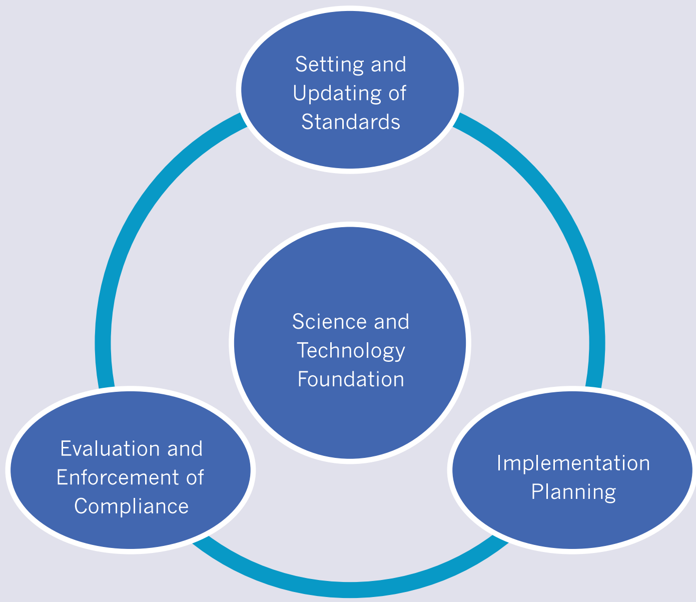
This section describes California's enabling environments for new technologies in three contexts: (1) the state's Diesel Risk Reduction Plan, which aims to achieve aggressive emissions reductions from diesel vehicles by 2020; (2) state VOC regulations for solvents, which are critical to meeting federal ozone standards; and (3) joint statewide air quality and GHG reduction planning, which aims to ensure consistency between efforts to attain compliance with air quality standards and efforts to meet GHG reduction goals.

3.2.1 California's Diesel Risk Reduction Plan

In 1998, ARB concluded a 10-year study on the health impacts of diesel exhaust exposure, which estimated that roughly 70% of airborne cancer risk in California was attributable to

[114] For a time line of air quality management in California, see ARB, "Key Events in the History of Air Quality in California." www.arb.ca.gov/html/brochure/history.htm

Figure 14: Science and Technology Basis of Air Quality Management in the United States



PM emissions from diesel vehicles and engines.[115] ARB subsequently designated PM emissions from diesel sources as a toxic air contaminant and began a dialog with stakeholders on plans to reduce associated emissions. These efforts culminated in ARB's *Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-fueled Engines and Vehicles* ("Diesel Risk Reduction Plan"), which was released in 2000.[116]

The Diesel Risk Reduction Plan was the first policy in the United States to target emissions from in-use diesel vehicles and engines. It set a goal of reducing total PM emissions from all diesel sources by 75% from 2000 levels by 2010, and by 85% by 2020. The plan consisted of three main components:

1. New emissions standards for all diesel vehicles and engines, equivalent to a 90% reduction in 2000 emissions levels;
2. Retrofit requirements for existing diesel vehicles and engines, where cost effective and technologically feasible; and
3. A mandate for low-sulfur diesel (≤ 15 ppm).

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[114] The World Health Organization's International Agency for Research on Cancer (IARC) similarly designated diesel engine exhaust as a carcinogen in 2012. See IARC, "IARC: Diesel Engine Exhaust Carcinogenic." www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf
[115] See ARB (2000).

ARB's plan and goals were informed by a determination that a control technology – diesel particulate filters – was already widely available.

Shortly after the ARB released the Diesel Risk Reduction Plan, the EPA issued new emissions standards for on-road diesel vehicles, requiring diesel on-road vehicle manufacturers to achieve steep reductions in both PM and NO_X emissions from new vehicles beginning in 2007. California adopted the same standards.

The Diesel Risk Reduction Plan's scope and ambition have required ARB to create (1) a comprehensive but differentiated approach to regulating different kinds of diesel vehicles and engines – from heavy-duty trucks to diesel generators; (2) strategies for reducing emissions from in-use vehicles, including flexible compliance strategies; (3) incentives and funding sources for vehicle fleet owners; (4) new enforcement programs; and (5) an open, inclusive stakeholder process.

The remainder of this section describes ARB's approach to addressing these challenges, focusing on how this approach created an environment that encouraged the development and adoption of new technologies.

3.2.1.1 Comprehensive Framework for Regulating Diesel Vehicles and Engines

Diesel vehicles and engines include a large and diffuse set of technologies, including heavy-duty trucks and buses, construction equipment, agricultural equipment, cargo handling equipment, transport refrigeration units, and stationary diesel generators. Implementing the Diesel Risk Reduction Plan required the creation of a regulatory framework for most of these sources.

Table 10 shows ARB's regulatory strategies for a number of different diesel emissions source categories. Each of these categories required a specific regulatory program.

ARB's general approach is consistent across most source categories. For new diesel engines, ARB requires manufacturers to certify that their products meet emissions standards through emissions testing procedures. For in-use diesel engines, ARB established best available control technologies ("verified diesel emissions control strategies," or VDECS) and requires vehicle or equipment owners to either install VDECS or meet fleet average emissions standards or other performance requirements by replacing vehicles and equipment. ARB's Truck and Bus Regulation, discussed in more detail in the next section, sets a schedule for in-use on-road vehicles to comply with emissions standards for new vehicles.

California has limited regulatory jurisdiction over some diesel emissions sources, such as ocean-going marine vessels and locomotives. To achieve emissions reductions from these sources, ARB used a combination of three strategies: (1) working collaboratively with EPA, which does have regulatory jurisdiction; (2) signing agreements with operators, such as railroad owners; and (3) issuing regulations that cover the portions of travel or use where California does have regulatory jurisdiction.

The third strategy has been most notably used for reducing emissions from marine vessels when they are near the California coast. ARB's At-Berth Regulation requires ship operators to reduce emissions while they are docked in port by 50% by 2014, 70% by 2017, and 80% by 2020. The main strategy for complying with these regulations is shore power, or when ships turn

Table 10: ARB's Regulatory Strategies for Different Diesel Emissions Source Categories

CATEGORY	REGULATION	STRATEGY
New on-road vehicles	Certification requirements	Certify that new engines meet emissions standards using testing procedures
In-use on-road vehicles	Truck and Bus Regulation (2008)	Set timeline for achieving standards compliance for existing vehicles
New off-road vehicles	Certification requirements	Certify that new engines meet emissions standards using testing procedures, expand inspection programs
In-use off-road vehicles (non-agricultural, non–cargo handling)	In-Use Off-Road Diesel Vehicle Regulation (2007)	Establish best available control technologies, set fleet average emissions factor targets, mandate reporting of all off-road vehicles to ARB, restrict additions of older vehicles to fleets
In-use off-road vehicles (cargo handling)	Regulation for Mobile Cargo Handling Equipment at Ports and Intermodal Rail Yards (2006)	Establish best available control technologies, set compliance schedule, establish inspection program
Locomotives	Agreements and memoranda of understanding	Encourage use of low-sulfur diesel, evaluate pollution control measures, encourage reduced idling
Marine vessels	Ocean-Going Vessel Fuel Regulation (2008) At-Berth Regulation (2007)	Require use of lower sulfur distillate fuel when near California coast, require use of shore power
Harbor craft*	Commercial Harbor Craft Regulation (2009)	Require use of lower sulfur diesel, establish best available control technologies, set compliance schedule
New stationary diesel engines	Stationary Diesel Engine Regulation (2011)	Certify that new engines meet emissions standards using testing procedures
In-use stationary diesel engines	Stationary Diesel Engine Regulation (2011)	Require use of lower sulfur diesel, set emissions standards

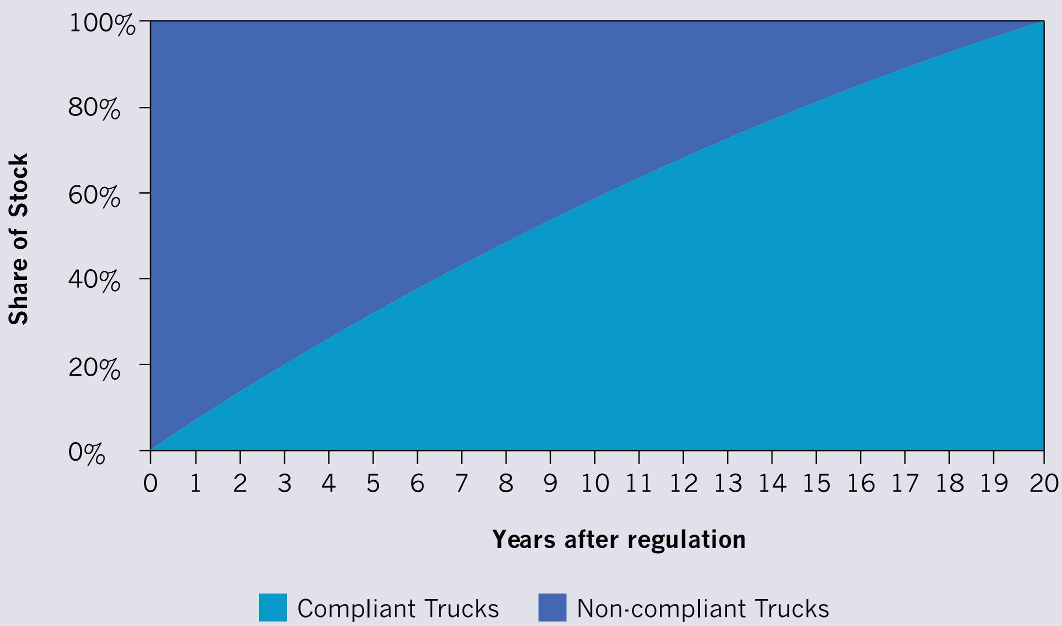
* Harbor craft includes "crew and supply boats, charter fishing vessels, commercial fishing vessels, ferry/excursion vessels, pilot vessels, towboats or push boats, tugboats, and work boats."

off all engines and plug into a power source. ARB also requires ships near the California coast to use low-sulfur distillate fuel.

3.2.1.2 Strategies for Reducing Emissions From In-Use Diesel Vehicles

Meeting the Diesel Risk Reduction Plan's total PM reduction goals required strategies for dealing with emissions from in-use vehicles and engines, while minimizing the financial impacts on vehicle owners. Diesel trucks, for instance, typically have more than 20-year lifetimes; thus, the composition of the diesel truck fleet changes slowly over time. As a result, the share of trucks in the fleet that are compliant with new emissions standards increases slowly over time. Figure 15 shows a simple illustration, in which 10 years after a regulation only 60% of the truck fleet is in compliance.

Figure 15: Illustration of Compliant and Noncompliant Trucks over Time, after Issuance of Regulation, Assuming 20-Year Average Vehicle Lifetime and 2% Annual Stock Growth



Source: This simple, illustrative example assumes that vehicles are replaced at the end of a 20-year lifetime, which implies that 5% of the initial vehicle stock is replaced in a given year (i.e., no new vehicles are being replaced until year 21).

To address emissions from in-use on-road diesel vehicles, ARB issued its Truck and Bus Regulation in 2008, which seeks to accelerate the natural turnover of the in-use fleet. It sets schedules for different vintages ("model-years") and weights ("heavier" and "lighter") of in-use trucks and private buses to install particulate filters and comply with federal PM and NO_X emissions standards, which apply to model-year 2010 and later vehicles. Table 11 shows the compliance schedule for heavier vehicles.

The Truck and Bus Regulation applies to all operators of diesel vehicles – from logistics companies to construction companies to bus lines. For truck and bus fleet owners, complying with the schedule requires replacing vehicles once they are just over 20 years old, either with a new vehicle or with an older vehicle that is still compliant under the schedule (e.g., a model-year 1997 vehicle could be replaced in 2021 with a model-year 2005 vehicle that has a particulate

Table 11: Truck and Bus Regulation Schedule for Emissions Control Compliance for Heavier Vehicles

VINTAGE	COMPLIANCE SCHEDULE
Pre-1994	No requirements until 2015, then must meet model-year (MY) 2010 emissions standards
1994–1995	No requirements until 2016, then must meet MY2010 emissions standards
1996–1999	Must install PM filter by 2012, must meet MY2010 emissions standards by 2021
2000–2004	Must install PM filter by 2013, must meet MY2010 emissions standards by 2022
2005–2006	Must install PM filter by 2014, must meet MY2010 emissions standards by 2023
2007–2009	No requirements until 2023,* then must meet MY2010 emissions standards
2010	Meets MY2010 emissions standards

* MY2007 and newer vehicles are required to be equipped with factory-installed diesel particulate filters to meet PM standards.

Source: ARB, "Truck and Bus Regulation Compliance Requirements Summary." www.arb.ca.gov/msprog/onrdiesel/documents/FSRegSum.pd

matter filter installed). By 2023, all vehicles in truck and bus fleets are, at a minimum, required to comply with model-year 2010 emissions standards.

ARB created a number of options to provide vehicle fleet operators with greater compliance flexibility for in-use vehicles, in order to limit the number of upgrades operators would be required to undertake in any given year to less than 25%:

1. An opt-in "phase-in option" that enabled fleet owners to comply with PM and NO_X standards on a fleet-wide basis, rather than on the basis of the compliance schedule;[117]
2. An opt-in "small fleet option" that enabled owners with small fleets (one to three vehicles) to comply on a numbers-of-vehicles basis, rather than on the basis of the compliance schedule;[118] and

[117] More specifically, this option required fleet owners to have diesel particulate filters on 30% of vehicles by 2030, 60% by 2013, 90% by 2014 and 2015, 100% by 2016, and all vehicles meeting PM and NOX standards by 2020.
[118] More specifically, this option required fleet owners to have one compliant vehicle by January 1, 2014, two by January 1, 2017, and three by January 1, 2018.

3. Compliance extensions for vehicles that are infrequently used or used for short trips, agricultural vehicles, and vehicles in less polluted areas.

For truck and bus operators who use these flexible compliance options, ARB created a reporting system whereby operators must identify vehicles that will use a particular option and provide required information (e.g., mileage for low-use vehicles) at the beginning of each compliance year.

3.2.1.3 Incentives and Funding Programs

Incentive funding is an important complementary policy to regulatory requirements. Upgrading and retrofitting a diesel vehicle and engine stock require significant capital investments. New heavy-duty trucks, for instance, typically cost between $100,000 and $150,000. To help diesel vehicle and engine owners achieve earlier compliance with – and exceed requirements for – its regulations, ARB has created funding assistance programs:

- **Low-interest loans.** Through a partnership with the California Pollution Control Financing Authority (CPCFA), ARB's Providing Loan Assistance for California Equipment (PLACE) program offers low-interest loans to vehicle or equipment owners. The CPCFA is funded through tax-exempt bonds.[119]
- **Direct incentives.** The Carl Moyer Memorial Air Quality Standards Attainment program, a partnership between ARB and local air quality management districts, provides roughly $60 million per year in grant funding to owners of on-road vehicles, off-road vehicles and equipment, agricultural equipment, trains, marine vehicles, and light-duty vehicles. The program is funded through a surcharge on tires and vehicle registrations. Funding levels vary by vehicle type and the emissions level of the new vehicle. For instance, the Carl Moyer program's On-Road Heavy-Duty Fleet Modernization source category provides funding to accelerate retirement of older, higher-emitting vehicles, with maximum amounts tied to emissions levels and vehicle gross weight (Table 12).[120]

These funding programs provide an important mechanism for encouraging adoption of cleaner technologies. Through these programs, California has invested heavily in reducing pollution from its existing fleet of diesel vehicles and engines.

3.2.1.4 Enforcement Programs

Enforcement of the Diesel Risk Reduction Plan built on ARB's existing inspection, maintenance, and labeling programs and collaborative activities, including the following:

- The Heavy-Duty Vehicle Inspection Program, which conducts random roadside inspections to ensure that vehicles are not smoking excessively, that they have not been

[119] For more on the CPCFA, see www.treasurer.ca.gov/cpcfa/
[120] For more on the Carl Moyer program, see www.arb.ca.gov/msprog/moyer/moyer.htm

Table 12: Maximum Funding Levels by Vehicle Type and Certified Emissions Level under the Carl Moyer Program's On-road Heavy-duty Fleet Modernization Source Category

VEHICLE TYPE	CERTIFIED EMISSIONS LEVEL	MAXIMUM FUNDING LEVEL
Heavy heavy-duty	0.20 g/bhp-hr	$60,000
	0.50 g/bhp-hr	$50,000
	1.20 g/bhp-hr	$40,000
Medium heavy-duty	0.20 g/bhp-hr	$40,000
	0.50 g/bhp-hr	$30,000
	1.20 g/bhp-hr	$25,000
School bus	n/a	100% of vehicle value
		100% of invoice

Source: Table values are based on sources in the text.

tampered with, and that they have appropriate emissions labels;

- The Periodic Smoke Inspection Program, which requires vehicle owners to conduct annual smoke opacity tests and maintain records for two years for each vehicle;
- Emissions Control Labels, which are required on engines of all heavy-duty vehicles and VDECS certifying that they comply with emissions standards; and
- Collaboration on enforcement with EPA and local air quality management districts.

ARB's enforcement programs were designed before the extensive use of exhaust aftertreatment systems to control NO_X and PM emissions. They were also designed before the required use of on-board diagnostic (OBD) systems, which monitor the performance of the vehicle's engine and emissions control systems. Regulators can use OBD systems to ensure that emissions control equipment is performing as expected, and that vehicle owners are maintaining and using control equipment.

To account for these changes, ARB is currently developing a proposal for amendments to the Heavy-Duty Vehicle Inspection Program and Periodic Smoke Inspection Program, to be implemented in 2017, and more comprehensive changes in the inspection and maintenance program for heavy-duty vehicles by 2020.[121]

[121] ARB, "Public Workshop to Discussion Potential Changes to the Heavy-Duty Vehicle Inspection Program and Periodic Smoke Inspection Program and Plans for a Future, Comprehensive Heavy-Duty Vehicle Inspection and Maintenance Program." www.arb.ca.gov/msprog/mailouts/msc1605/msc1605.pd

3.2.1.5 Stakeholder Engagement

From the outset, ARB attempted to ensure that the Diesel Risk Reduction Plan's development and implementation were open and inclusive. Shortly after its designation of diesel PM as a toxic air contaminant in 1998, ARB formed a Diesel Advisory Committee that included staff from ARB, EPA, other state and local government agencies, industry, environmental groups, and other organizations. The Advisory Committee guided ARB in developing the Diesel Risk Reduction Plan through a combination of formal and individual meetings.

As ARB began to develop specific regulations to implement the Diesel Risk Reduction Plan, it conducted public workshops throughout the state to solicit inputs from manufacturers, vehicle owners, other industry groups, and environmental groups. It created stakeholder advisory committees for individual regulations, such as the Truck Regulations Advisory Committee for the Truck and Bus Regulation, as a means to better communicate with stakeholders and identify implementation issues.

Stakeholder engagement allowed for targeted flexibility to be built into the Truck and Bus Regulation (see Section 2.2.1.2), likely increasing its chances of success and lowering the overall cost of compliance. Engagement with stakeholders also allowed ARB to openly and explicitly address stakeholder concerns about the cost, effectiveness, and safety of diesel particulate filters, which it did through a field investigation.[122]

3.2.2 VOC Regulation in California

California began to regulate VOC emissions from mobile and area sources in the 1960s to address ozone pollution in the Los Angeles Basin.[123] Shortly thereafter, the U.S. government followed suit. The 1970 Clean Air Act Amendments required the EPA to set hydrocarbon (VOC) emissions standards for light-duty vehicles and new source performance standards for VOC-emitting stationary sources. VOC limits for area sources, such as solvents, were addressed in the 1977 Clean Air Act Amendments. California has often led U.S. federal regulations for VOC emissions, setting more stringent limits on a broader range of activities and products.

This section examines emerging approaches in California to regulate VOC and other emissions from solvents, which may also be a source of greenhouse gas, ozone-depleting substance, or hazardous air pollution emissions depending on the chemical compounds involved.

3.2.2.1 Area Source Regulation of Multiple Pollutants: Solvents

Regulation of solvent emissions involves a complex overlay of regulation and regulatory agencies. The EPA regulates ozone-depleting substances in solvents, in accordance with U.S. commitments under the Montreal Protocol. The EPA also regulates hazardous air pollutants from solvents and other substances, based on the framework established in Title III of the 1990 Clean Air Act Amendments. California's 1987 Air Toxics "Hot Spots" Information and Assessment Act

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122 ARB (2015b).

123 Regulatory efforts included Rule 66 to limit reactive VOC emissions from solvents, adopted by the Los Angeles Air Pollution Control District in 1966, and hydrocarbon emissions standards from light-duty vehicles, established by the California Motor Vehicle Pollution Control Board, also in 1966.

requires facilities to calculate, report, and control emissions of controlled substances, including solvents. ARB's Air Toxics Program has banned the use of some solvents.[124]

The environmental impacts of VOC emissions from solvents, alternatively, are local rather than regional. Rural parts of California, for instance, may have low ozone concentrations because of low NO_X emissions. Thus, in California VOC limits on solvents are regulated by local air quality districts, rather than by ARB.

This multi-level regulatory framework creates a patchwork of regulations. Some solvents that use ozone-depleting substances are effectively banned, while the production and import of others are scheduled to be phased out by 2020. Title III requires the control, but not the outright ban, of hazardous air pollutants. Local regulation of VOC emissions can result in different VOC limits for the same product in different counties within the same state.

Standardization and labeling have helped overcome the challenges of regulating the multi-pollutant nature of solvents and their varying local and non-varying global impacts. For instance, to encourage greater convergence in VOC limits across California, ARB has published "suggested control measure" guidelines since 2000, drawing on rules adopted by the South Coast Air Quality Management District. These guidelines are model rules that local air quality districts can adapt to their local requirements.

To allow more informed decision making by end users and greater ease of compliance for manufacturers, the South Coast Air Quality Management District developed voluntary certification programs for "clean air solvents." Certification for a clean air solvent requires that the product meet emissions criteria for multiple pollutants:

- Contains no more than twenty-five (25) grams of VOC per liter of material, as applied;
- Has a VOC composite partial vapor pressure less than 5 mm Hg at 20° C (68° F);
- Reacts to form ozone at a rate not exceeding that of toluene;
- Contains no compounds classified as Hazardous Air Pollutants (HAPs) by the Federal Clean Air Act, or Ozone Depleting Compounds (ODCs) and Global Warming Compounds (GWCs) as defined by the District; and
- Has been certified by the district to meet the criteria stated above according to test methods and procedures approved by the District.[125]

3.2.3 Joint Air Quality and Greenhouse Gas Planning in California

As a result of recent strengthening of its 8-hour ozone standard (in 2008) and annual standard for $PM_{2.5}$ (in 2012), the EPA designated a number of areas within California as being in non-attainment. This designation requires ARB to develop a state implementation plan demonstrating how these areas will achieve attainment starting in the early 2020s.[126] At the

[124] For instance, ARB's Airborne Toxic Control Measure for Emissions of Hexavalent Chromium and Cadmium Motor Vehicle and Mobile Equipment Coatings bans hexavalent chromium and cadmium from automotive coatings.
[125] SCAQMD (2014).
[126] Specifically, 16 areas in California must achieve attainment of the 8-hour ozone standard, with attainment dates ranging from 2017 in moderate non-attainment areas to 2031 in the two extreme non-attainment areas – the South Coast and San Joaquin Air Quality Management Districts. The four areas in California that were designated as non-attainment for the $PM_{2.5}$ standard are required to achieve "moderate area" compliance by 2021. See ARB (2016).

same time, California's 2006 Global Warming Solutions Act (Assembly Bill, or AB, 32) and subsequent executive orders have set targets of reducing the state's GHG emissions by 20% from 1990 levels by 2020, 40% by 2030, and 80% by 2050.[127] ARB is required to develop "scoping plans" that describe how the state will meet the 2020 and 2030 targets.

Many of the strategies to meet federal air quality standards and GHG reduction goals – technologies, policies, and regulations – will overlap. Additionally, given the time and investment needed to develop and deploy new technologies, meeting air quality standards and GHG reduction goals in tandem will likely be less costly than meeting them separately. ARB has created a number of mechanisms to better coordinate between state planning for air quality and GHG emissions reductions. Two of these mechanisms are described next.

3.2.3.1 Strategy and Visioning Studies

ARB has historically used public studies to develop strategies and targets for achieving longer-term goals. For instance, what technologies might be required to meet these goals? Can they be met with existing technologies, or do they require the development of new technologies ("technology forcing")? What kinds of technologies and regulations are likely to be most effective in meeting goals, and in which sectors? Studies addressing these kinds of questions often accompany state implementation plans and GHG planning, and they are often made through white papers or reports. Two recent studies illustratse this approach in the context of coordinated air quality and GHG planning.

In some parts of California, meeting federal ozone standards will require nearly 90% reductions in NO_X emissions by the early 2030s.[128] Mobile sources are the largest source of NO_X emissions in California. Thus, achieving these levels of NO_X reductions will require the large-scale deployment of near-zero- to zero-emissions vehicles, and in particular passenger cars and trucks.

In 2012, ARB released its study *Vision for Clean Air: A Framework for Air Quality and Climate Planning*, which quantitatively examined the technological transformations needed to meet longer-term air quality and GHG goals through scenario analysis, focusing on mobile sources.[129] The study asked: How are strategies to meet air quality and GHG goals complementary? How do they differ? What are the key decision points for technology development and deployment? How do these decisions impact energy infrastructure investment decisions? What does the scope of technological change imply for coordinating future planning efforts?

The *Vision for Clean Air* study highlighted the significant nature of technological change required to meet both air quality and GHG goals, implying a longer-term transition to zero to near-zero emissions vehicle technologies. It also illustrated the variety of technologies available to meet both goals, the need for a diverse portfolio of emissions reduction strategies, and the importance of coordinated air quality and GHG planning to evaluate trade-offs and linkages among strategies and technologies.

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[127] The 2030 goal was signed into legislation through Senate Bill 32 in September 2016.
[128] ARB (2016a).
[129] ARB (2012).

In 2016, ARB followed the *Vision for Clean Air* with its *Mobile Source Strategy*, which lays out a 15-year (2015–2030) strategy for mobile emissions sources to simultaneously meet air quality and greenhouse gas emissions reduction goals.[130] The *Strategy* draws on an updated version of the scenario-planning tool developed in the *Vision* study, and it uses quantitative analysis to back its recommendations. It favors supporting a significant increase in sales of zero-emissions light-duty vehicles, as well as developing the infrastructure to support them. For heavy-duty vehicles, the *Strategy* recommends a 90% reduction in NO_X emissions standards, fuel efficiency improvements, support for renewable fuels, and longer-term transition to zero and near-zero technologies.

Both the *Vision for Clean Air* and the *Mobile Source Strategy* are publicly available documents that incorporated comments from the public. This process of developing longer-term vision and strategy helps provide manufacturers with greater certainty on longer-term regulatory requirements and required technologies.

3.2.3.2 Coordination between planning processes

In addition to visioning and strategy planning documents, ARB created linkages between the air quality (state implementation) planning and greenhouse gas reduction plans. California's Global Warming Solutions Act (AB32) requires the state to develop a "scoping plan" every five years that details how the state will meet interim (2020, 2030) targets for greenhouse gas emissions reductions. Practically, coordination between the two planning processes has been achieved by using the outputs of one plan as inputs in another. For instance, the South Coast Air Quality Management District's air quality plans include statewide measures from the scoping plan.[131] This kind of coordination requires greater collaboration among local air quality management districts, ARB, and state energy regulators.

This coordination between planning processes enables lower-cost solutions to meeting air quality and climate goals by ensuring that the emissions benefits of control measures that reduce multiple pollutants are accounted for in different plans. If implementation plans for different pollutants are undertaken in isolation, there is a potential for implementing measures that work at cross-purposes, or for implementing costly measures that are not needed to meet goals.

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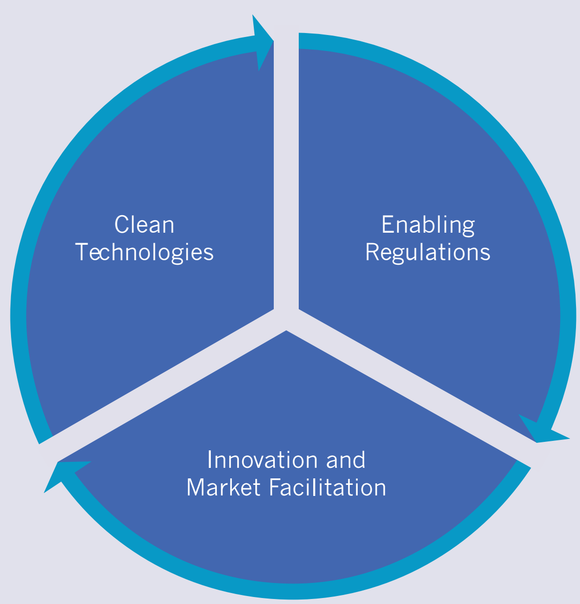
130 ARB (2016b).

131 See South Coast Air Quality Management District, "Preliminary Draft of SCAQMD 2016 AQMP Stationary Source Measures." www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2016-air-quality-management-plan/control-strategies/1_stationarysourcemeasures_040816.pdf?sfvrsn=4

4. PRIORITY AREAS FOR CHINA-U.S. COLLABORATION ON CLEAN AIR TECHNOLOGIES AND POLICIES

CHINA AND THE UNITED STATES HAVE A LONG HISTORY of cooperation on environmental policy and technology, at both national and local levels.[132] As both countries make continued efforts to improve air quality and reduce greenhouse gas emissions, there are opportunities for sharpening existing collaboration and expanding collaboration to new areas. Drawing on the previous analysis and a short survey of U.S.-based manufacturers, this section assesses priority areas for near-term collaboration in the three interactive areas shown in Figure 16.

Figure 16: Three Categories of Priorities for China-U.S. Collaboration on Clean Air Technologies



[132] For an overview of the EPA's collaborative activities with China, for instance, see EPA, "EPA Collaboration with China." www.epa.gov/international-cooperation/epa-collaboration-china. For an overview of California's governmental and non-governmental partnerships with China on climate policy and clean energy, see Asia Society (2014).

4.1 CLEAN TECHNOLOGIES

Which emerging clean technologies in the United States have the potential to have transformative impacts in China? Our assessment of priority technology areas is based on three criteria:

1. Do the technologies in this area address a critical air quality issue in China?
2. Are technologies commercially available or can they be in the near term?
3. Do the technologies in this area have the potential to reduce multiple kinds of emissions, in particular air pollutant and GHG emissions?

Based on these criteria, we identify five priority technology areas, listed next.

Advanced air quality monitoring. Improvements in information and communications technology are enabling the development of advanced air quality monitors that can monitor pollution anywhere and generate data in real time, as part of or complementing a regional air quality monitoring network. For China, advanced air quality monitors have particular promise. As part of, or checked against, regional monitoring networks, they can shed new light on patterns in the timing and location of pollution, leading to a better understanding of emissions sources and exposure levels and a more informed prioritization of strategies to control the most harmful sources of pollution. New approaches and technologies for monitoring air quality are now being developed, tested, and demonstrated in the United States.

Integrated designs and clean fuels for heavy-duty vehicles. Heavy-duty diesel vehicles are a major source of $PM_{2.5}$ and NO_X emissions in China and the United States. In the United States, a decade of federal emissions standards for new on-road diesel vehicles has encouraged new integrated engine and pollution control system designs that meet low emissions standards while optimizing fuel efficiency and vehicle performance. In China, the availability of these technologies would enable air regulators to address a major source of pollution by lowering emissions standards for new heavy-duty vehicles. Over the longer term, there is considerable potential for China and the United States to partner in the development of a next generation of emissions controls and cleaner fuels for heavy-duty vehicles, which states such as California anticipate needing by 2030 to meet air quality and climate policy goals.

Electrification of passenger vehicles and buses. Electrification of passenger vehicles, buses, and short-haul trucks represents an important area in which air quality and climate policies can be pursued in tandem. Electric vehicles have no tailpipe emissions and may be a low source of overall emissions depending on the source of their electricity. A number of Chinese cities are encouraging adoption of electric cars and buses. Several U.S. states, led by California, have goals for the rapid deployment of electric and other zero-emissions vehicles over the next decade. New and lower-cost battery technologies, as well as new information and communications technologies for integrating electric vehicles into electricity systems, could have a transformative impact on vehicle adoption. Innovative work in this area is ongoing in both China and the United States.

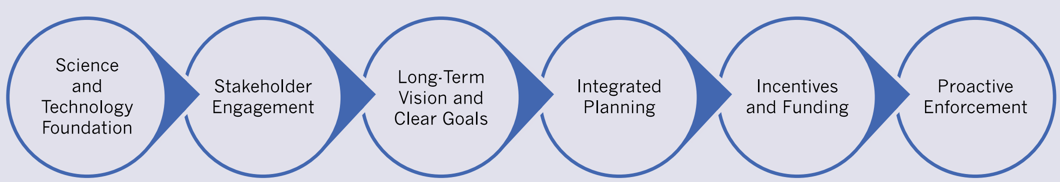
Low environmental impact solvents. Solvents – used in paints, lubricants, inks, adhesives, and cleaning products – are often the second-largest source of VOC emissions, which contribute to ozone pollution. Substitutes for high-VOC solvents may lead to other environmental problems, such as ozone depletion, climate change, or hazardous indoor air quality. China has only recently begun to regulate VOC emissions from solvents; in urban areas, controlling solvent emissions will likely be a critical measure for managing ozone. A new generation of solvent technologies is emerging in the United States that can meet limits for multiple pollutants, while still delivering desired performance.

Leak detection and repair for refineries, chemical facilities, and pipelines. Refineries and chemical facilities are a major source of fugitive VOC emissions and hazardous air pollutants. Natural gas wells and pipelines are a major source of fugitive methane, a potent greenhouse gas. In many cases, these emissions result from leaks in equipment that have historically been difficult and costly to detect and repair. In China, refineries, chemical facilities, and pipelines have only recently begun to come under greater regulatory scrutiny. In the United States, emissions from refineries, chemical facilities, and pipelines have been regulated for decades, but studies have shown that actual emissions from these facilities are much higher than reported emissions. New remote sensing technologies are emerging in the United States that enable better control of fugitive VOC and methane emissions, by lowering the cost of leak detection and repair.

4.2 ENABLING REGULATORY ENVIRONMENT

Which approaches to enabling regulation for clean technologies in the United States could be a useful reference for China? California has more than 60 years of experience in creating a regulatory environment that enables the development and deployment of clean technologies. We identify a number of areas where California's experience could provide a useful reference for policymakers and regulators in China. These include the importance of six elements, shown in order of sequential importance in Figure 17.

Figure 17: Priority Areas for Creating a Regulatory Framework That Enables Clean Air Technologies



Science and technology foundation. Science and technology are the basis for understanding air quality, its impacts on human and ecosystem health, and measures for mitigating its impact. California and U.S. experience demonstrates the importance of rooting air quality management in a science and technology foundation for setting and updating air quality and emissions standards, implementation planning, and developing an economic framework for prioritizing control measures.

Stakeholder engagement. Engaging stakeholders, and particularly industry stakeholders, early in the process of developing new regulations creates the trust, consensus, and buy-in needed to enable larger-scale technological change. There are a number of approaches to engaging stakeholders: advisory committees with broad representation that help to guide the development of standards and programs, public workshops that describe proposed regulatory changes and incorporate stakeholder feedback, and ongoing engagement through committees. The implementation of California's Truck and Bus Regulation (Section 3.2.1.2) illustrates the ways in which stakeholder engagement can help negotiate the flexibility needed by industry to ensure successful outcomes, without compromising air quality goals.

Long-term vision and clear goals. Long-term visioning and strategy planning processes, combined with clear goals and specific targets, provide greater visibility and certainty for manufacturers, equipment owners, policy makers, and the public. California's experience suggests that this longer-term certainty enables manufacturers to invest more in the capital-intensive research and development required to make significant improvements in technology. It also provides regulators with the ability to set longer lead times for manufacturers and equipment owners to meet standards, increasing the chances of successes.

Integrated planning. Increasingly, environmental regulators are being required to meet goals for multiple pollutants and GHG emissions. Meeting all of these goals simultaneously, rather than trying to meet each of them separately, will likely lower costs. California's experience highlights the importance of long-term strategy planning, coordinating planning processes, and collaboration among government agencies for successfully integrating air quality and GHG planning.

Incentives and funding. Incentives can play an important role in encouraging adoption of new technologies. In California, for instance, grants and loans have been important in encouraging diesel vehicle owners to purchase new vehicles that meet emissions standards. Identifying a source of funds, for instance, through taxes or surcharges, is important for ensuring the sustainability of funding.

Proactive enforcement. Enforcement is often the most critical, tedious, and difficult part of air quality management. New technologies, such as advanced air quality monitoring and on-board diagnostic systems, are opening up new frontiers for enforcement. In California, taking advantage of these opportunities has required proactively upgrading enforcement programs and tackling new issues – for instance, how can regulatory agencies ensure that the data from on-board diagnostic systems is accurate? Warranties and labeling are also important elements of enforcement.

California-China Collaboration

Over the past two decades, California state agencies have developed a number of collaborative agreements and activities with their counterparts in China. These relationships have deepened and grown richer over time, and they are now beginning to bear fruit.

For instance, ARB supported the Beijing Environmental Protection Bureau's (EPB's) development of new emissions standards for light- and heavy-duty vehicles. Beijing's proposed Beijing 6 and VI standards (2015) incorporated a number of elements from California's mobile source regulations. As another example, under California's memorandum of understanding (MOU) with Guangdong Province, California state agencies have supported the design of Guangdong's cap-and-trade system and a potential carbon-labeling program.

The most important form of collaboration between California state agencies and government agencies in China has been information exchange. Through cooperation, both sides have developed a deeper understanding of how and why different policies and practices have evolved in each area, beginning to bridge the information gaps between policymakers and regulators in China and the United States. Collaboration has also enabled government agencies in China to translate policies and practices from California to their own contexts and will help California learn from China's experience. Collaboration between entities in China and California on environmental issues, and particularly climate change, is serving as a successful model for subnational collaboration elsewhere.

Going forward, focal areas of collaboration between California state agencies and provincial-level governments in China include clean technology development and innovation, long-term strategies for reducing GHG emissions, energy efficiency and renewable energy, and market-based solutions for reducing GHG emissions.

4.3 MARKET FACILITATION

As part of this report, we conducted a small survey of 18 U.S. clean air technology companies, to understand perceived barriers to market entry in China. These surveys consisted of short interviews with business development managers and executives in a number of industries germane to the technology categories in this report: air quality sensors, diesel emissions controls, electric vehicle equipment, heavy-duty alternative fuel vehicles, VOC end-of-pipe treatment, VOC leak detection and repair, and low-impact solvents. While not a representative survey, the results provide insight into some of the key challenges faced by U.S. clean air technology suppliers in entering the Chinese market.

Survey respondents identified five areas in which support from governmental and non-governmental organizations could facilitate smoother market entry in China:

- Local partnerships;
- Intellectual property rights;
- Regulatory framework;
- Public awareness of air pollution issues; and
- Technology harmonization.

Table 13 shows the number of companies that believed each of these five areas was a key concern in entering the Chinese market. The remainder of this section explores these responses in greater detail.

Table 13: Summary of China Market-Entry Barriers for U.S. Clean Air Technology Providers

TECHNOLOGY CATEGORY	SURVEY COUNT	LOCAL PARTNERSHIPS	INTELLECTUAL PROPERTY	REGULATORY FRAMEWORK	PUBLIC AWARENESS	TECH. HARMONIZATION
Air quality sensors	3	1	1		1	1
Diesel emissions controls	3	1		3	1	3
Electric vehicle equipment	1	1				1
Alternative fuel heavy-duty vehicles	6	4	3	1	2	1
VOC end-of-pipe treatment	1	1		1		
VOC leak detection and repair	3	3	2	2	2	1
Low-impact solvents	1			1		

4.3.1 Local Partnerships

A number of survey respondents, particularly in emerging technology areas, identified the need for a platform to identify and build partnerships with Chinese domestic organizations as the largest barrier to entering the Chinese market for clean technologies. Respondents noted that in a country such as China with a business culture heavily built around personal relationships, networking opportunities at trade shows or other conferences are a crucial mechanism through which to build partnerships. A number of companies, even those with established partners and supply chains in China, also cited the difficulty of staying up-to-date on recent developments in regulation, technology, and markets in China.

To overcome the challenges of developing local partnerships and maintaining local knowledge, respondents suggested that market facilitators – government agencies, think tanks, industry associations, and innovation centers in the United States and in China that focus on market development – could organize regular conferences or business matchmaking tours for specific industries or technologies. Market facilitators could provide news and market updates through familiar media, such as trade association newsletters.

4.3.2 Intellectual Property Rights

Concerns over protection of intellectual property rights were mentioned by a number of respondents as a barrier to entering the Chinese market. For technologies that are considered advanced or emerging, companies noted that intellectual property is their key asset. According to respondents, there is a general perception that China does not provide adequate protections for intellectual property, which has made U.S. companies more cautious when considering joint ventures or other kinds of partnerships, and more reluctant to enter the market overall.

4.3.3 Regulatory Framework

Survey respondents also cited differences in regulatory frameworks – air quality standards, emissions standards, warranty requirements, enforcement, incentives, and other regulatory elements – between the United States and China as a barrier to entering the Chinese market. That is, regulatory standards and enforcements in China are not yet sufficiently stringent for the respondents to feel that their technologies will be cost effective. For emerging technologies, incentives and financing options may not yet be sufficient to bridge the gap between benefits and costs. In the United States, incentives and financing play an important role in technological change.

For pollutants that have only recently begun to be regulated in China, such as VOCs, respondents noted that current policies and regulations in China do not yet clarify which government agency is responsible for enforcement, practices by local environmental protection bureaus are often different and may not be easily available or available in English, and enforcement may not yet be sufficiently stringent or consistent to drive end-user adoption. For diesel emissions control technologies, respondents noted that difficulties in enforcing the use of low-sulfur diesel were a barrier to U.S. technologies.

4.3.4 Public Awareness

Some clean air technologies, such as remote air quality sensors and zero-emissions transit buses, are procured by government agencies in the public interest. While public awareness of environmental issues in China has risen dramatically, some respondents cited increased public awareness as a necessary driver for more widespread adoption of specific clean air technologies. This argument is premised on the notion that a more environmentally conscious public will encourage government agencies to purchase more advanced monitoring equipment and pollution control equipment on public vehicles in the public interest.

4.3.5 Technology Harmonization

Survey respondents observed that the lack of harmonized technologies and technology standards between the United States and China is also a market barrier for U.S. companies. For instance, without more stringent standards for particulate emissions, diesel manufacturers and vehicle owners are unlikely to install diesel particulate filters. Emerging technologies also often have competing technology standards, such as has been the case with electric vehicle charging standards. Some respondents noted a willingness to enter the Chinese market "early," in anticipation of technology harmonization, to build supply chains and a customer base.

5. CONCLUSIONS AND RECOMMENDATIONS

Achieving China's goals for cleaner air will require an extensive deployment of technologies over the coming decade. In many instances, there will be synergies between efforts to reduce air pollution and efforts to reduce greenhouse gas emissions and meet longer-term climate policy goals. Clean air technologies and regulatory experience from the United States could play an important supportive role in helping China meet its air quality goals, and in helping align the technology transformations needed to meet air quality and climate goals over the longer term.

To more fully capitalize on the potential for China-U.S. collaboration on clean air technologies, we recommend three activities with which near-term partnerships and exchange between China and the United States could produce transformative results.

Joint collaboration on strategies for meeting long-term air quality and climate goals. As has been the case in California, long-term visioning and strategy studies would provide manufacturers with greater certainty on the kinds of technologies needed to meet longer-term goals, as well as the size of markets and the magnitude of investments. China-U.S. collaboration in this area would enable greater harmonization and eventual convergence in longer-term air quality and emissions standards, creating much larger markets for clean air technologies, spurring innovation, and driving down technology costs.

To our knowledge, China and the United States have not formally engaged in this kind of joint visioning exercise, though there are a number of potential platforms for doing so. These include existing intergovernmental relationships (e.g., NDRC-MEP and EPA), the U.S.-China Climate Change Working Group, and non-governmental partnerships (e.g., the Deep Decarbonization Pathways Project, the International Zero-Emission Vehicle Alliance).

Deeper collaboration on enabling regulatory strategies. As China develops the regulatory systems needed to address more complex pollution problems, U.S. experience could provide a valuable resource. Significant exchanges have already taken place between EPA and MEP at a national level, and ARB and the Beijing Environmental Protection Bureau at a local level. Establishing these kinds of partnerships will also enable air regulators in the United States to learn from regulatory innovations in China over the next decade, as China moves to improve air quality. Deepening exchanges between regulators in China and the United States and expanding them to other provinces in China and states in the United States require new thinking about forms of collaboration, sources of funding, goals, and metrics for success.

Non-governmental actors can play an important role in facilitating exchange between government agencies in China and the United States on detailed regulatory issues. For instance, UCLA's Center for Clean Air holds an annual air quality management training workshop, in collaboration with the South Coast Air Quality Management District and ARB, that introduces regulators in China to California's regulatory experience. The Energy Foundation and the Clean Air Alliance of China have also played an important role in supporting this kind of exchange.

Joint efforts to facilitate market entry, innovation, and healthy competition. As two of the world's largest markets for clean air technologies, China and the United States have a powerful influence on the direction of global technology development. Together, through a common market, China and the United States can drive innovation and competition to lower the costs of cleaner air and efforts to reduce the risks of climate change. Creating this larger market likely requires joint efforts to identify existing barriers to market entry and taking reciprocal steps to reduce them.

More formally, such efforts could consist of joint studies as part of the Strategic and Economic Dialogue. More informally, they could consist of studies or facilitative efforts undertaken by nongovernmental organizations, such as industry associations or trade and business development agencies.

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